Design of a continuous flow biodiesel production research unit

Collaboration Project Between

McGill University, Macdonald Campus, Bioresource Engineering Department
And
Tamil Nadu Agricultural University, BioEnergy Department

Presented to

Dr. G. S. V. Raghavan, James McGill Professor, McGill University

Dr. A. Sampathrajan, Dean Agri. Eng. College & Research Institute, TNAU

Dr. P. Venkatachalam, Professor and Head of BioEnergy Department, TNAU

By

Thomas Fortin-Chevalier
Pénéloppe Thériault

Tamil Nadu Agricultural University
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McGill

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1. Executive Summary

Collaboration work between McGill University and TNAU started in 2002. The collaboration started through a CIDA financed project called: "Food security in South India". The Post Harvest Technology Center has been the main department involved in this project. Collaboration has also been established with the BioEnergy Department over time. This is a report on the second collaboration project between the McGill Bioresource Engineering Department and the TNAU BioEnergy Department since 2005.

The BioEnergy Department of TNAU has been investing a lot of efforts in biodiesel production from Jatropha oil. The department has looked at batch type production from Jatropha: its efforts resulted in the achievement of a pilot-plant for biodiesel production and the exportation of its know-how for commercial uses. The current project is to improve efficiency and performance of biodiesel production by shifting from a batch production to a continuous production. The designed unit will also allow for methanol recovery.

The batch type system that was developed at TNAU has a reaction time of about 2 hours, a methanol to oil molar ratio of 6 to 1, and does not recover the remaining methanol. With the continuous flow research unit, the students are aiming to achieve the reaction within 10 minutes and to use a lower methanol to oil molar ratio of about 4 to 1. Furthermore, the design is expected to be highly effective to recover methanol.

The lab scale unit will allow to monitor the reaction parameters and to better understand the system as a whole. The unit was designed to be very versatile: every component can be analyzed and understood separately. The feasibility of using such a system for continuous flow production can be assessed and consequent scale-up may occur.

The design is a scale up of the experimental set-up of a team from Idaho University, Moscow, Idaho. (Singh, Thompson et al. 2004; He, Singh et al. 2005; He, Singh et al. 2006; He, Singh et al. 2007). Its principle relies on the use of a reactor where recovered methanol vapor travels up and the reacting solution flows down. Thus, this vapor-liquid reaction allows for faster and

more efficient biodiesel production. The lab-scale unit will work under gravity only, which therefore allows for very small flows. This also reduces the fabrication cost as well as the energy consumption.

2. Acknowledgements

The project presented in this document would not have been possible without the generous help of many people. The students' recognition goes in the forefront to Dr. G. S. V. Raghavan without whom this project would not have existed. Thanks for his wise advices and motivating energy.

Secondly, the students would like to thank students and staff members from TNAU for their kind reception. Special thanks to the Dean of the Agricultural Engineering College and Research Institute, Dr. Sampathrajan and the Head of the BioEnergy Department, Dr. Venkatachalam for their precious advice on site, their great and immediate support as well as their warm welcome in the faculty and department.

Thanks to all the departmental staff from the BioEnergy Department, especially P. Chitra who facilitated the students' integration into the department. Thanks to all the workers in the BioEnergy and Food Processing engineering workshops for their help. Thanks to the Head of Post Harvest Technology Center, Dr. N. Varadharaju and all his team. Special mention to Sir Sivakumar, who was always available for help and advice, and who greatly helped the students to get organized during the first weeks.

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3. Introduction

Human development towards advance society would not be possible without energy. Recently, there have been major advances in the techniques and technologies used to obtain energy, which allowed to improve well-being for most of the world population. However, parallel to this increase in well-being and comfort is a growing demand on the resources required to get the energy. Moreover, because energy is affordable, people tend to consume more than they really need.

The overall energy consumption will keep increasing along with the increase in world population. This increase in consumption will become a serious issue as more and more people will have purchasing power, thus consuming more and more goods. Such phenomenon will mostly be felt in highly populated countries like China and India. For instance, it is believed that the number of car in India will increase from 14 to 48 per 1000, while the number of 2 wheelers from 102 to 393 per 1000 in the next 20 years. (Francis, Edinger et al. 2005)

The major concern is that the worldwide oil production is expected to peak around 2012. At this time, energy consumption will still be rising exponentially. Therefore, there will be a growing gap between the energy needs and the energy available, which is most likely to result in the cost of energy becoming outrageously expensive.

India's economical development directly relies on its ability to get cheap energy. The government is aware of this and is already foreseeing the energy crisis. Hence, the production of biodiesel from non-edible oil is part of the solution to decrease India's dependence on fossil fuel. Some projects have already started to invest the potential of biodiesel production in an Indian context.

At Tamil Nadu Agricultural University, the BioEnergy Department of the Agricultural Engineering College and Research Institute has invested efforts in this energy challenge proposed by the government to the Indian scientists' community. A biodiesel batch type unit was developed to produce diesel in a 2 hours delay. This unit serves as a model for some

industries ~~in the university area~~. In addition, the TNAU Forest Institute, located outside the main campus, is looking at the optimal biomass source for the production of non-edible oil dedicated to be transformed into biodiesel. Their main focus is on Jatropha.

Now that the biodiesel challenge has been assessed and accepted as a sustainable solution, the next logical step is to improve the production process. It has to become more beneficially economically, and more efficient in terms of energy and resource consumption. This design project explores the avenues of continuous flow production using reactive distillation technologies which would allow for faster and cheaper process.

The first part of this document is a general overview of the biodiesel production from chemical, technical, contextual, and economical point of views. Then, all the design considerations are explored and sizing calculations presented. Since this project is done in the scope of the "BREE-492 Design course" of McGill University and consists of the first design process for the students, all the design steps are explained clearly. Finally, recommendations for the future utilization of the unit are presented.

4. Objectives

Already equipped with a batch type biodiesel production system, the staff from TNAU BioEnergy Department showed interest in studying the production of biodiesel using a continuous flow unit which allows for methanol recovery. The design of such a unit will allow: to study and to understand the different mechanisms that drive the system, to optimize the system and to eventually scale it up. Literature suggests that reactive distillation column system is an efficient way of producing biodiesel and to recover methanol. The objective of the project was formulated upon this information.

To design a lab-scale flexible continuous flow reactive distillation unit for research on biodiesel production including methanol recovery.

The research unit must fulfil the following criteria:

a) To convert *Jatropha curcas* oil to biodiesel conform to the ASTM standards
b) To decrease the demand of alcohol for the reaction
c) To decrease the reaction time for biodiesel production
d) To recover the methanol that has not reacted in the process
e) To be as flexible as possible to allow for further modifications and research , such as:
   - Reactions in each part of the system could be analysed separately
   - Supplemental technologies such as ultrasounds devices could easily be added

5. Literature Review

(Note: this section is taken directly from the proposal)

With the upcoming peak in oil production and the never ending increase in energy demand, societies are searching to rely on sources of energy other than fossil fuel. One of the promising fields in the renewable energy production is the use of biomass. The consumption of diesel oil in India was about 87.5 millions tons in 2003-2004 (Mohibbe Azam, Waris et al. 2005). Hence, part of this fuel could be replaced by biodiesel.

Made from vegetable oil, biodiesel would consequently decrease the country dependence on fossil fuel. Considering the high demand for edible oil in the country, it would not be a viable solution to produce biodiesel out of such oil; instead research has been done to look at the use of non-edible oil. From those investigative efforts, the *Jatropha curcas* has been identified as one of the most promising crops: it can grow in arid, semiarid and wasteland (Mohibbe Azam, Waris et al. 2005); (Kumar and Sharma 2005); (Openshaw 2000); (Banerji, Chowdhury et al. 1985); (Kandpal and Madan 1995); (Augustus, Jayabalan et al. 2002). It requires little water and fertilizer, can survive on infertile soils, and is not browsed by cattle (Sarin, Sharma et al. 2007).

Based on Mohibbe, the entire Indian diesel consumption could be replaced by biodiesel by dedicating 45% of the 96 millions hectares of the country wasteland to *Jatropha curcas* crop (Mohibbe Azam, Waris et al. 2005). However, the seeds contain toxins which make the *Jatropha curcas* crude cake toxic and not directly usable as animal feed.

5.1 Biodiesel production

The production of biodiesel from vegetable oil consists of a simple chemical process called the transesterification which has been used since 1944. It was first patented for the soap production from natural oils and fats (Ma and Hanna 1999). The vegetable oil, consisting of triglyceride, is mixed with an alcohol and a catalyst. The solution is heated up just below the boiling point of the alcohol to allow the reaction to occur. This yields a mixture of free acid methyl ester (FAME, which is biodiesel), glycerol and other by-products (soap). The alcohol and the oil are

not miscible and need a vigorous mixing to allow the reaction to start. (Meher, Vidya Sagar et al. 2006)

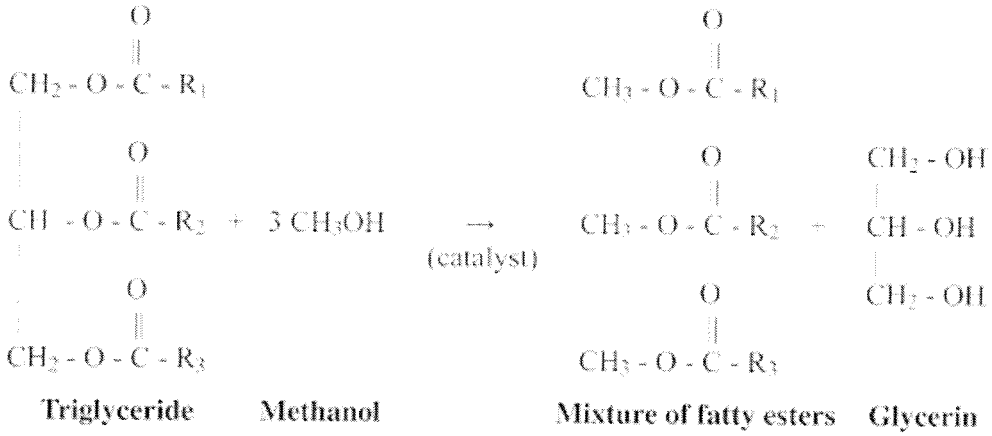


Figure 5.1: Transesterification chemical reaction
(Singh, Thompson et al. 2004; Thompson and He 2007)

From a strict stoichiometric view, the reaction would need oil to alcohol ratio of 3 to 1. However, the reaction being an equilibrium equation, it requires an excess quantity of alcohol to ensure the complete reaction of the oil. The general accepted value in the literature for this ratio is 6 to 1 (Ma and Hanna 1999).

The formation of soap during the process is an issue: it reduces catalyst efficiency, favors formation of gels and makes the separation of glycerol from the biodiesel difficult (Ma and Hanna 1999). However, the saponification reaction can be significantly reduced by ensuring that the oil has low water content and low level of free fatty acids.

There are three possible types of catalysts: acidic, alkaline or enzymatic. The alkaline process performs faster than the other two (Ma and Hanna 1999). However, this type of catalyst works better in absence of water and with low level of free fatty acids (FFA) in the oil (Ma and Hanna 1999). For FFA levels below 5%, the addition of a base catalyst compensates for the higher acidity while for levels higher than 5%, the reaction is inhibited (Gerpen, 2005). In addition, alkaline reactions with high concentrations of FFA will result in higher levels of soap formation. Consequently, this increases the viscosity and the formation of gels, which both interfere with the reaction and harden the separation of glycerol (Meher, Vidya Sagar et al. 2006).

Acidic catalysts are preferred for cases with high levels of free fatty acid (Ma and Hanna 1999; Gerpen 2005). Concerning processes using enzymatic catalysts, they have greater tolerance to free fatty acids and they yield little by-products. Glycerol separation is also easier with such processes. The down sides are the significantly greater cost of production and the fact that no satisfactory levels of completion have been obtained yet (Gerpen 2005; Meher, Vidya Sagar et al. 2006).

Many parameters influence the transesterification process: amount of water in the oil, level of free fatty acid, feed molar ratio, reaction time, catalyst concentration, and catalyst type.
Even though each of the individual parameters affects the process efficiency separately, the interaction between the parameters seem to have a synergistic effect and affect the overall process more significantly (He, Singh et al. 2005).

5.2 Biodiesel production systems

The transesterification process can be carried through batch or continuous system. Continuous systems include techniques such as supercritical alcohol, the use of reactive distillation columns, and the use of static mixers. Newer techniques incorporate the use of microwaves and ultrasounds. Table 5.1 resumes the major features differentiating those production processes.

Table 5.1: Characteristics of different biodiesel production types

Process Type	Reaction Time	Alcohol to oil ratio	Yield	Temperature (°C)	References
Batch	1 - 2 hr	6:1	up to 98%	60	Ma, 1999
Continuous					
Supercritical	2-4 min	40:1	up to 96%	340	Bunyakiat, 2006
Reactive Distillation	3 - 6 min	3.0 - 4.5 :1	up to 98.8%	50 - 65	He, 2005; Peterson 2004
Static mixers	15-30 min	6:1	*	30 - 60	Thompson, 2007
Microwaves	1- 5 min.	6 – 18:1	up to 98%	50-65	Mazzocchia 2006

* *Different way to calculate yield: less 1% glyceride present in final product*

Batch production is known to be slow, tedious, labor intensive and low in productivity (Singh, Thompson et al. 2004). On the other side, production using continuous flow generally produces more fuel per unit of labor and allows for larger scale projects, thus reducing the overall cost of production (Peterson, Cook et al. 2002).

5.2.1 Supercritical

One of the commonly studied processes is the supercritical method. It is advantageous due to its short reaction time. On the other hand, the alcohol to oil ratio and the reaction temperature are the highest of all processes showed in Table 5.1. Because of those two reasons, this method was not considered appropriate to suit the needs of TNAU and India energy situation.

5.2.2 Reactive distillation

Another relatively new and unexplored way of producing biodiesel is the reactive distillation method. It implies simultaneous chemical reactions and distillation processes in a counter-current column (Singh, Thompson et al. 2004). The reaction time is not much longer than for the supercritical method, while the alcohol to oil ratio as well as the reactor temperature are both considerably lower.

The system consists of a reactive distillation column fed at the top with the initial reactive solution (oil, alcohol, catalyst). This solution slowly travels down between the plates (*refer to figure 5.2*). When the solution exits the column, the alcohol that has not reacted is recuperated by evaporation. Then, the vapours are re-circulated in the reactive distillation column in the upward direction passing through the plates.

As the vapours travel through, interactions between the gaseous alcohol and the liquid solution occur. This then would increase the effective oil to alcohol ratio up to 20:1 (He, Singh et al. 2006), thus shifting the reaction equilibrium to the product side and therefore increasing the reaction efficiency. Finally, once the alcohol vapours have reached the top of the reactive distillation column, they are condensed through a condenser allowing the remaining alcohol fraction to re-enter the system.

Prior to enter the reactive distillation column, the solution has to be well mixed to allow the reaction to start. Hence, a pre-reactor, consisting of a heated static mixer, is needed. This unit not only mixes the solution but also carries substantial part of the actual reaction (Singh, Thompson et al. 2004; He, Singh et al. 2006). Based on this notion, one study has been conducted (Thompson and He 2007) to evaluate the potential of using only the pre-reactor to complete the transesterification reaction. Results from this experiment showed the biodiesel quality was above the ASTM standard. Unfortunately, it did not give results on the conversion yield.

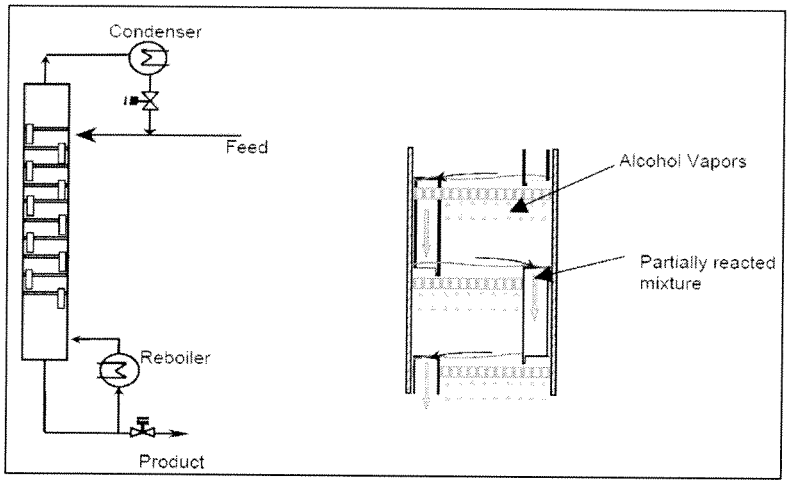


Figure 5.2: Reactive distillation column
(Singh, Thompson et al. 2004; Thompson and He 2007)

Another advantage of this system is its relatively low reaction temperature and alcohol to oil ratio compared to Supercritical system, making it more energy efficient. Hence, this is the chosen system for the design. The feedback from the staff of BioEnergy Department and the designers' background knowledge suggest that such a system would answer best the needs of TNAU and allow for further research in the future.

6. Design

The design of this unit was based on papers published by a team from Idaho University, Moscow, Idaho. Their simple reactive distillation system for production of biodiesel was tested under different experimental conditions since 2004 and showed very good results. Therefore, this type of process was selected by the student since it seems to be a viable option for continuous flow process. The original parameters for this design were directly taken from those papers. (Singh, Thompson et al. 2004; Singh, He et al. 2005; He, Singh et al. 2006, Thompson et al. 2006) The points that were selected as design criteria were: the retention time in the reactor, the working volume of the reactor, the alcohol to oil ratio, and the overall process time. The idea behind this design is to verify the general driving principles and the feasibility of producing biodiesel under such process. The approach used in regard to the fabrication is that no expensive piece of equipment has to be purchased. Instead, the various components of the system are designed by the two students and fabricated by local suppliers.

6.1 Design considerations

6.1.1 Sizing parameters

The retention time used by the Idaho team varies from 2 to 10 minutes. (Singh, Thompson et al. 2004; Singh, He et al. 2005; He, Singh et al. 2006, Thompson et al. 2006). The present research unit is designed to operate within the same range of retention times. The reactor (distillation column) used in the literature has a working volume of 10 mL (Singh, Thompson et al. 2004; Singh, He et al. 2005; He, Singh et al. 2006, Thompson et al. 2006). With such retention time and working volume, the overall flow in the system varies between 1 and 5 mL/min. This results in a flow of methanol as low as 0.2 mL/min. Such parameters are achievable, but require very expensive and precise pieces of equipment. Instead, the working volume of the reactor is increased to 100 mL, which results in a flow range varying from 10 to 50 mL/min and a bigger methanol flow.

Another important criterion to consider while sizing the equipment is the alcohol to oil molar ratio. The general accepted value is six moles of methanol for one mole of oil. However, with this apparatus, the students are aiming to decrease the molar ratio.

The last design factor to be fixed is the unit process time. The maximum running time has been fixed to 3 hours: during the first hour, adjustments will be made and the unit is expected to reach its maximum conversion capacity during that time period; during the last two hours, the unit should work under its full potential and samples could be taken. In addition, having a production time set to 3 hours allows separation process to be done in decanters instead of using centrifugal pumps.

Based on those previous fixed parameters, it was possible to calculate and size every component of the system (*refer to section 7 - Calculations*).

6.1.2 Gravity

One of the major feature and advantage of the system is that it uses gravity. This offers many advantages. First, using valves is enough to regulate the methanol and oil flows since they are relatively small. Consequently, it decreases material requirement since no pump or flow meter is required. Secondly, it decreases the energy consumption of the system and makes it more energy efficient. However, there are also disadvantages associated with valve regulated flows: a longer time is required to set-up an experimental run and the flows might be less accurate and ~~slightly~~ fluctuating.

6.1.3 Versatile

Another important point that has been considered is the versatility of the system. Since this is a research unit, many types of experiments must be easily performed and the unit should be easily modified in order to suit the experimental set-ups. One of the major features is that every component can be by-passed. Connections and pipes have been installed for easy redirection of the flow. This enables the study of each component and a good understanding of its influence on the overall conversion of oil to biodiesel. In addition, the structural frame is done with slotted angles; therefore, components can easily be moved or added.

6.1.4 Monitoring

In order to understand the system, monitoring of the temperature is essential. Also, the temperature of the pre-reactor and the reactor are to be constant at all time to 55 and 60 degree Celsius respectively. Therefore, thermocouples are essentials and are installed at six different places in the system. A thermoregulator is also used to regulate the temperature of the solution in the reactor.

6.2 Components information

6.2.1 Materials

Methanol and sodium hydroxide, two reactive components, are present in the system. Hence, building materials were chosen consequently to avoid any reaction: the components are constructed in stainless steel and glass; the pipes are either silicone tubes or braided nylon, which are known to be non-reactive. The methanol containers consist of urine bags used in hospitals. The material is polythene.

6.2.2 Oil container

The design of the oil container did not represent any major challenge. Since the flow is powered by gravity, the height of the container needs to be small to avoid significant change in head pressure. Also, due to fire concern and to ensure that no impurity gets in contact with the oil, the container must be covered.

6.2.3 Methanol container and collector

Methanol vapor is harmful for human health and represents a fire/explosion hazard. For this reason, the design of the methanol container and the methanol collector presented a challenge. After many ideas and preliminary designs of containers using one-way valves, the methanol container and collector became simple bags. This option eliminates the problem of having methanol vapor exiting the containers when they are filled. Instead, the empty bags simply open up as methanol enters.

The bags selected are urine bags taken directly from a hospital supplier. They are the best option since they are cheap, they can hold large volume of liquid, they are easily available, and

they are already equipped with inlet and outlet. In addition, those bags are easily filled with a 60 mL syringe. However, there might be undesired reactions since those bags are made out of polythene. (did you check the reactivity with methanol?)

6.2.4 Pre-reactor

The initial pre-reactor was supposed to be an in-line static mixer. However, since no pump is used in the system, concerns about mixing efficiency arose because pressure would not be sufficient. Consequently, the pre-reactor was changed to be an erlen meyer with a magnetic stirrer. The shape of the container is ideal: the top is easily closed to avoid methanol vapor to exit; the flat bottom allows to install the container on a hot plate and to use a magnetic stirrer for efficient mixing.

In order to work under continuous flow, some modifications were done to the erlen meyer. Based on the flow and the desired retention time, the liquid working volume in the pre-reactor was found (*refer to section 7 - Calculations*). An inclined pipe was inserted at the desired liquid level (*see outlet #1 in Figure 6.1*). Therefore, the hot liquid layer, located at the top, is drained out as the colder solution flows into the pre-reactor.

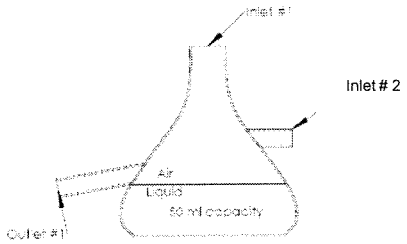


Figure 6.1: Pre-Reactor

6.2.5 Burettes

The burettes were designed to hold the maximum flow for about four minutes in order to calculate the actual flow and adjust it if required. Each of the burette top was modified with a restriction so the pipe can directly be installed on it. A small air outlet was also perforated at the top so that burettes could be filled even when the stopcocks are closed.

6.2.6 Reactor

The reactor is the main component of the system. It is this particular item that contributes to decrease the required oil to methanol molar ratio and to increase the overall efficiency of the process.

The reactor was complex to design, and by far the most complicated component to ~~get~~ built since precise machinists that understand CAD drawings were extremely hard to find in Coimbatore. The component has three main parts: a top, an outer shell, and a plate system. All parts are made of stainless steel.

The top is basically a cone with a flange for solid fixing with the outer shell. This part has an outlet for the methanol vapor to exit. There is also a 3/8'' female connection so that a manometer can be connected to the reactor.

The outer shell was made using a standard pipe, with a cone at the bottom and a flange at the top. There is an inlet at the top, for the liquid solution to enter. The solution exits by a ½'' orifice at the bottom of the cone. The outlet has a bigger size since it is predicted that the solution's viscosity will increase in the reactor. There is also a vapor inlet in the cone. A 3/8'' female connection is also present at the bottom of the column for potential pressure measurement.

The section that requires the most design precision is the plate system. It ~~constitutes~~ consists of a central treaded rod on which perforated plates are inserted and fixed using bolts. Each plate has approximately one hundred perforations of 0.5 mm. The plates' diameter is equal to the inner diameter of the outer shell. Also, weirs were made by inserting small pipes through each plate. Those pipes extend 2 mm from the plate top surface. This allows for the proper hold up of solution on each plate. Also, the bottom end of those pipes is at a distance of 1mm from the plate underneath. This ensures that no methanol vapor enters by the weir.

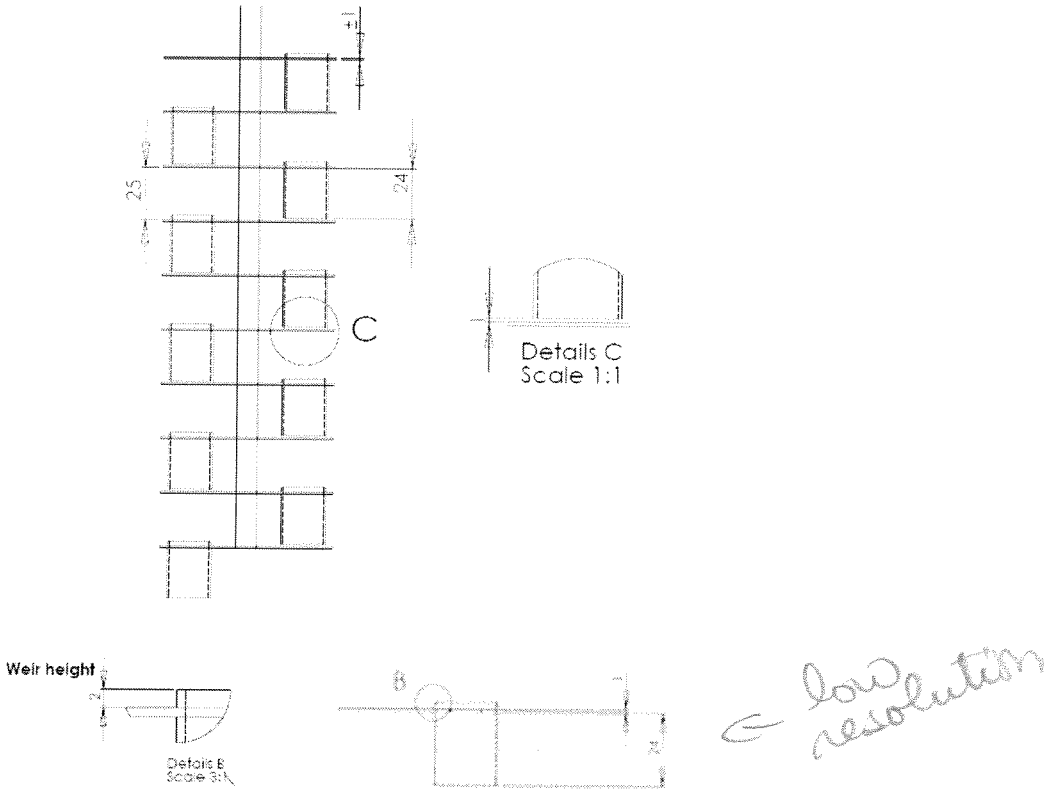


Figure 6.2: Plates inserted inside reactor

The reactor is fixed to the frame using a rod (welded to the column's top) and a clip that holds the bottom part. A heating mantle was designed for this component. With a thermoregulator, the temperature inside the reactor will be kept at 60°C.

6.2.7 Evaporator

Based on the required working volume for the evaporator (*refer to section 7 - Calculations*), a round flask of 500 mL seemed to best fit the requirements. Like with the pre-reactor, a pipe was inserted at the desired liquid level to maintain the right working volume. A vapor outlet was also added on the flask. To avoid having vapor escape by the inlet, entering solution flows through a glass pipe with submerged end.

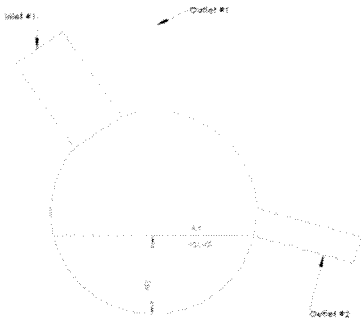


Figure 6.3: Evaporator

6.2.8 Decanter

The unit deals with low volume. Hence, the usage of a centrifugal separator is not required as it is usually done with continuous flow. Instead, glass containers are used for separation. This material was selected to allow to see the solution when doing the separation process and consequently to make a better separation. Because part of the final solution is semi-solid impure glycerol at room temperature, the outlet was designed bigger than the inlet, with a diameter of one inch.

6.2.9 Vapor pipes between reactor and condenser

After preliminary testing with water vapor, the students realized that condensation occurred in the silicone tubes connecting the reactor to the condenser, as well as in the reactor by-pass. Consequently, the methanol vapor would not reach the condenser. Therefore, stainless steel pipes covered with heating coils were used to replace the silicon tubes. As a result, the vapor is kept to the desired temperature and a natural upward convection is generated. This generates a suction effect. The temperature is monitored and controlled with the thermocouple installed at the entrance of the condenser.

6.2.10 Condenser

A colloidal condenser of 30 cm length was purchased. This size offers a bigger contact area than the minimal required area calculated for heat transfer. The ends of the cooling fluid compartment were restricted so pipes would easily connect on it. Apart from this, no other modification was made on the condenser.

Pictures of the actual components are included in *Appendix 1*.

6.3 Future experimental set-ups

Many experiments need to be done to test the performance of the unit and to verify the feasibility of producing biodiesel with such a system. Considering the unit's high versatility, many different experimental set-ups can be done.

6.3.1 Preliminary testing

The preliminary testing involves performing simple tests with parameters similar to those used in the literature. This allows to assess the quality of the biodiesel yield. In addition, it permits to verify if calculations match the actual measured parameters. Those preliminary tests are done to evaluate how the system works and to better understand it. They are not aiming at finding optimal conditions for biodiesel production.

6.3.2 Optimization

The major set of experiments consists in the optimization of the system. Those experiments should be run with the full system and include all the components. Retention time, molar ratio, concentration of NaOH, and evaporator temperature should all be tested within the expected range. From those tests, it is possible to find the optimal conditions under which yield of biodiesel is the highest.

6.3.3 Components efficiency

The last set of experiments would be to by-pass some components, such as the pre-reactor or the reactor, and to evaluate their actual contribution to the overall oil to biodiesel conversion. In addition, another set of experiments could be ~~run~~ done to see where the recovered methanol should be re-inserted in the system: in the initial methanol container, before the pre-reactor, or before the reactor.

7. Calculations

7.1 Starting point parameters for the design

In order to design the system, some starting point parameters had to be determined and fixed. From those initial design parameters, all the sizing calculations could be done and an integrated excel worksheet could be completed. In this design, the basic parameters were:

- Retention time in the distillation column
- Minimum allowable flow of reactant
- Maximum unit operation time

7.2 Volume and retention time of reactor

The distillation column tested in the literature (He, Singh et al. 2005; He, Singh et al. 2006; He, Singh et al. 2007) had good biodiesel yield with retention times inside the column varying from 2 to 10 minutes. Therefore, the present research unit was designed to operate within the same range of retention times.

The working volume of the reactor has been fixed through trial and error using an excel sheet. The design criterion was to get methanol flow above 1 mL/min due to flow measurement constraints. A 100 mL reactor was chosen, which therefore gave overall flows varying between 10 and 50 mL/min and a minimal methanol flow of 1.1 mL/min.

$$Q_{max} = \frac{V_{RD\,Column}}{RT_{min}} = \frac{100\,ml}{2\,min} = \mathbf{50}\,\frac{\mathbf{ml}}{\mathbf{min}}$$

$$Q_{min} = \frac{V_{RD\,Column}}{RT_{max}} = \frac{100\,ml}{10\,min} = \mathbf{10}\,\frac{\mathbf{ml}}{\mathbf{min}}$$

Table 7.1: Flow in function of reactor volume

Reactor_Volume (mL)	Flow (mL/min) 2 min	10 min
60	30	6
70	35	7
80	40	8
90	45	9
100	50	10
110	55	11
120	60	12
130	65	13

7.3 Unit operation time

As mentioned in the design section (*refer to section 6.1.1 - Sizing parameters*), the maximum operating time was fixed to 3 hours: during the first hour, the unit is expected to stabilize and reach its maximum conversion capacity; during the last two hours, the unit should work under its full potential and samples could be taken. In addition, having a maximum production time set to 3 hours allows the separation process to be done in decanters instead of using centrifugal pumps. Why is that ?

7.4 Required volume for pre-reactor

The range of retention time in the pre-reactor should be between 1 and 4 minutes as cited in the literature (Singh, Thompson et al. 2004; He, Singh et al. 2006). Such a retention time should be long enough to heat the solution to 55°C and allow for adequate mixing. The reaction is expected to start in the pre-reactor.

By trial and error and by considering the overall flow, the ideal working volume was fixed at 50 mL.

$$RT_{min-pre\text{-}reactor} = \frac{V_{pre\text{-}reactor}}{Q} = \frac{50\ ml}{10\ \frac{ml}{min}} = 5\ min$$

Table 7.2: Retention time in the reactor based on the working volume

Volume	Retention Time (min)	
	Qmin=10mL/min	Qmax=50mL/min
20	2	0,4
30	3	0,6
40	4	0,8
50	5	1
60	6	1,2
70	7	1,4
80	8	1,6
90	9	1,8

7.5 Required range of pumping rates

Based on the literature(He, Singh et al. 2005), the expected methanol to oil molar ratio for this research unit will varies between 3:1 and 6:1.

Step 1: Find the molar volume of reactants at room temperature

The unit is located in Coimbatore in an open environment without air conditioning. Therefore the room temperature was set to 30°C.

$$\textbf{Molar volume} = \frac{\textbf{Molar mass}}{\textbf{Density}}$$

$$\text{Molar volume Jatropha Oil}_{(30\,^\circ\text{C})} = 870\,\frac{\text{g}}{\text{mol}} \times \frac{\text{m}^3}{886\,\text{kg}} \times \frac{\text{kg}}{10^6\,\text{g}} \times 10^6\,\frac{\text{mL}}{\text{m}^3} = 981.94\,\frac{\text{mL}}{\text{mol}}$$

Table 7.3: Molar volumes for all chemicals involved in the reaction at different temperatures (mL/mol)

Subtance	30°C	60°C	92,5°C	110°C	130°C
Jatropha oil	982	1014	1052	1073	1098
Glycerol	73	75	75	76	76
Biodiesel	338	343	348	351	355
Methanol	41	42			

Step 2: Find the volume ratio

Based on the molar volume, the quantity of methanol solution that should be supplied to the system for every mL of oil entering the system can be calculated. Hereafter, this value will be called *Volume Ratio*.

$$\text{Volume Ratio} = \frac{V_{Methanol}}{V_{\text{Jatropha Oil}}} = \frac{N_{\text{Methanol}} \text{ x Molar Volume}_{\text{Methanol}}}{N_{\text{Jatropha Oil}} \text{ x Molar Volume}_{\text{Jatropha Oil}}}$$

$$Volume\ Ratio_{3:1} = \frac{3\ mol \times 41\ \frac{mL}{mol}}{1\ mol \times 982\ \frac{mL}{mol}} = 0.125$$

Table 7.4: Volume ratio

Molar Ratio	Volume (mL)		Volume Ratio
	Oil	Methanol	
3 : 1	1,00	0,125	0.125:1
4.5 : 1	1,00	0,19	0.19:1
1 : 6	1,00	0,25	0.25:1

Step 3: Find the pumping rates

This calculation is crucial since it allows for the proper sizing of the initial containers as well as the volume of the reactor as discussed earlier (*refer to section 7.2 - Volume and Retention Time of Reactor*).

Example for minimum pumping rate of oil [with molar ratio of 3:1 & flow of 10 mL/min]

$$Pumping\ \text{rate}_{oil} = \frac{1\text{ml}_{\text{Oil}}}{1\text{ml}_{\text{Oil}} + 0.125\text{ml}_{\text{Methanol}}} \text{ x } 10\ \frac{\text{mL}}{\text{min}} = 8.9\ \frac{\text{ml}}{\text{min}}$$

Table 7.5: Pumping rate for oil and methanol

	Flow (mL/min)	Molar ratio (methanol :oil)		
		3:1	4.5:1	6:1
Methanol	10,0	1,1	1,6	2,0
	50,0	5,6	7,9	10,0
Oil	10,0	8,9	8,4	8,0
	50	44,4	42,1	40,0

The flow ranges for the methanol and the oil are therefore set between the following limits.

Table 7.6: Range of pumping rate

	Flow (mL/min)	
	Min	Max
Methanol	1,1	10,0
Oil	8,0	44,4

7.6 Required diameters for the pipes

The constraint to respect when selecting the appropriate pipe diameter is the time spent by the solution between the system components.

The maximum length (x) is approximated at 20 cm and the maximum allowable retention time (t) between the components should be close to 30 seconds.

A size of 10mm is selected based on trial and error.

$$x = v \cdot t \qquad Q = v \cdot A$$

$$t = \frac{x}{v} \qquad v = \frac{Q}{A}$$

$$t = \frac{x \cdot A}{Q}$$

Example with a 10mm diameter pipe:

$$t = \frac{20\,cm \times \pi \times (1cm)^2}{30\,\text{mL/min} \times 4} = 31\,\text{sec}$$

Table 7.7: Pipe retention time in function of pipe diameter

Diameter cm	Area cm^2	Retention_Time sec
0,25	0,05	2
0,50	0,20	8
0,75	0,44	18
1,00	0,79	31
1,50	1,77	71
2,00	3,14	126
2,50	4,91	196
3,00	7,07	283
3,50	9,62	385

7.7 Required size for containers

The main system's driving force is gravity, and the flows are regulated by valves only. Hence, the height of liquid above the valves needs to be considered to limit flow fluctuations. Based on simple experimentations done with a conventional 50 mL burette, it was possible to notice a flow difference with a 20 cm head difference. From those observations, it was decided that the container height should not exceed 15 cm.

The oil container was designed by the students, while a urine bag was used to hold the methanol.

To size the oil container, a certain portion of the volume was dedicated to the upper cylinder part and the remaining portion to the lower conical part. This is done partly to ensure shallow container.

Sizing the Methanol & NaOH Container:

$$\text{Minimum Required Volume} = (\text{Maximum Flow}) \times (\text{Required time without refill})$$

$$= 10\ \frac{mL}{min} \times 3\ \text{hours} \times \frac{60 min}{hour} = 1800\ mL$$

Sizing the Jatropha Oil Container:

$$\text{Minimum Required Volume} = 44.4\ \frac{mL}{min} \times 3\ \text{hours} \times \frac{60 min}{hour} = 7\,992\ mL = 8.0\ L$$

The use of a bag to contain the methanol is very convenient since it reduces the vapor emanation. The bag opens up as methanol enters, without any vapor exiting. Similarly, the bag shrinks as methanol exits. This option is a good way to avoid using non return valves. Moreover, such valves perform well under higher pressure only.

7.8 Flow regulation

The system is working without pump and flow meter. Therefore, the flow is monitored and calibrated with burettes connected to the outlets of the methanol and oil containers. When the solutions are diverted to their respective burette, it is possible to determine the flow and make adjustments if needed. The volumes of the burettes are selected to allow testing for a minimum of 4 minutes under maximum flow.

$$\text{Volume} = \text{Time} \times \text{Flow}$$
$$\text{Volume}_{\text{oil regulator}} = 4\ \text{min} \times 50\ \text{mL/min} = 200\text{mL}$$

The volume of the methanol burette was selected based upon available burettes on the market.

Hence, the selected volumes are:

Oil burette	→	200 mL
Methanol burette	→	50 mL

7.9 Required mass of NaOH

In the literature, the quantity of NaOH to use for biodiesel production with Jatropha seed oil should vary between 0.5 and 1.5% of the oil mass (Chitra, Venkatachalam et al. 2005). Therefore, the maximum mass was determined with 1.5%, maximal flow rate, and a methanol to oil molar ratio of 3 to 1.

$$\text{Max. Mass flow rate}_{\text{NaOH}} = 1.5\% \cdot \left[\frac{V_{\text{oil}}}{V_{\text{solution}}} \cdot Q_{\text{max}} \cdot \rho_{\text{oil},30\,^{\circ}\text{C}} \right]$$
$$= 1.5\% \cdot \left[\frac{1\,\text{ml}_{\text{oil}}}{1.125\,\text{ml}_{\text{solution}}} \cdot 20\,\frac{\text{ml}}{\text{min}} \cdot 886.4\,\frac{\text{kg}}{\text{m}^3} \cdot \frac{\text{m}^3 \cdot \text{g}}{10^3\,\text{ml} \cdot \text{kg}} \right] = 0.236\,\frac{\text{g}}{\text{min}}$$

7.10 Reactor

The reactor consists of a reactive distillation column. A working volume of 100 mL is desired, distributed over 10 plates (Singh, Thompson et al. 2004; He, Singh et al. 2005; He, Singh et al. 2006). Hence, each plate holds 10 mL of solution. The distance between the plates is selected at 25 mm based on information found in the literature (Singh, Thompson et al. 2004; He, Singh et al. 2006; He, Singh et al. 2007).

The depth of solution on each plate is chosen to be 2 mm and the surface area dedicated to the weir is chosen to be 5% as mentioned in the literature. (He, Singh et al. 2005; He, Singh et al. 2006).

Once those fixed parameters are chosen, the diameter of the column needs to be determined.

Step 1: Find the plate working area (plate area which holds the solution)

$$\text{Plate Working Area} = \frac{V}{h}$$

$$= \frac{10\ \text{mL}}{2\ \text{mm}} \times \frac{1000^3\ \text{mm}^3}{\text{mL}}$$

$$= 5000\ \text{mm}^2$$

Step 2: Find the total plate area

As mentioned earlier, the weir should represent 5% of the total plate area. Therefore, the working area represents 95% of the total plate area.

$$\text{Total Plate Area} = \text{Working Area} \times \frac{\%\text{Total Area}}{\%\ \text{Working Area}}$$

$$\text{Total Plate Area} = 5000\ \text{mm}^2 \times \frac{100\%}{95\%} = 5265\ \text{mm}^2$$

Step 3: Find the column diameter

$$A = \frac{\pi \times D^2}{4}$$

$$D = \sqrt{\frac{4 \times A}{\pi}} = \sqrt{\frac{4 \times 5265\ mm^2}{\pi}} = 81{,}8mm \approx 82mm$$

7.11 Methanol evaporator

The evaporator is designed for the worst case scenario, which occurs under the highest flow, the highest expected evaporator temperature, the highest methanol to oil molar ratio, and the lowest system efficiency.

This translates into:

- Flow of 50 mL/min
- Temperature of the solution entering the evaporator is around 60°C and temperature of the solution leaving is around 130°C
- Methanol to oil molar ratio of 6 to1
- 60% reaction efficiency

The balanced chemical equation under reaction efficiency of 60% becomes:

1 mol $_{oil}$ + 6 mol $_{methanol}$ –> 0.4 mol $_{oil}$ + 4.2 mol $_{methanol}$ + 1.8 mol $_{biodiesel}$ + 0.6 mol $_{glycerol}$

Since the efficiency is 60%, only 0.6 mol of oil is converted to biodiesel. Therefore the final quantities are:

→ oil : 0.4 mol = 1 mol - 0.6 mol $_{reacted}$

→ methanol : 4.2 mol = 6 mol - (0.6 mol x 3)$_{reacted}$

→ biodiesel: 1.8 mol = (0.6 x 3) mol

→ glycerol : 0.6 mol = (0.6 x 1) mol

To have complete methanol evaporation in the evaporator, one needs to know the minimal evaporator volume required. To do so, the energy and the mass transfer need to be quantify.

Step 1: Mass flow of each component entering the evaporator

When the solution gets to the condenser, the reaction has occurred and therefore the nature of the initial solution has changed. Consequently, the mass flow rate of each component (oil, methanol, biodiesel, and glycerol) has changed from the initial known mass flow rate. The mass flow rate of each component entering the evaporator is determined using molar flow.

The molar flow of each component entering the evaporator is found using stoechiometric coefficients from the balanced reaction equation under worst case conditions (*described at the beginning of section 7.11*).

Therefore, the reaction of one mole of oil will translate into products formation accordingly to the stoechiometric coefficients. Since the initial mass flow of oil is known, it is possible to find the oil molar flow.

$$\text{Molar flow} = \text{mass flow rate} \times \text{molar mass}$$

$$\text{Molar flow}_{\text{oil}} = 39\,\frac{\text{g}}{\text{min}} \times \frac{1}{870}\,\frac{\text{mol}}{\text{g}} = 0{,}00407\,\frac{\text{mol}}{\text{min}}$$

Therefore, it is possible to calculate the number of moles of all components entering the evaporator using the stoechiometric coefficients, and consequently to find their mass flow rate. [Note that the properties are evaluated at 60°C.]

$$\dot{m} = \text{Molar flow} \times \text{Stoechiometric coefficient} \times \text{Molar mass}$$

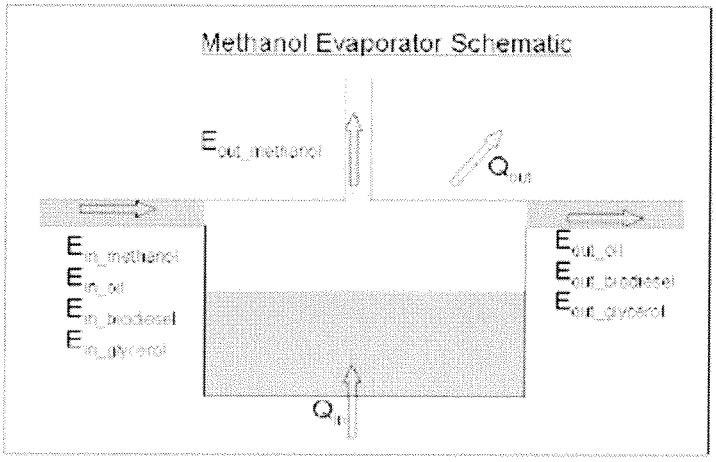
$$\dot{m}_{\text{oil}} = 0.00407\,\frac{\text{mol}}{\text{min}} \times 0.4\,\text{mol} \times 870\,\frac{\text{g}}{\text{mol}} = 14.16\,\frac{\text{g}}{\text{min}}$$

Table 7.8: Mass flow rate of each component entering the evaporator

Component	Stoechiometric Coeffficient	Mass flow rate g/min
Oil	0.4	14.16
Methanol	4.2	5.48
Biodiesel	1.8	21.34
Glycerol	0.6	2.25

Step 2: Energy Balance

The following schematic is a representation of the evaporator energy situation.



low resolution

Figure 7.1: Energy balance in methanol evaporator

From the Energy Equation:

$$\dot{Q} + \Delta E = 0$$

$$\Delta\dot{Q} = \Delta\dot{E}$$

$$\dot{Q}_{out} - \dot{Q}_{in} = \dot{E}_{in} - \dot{Q}_{out}$$

In this system, it is assumed that heat lost is negligible. Therefore, $Q_{out} = 0$

Consequently,

$$\dot{Q}_{IN} = \Delta\dot{E}$$

$$\dot{Q}_{IN} = \Delta\dot{E}_{oil} + \Delta\dot{E}_{methanol} + \Delta\dot{E}_{biodiesel} + \Delta\dot{E}_{glycerol}$$

Where:

$\Delta \dot{E} = \dot{m} \times C_p \times \Delta T$ (applicable when no phase change occurs)

Example:

$$\Delta E_{oil} = \dot{m}_{oil} \cdot C_{p\,oil,\,30\,^\circ C} \cdot \Delta T = \left(14{,}18\ \frac{g}{min} \times \frac{kg}{1000\ g} \times \frac{min}{60\ sec}\right) \cdot 1{,}67\ \frac{kJ}{kg \cdot K} \times (130 - 55)^\circ C$$

$$= 0.0295\ \frac{KJ}{sec} = 2{,}95\ E-2\ KW$$

$\Delta E = \Delta E_{liquid\ phase} + \Delta E_{phase\ change} + \Delta E_{vapor\ phase}$ (*Applicable when there is phase change*)

Example:

$$\Delta E_{methanol} = \left[\dot{m}_{methanol} \cdot C_{p \cdot (liquid\ methanol,\ 30\,^\circ C)} \cdot \Delta T\right]_{liquid\ phase}$$

$$+ \left[\dot{m}_{methanol} \cdot h_{fg}\right]_{phase\ change}$$

$$+ \left[\dot{m}_{methanol} \cdot C_{p \cdot (vapor\ methanol,\ 100\,^\circ C)} \cdot \Delta T\right]_{vapour\ phase}$$

$$= \left[9.125\ E-5\ \frac{kg}{s} \cdot 2.55\ \frac{kJ}{kg \cdot K} \cdot (65 - 55)^\circ C\right]_{liquid\ phase}$$

$$+ \left[3.648\ E-5\ \frac{kg}{s} \cdot 1105\ \frac{kJ}{kg}\right]_{phase\ change}$$

$$+ \left[9.125\ E-5\ \frac{kg}{s} \cdot 1.86\ \frac{kJ}{kg \cdot K} \cdot (130 - 65)^\circ C\right]_{vapour\ phase}$$

$$= 0.206\ kW$$

Therefore,

Table 7.9: Energy for each component

Component	Phase Change	Δ E (kW)
Oil	No	2.96E-02
Methanol	Yes	1.14E-01
Biodiesel	No	5.57E-02
Glycerol	No	6.84E-03
Total	-	2.06E-01

Step 3: Find the minimal evaporator volume required

The methanol evaporates quickly from the solution. Hence, the properties of the remaining solution are taken assuming no methanol is present.

$$\Delta\dot{E} = \rho_{solution} \times C_{p\cdot solution} \times Volume \times \frac{dT}{dt}$$

$$\Rightarrow \frac{Volume}{\Delta t} = \frac{\Delta\dot{E}}{\rho_{solution} \times C_{p\cdot solution} \times \Delta T}$$

1- Find the density of the solution:

$$\rho_{solution} = \rho_{glycerol} \times Ratio\ vol_{glycerol} + \rho_{biodiesel} \times Ratio\ vol_{biodiesel} + \rho_{oil} \times Ratio\ vol_{oil}$$

$$= 1124.9 \frac{kg}{m^3} \times 39.1\ \% + 831.9 \frac{kg}{m^3} \times 56{,}8\ \% + 825.3 \frac{kg}{m^3} \times 4.1\ \%$$

$$= 842.81 \frac{kg}{m^3} \times 1000 \frac{g}{kg} \times \frac{m^3}{10^6\, mL} = 0.842 \frac{g}{ml}$$

Where the ratio volume is determine as follow:

$$V = \frac{\dot{m}}{\rho}$$

Example

$$V_{oil} = 14.16 \frac{g}{min} \times 827 \frac{kg}{m^3} \times \frac{1000\ g}{kg} \times \frac{m^3}{10^6}\ mL$$

Table 7.10: Volume ratio of each component entering the evaporator

Component	Volume Flow (mL/min)	Volume ratio (%)
Oil	17.9	39.1
Biodiesel	26.0	56.8
Glycerol	1.9	4.1
Total	45.8	100.0

2- Find the specific heat of solution:

$$C_{p\,solution} = C_{p\,oil} \times \text{Mass Ratio}_{oil} + C_{p\,biodiesel} \times \text{Mass Ratio}_{biodiesel} + C_{p\,glycerol} \times \text{Mass Ratio}_{glycerol}$$

$$= 1.67 \frac{kJ}{kg \cdot K} \times 37.5\% + 2.09 \frac{kJ}{kg \cdot K} \times 56.5\% + 2.43 \frac{kJ}{kg \cdot K} \times 6.0\%$$

$$= 1.953 \frac{kJ}{kg \cdot K}$$

Where: Mass ratio is established from previous calculations (see step one)

Table 7.11: Mass flow of each component leaving the evaporator

Component	Mass flow rate (g/min)	Mass Ratio (%)
Oil	14.16	37.5
Biodiesel	21.34	56.5
Glycerol	2.25	6.0
Total	37.8	100.0

$$\therefore \frac{Volume}{\Delta t} = \frac{0{,}206\,kW}{842.81 \frac{kg}{m^3}\ x\ 1.953 \frac{kJ}{kg \cdot K}\ x\ (130 - 55)^\circ C} = 1.66E-6 \frac{m^3}{\text{min}} = 99.7 \frac{ml}{\text{min}}$$

This result can be interpreted as the quantity of incoming solution at 55°C that can be heated to 130°C in one minute. Considering that the maximum flow is 50 mL/min, it can be expected that all methanol will evaporate.

The evaporator working volume is chosen to be 200 mL. Hence, with Q_{max} at 20 mL/sec, it will take about 13 seconds to heat the entering solution to the desired temperature (130°C).

7.12 Decanter

The volume of biodiesel produced varies proportionally with the oil flow. Assuming maximum flow conditions and all the oil is converted to biodiesel and glycerol (100% efficiency), one can size the decanter.

As mentioned earlier, the maximum working time of the unit is 3 hours.
For each mole of oil entering the system, 3 mol of biodiesel and 1 mol of glycerol is yield.

$$\mathbf{1}\, mol_{oil} + \mathbf{3}\, mol_{methanol} \Leftrightarrow \mathbf{1}\, mol_{glycerol} + \mathbf{3}\, mol_{BioDiesel}$$

From this, it is possible to find the minimum volume required for the decanter.

Step 1: Find the maximum number of moles of oil entering the system during a 3 hours period

$$\text{Mole Total} = Q \times \text{Molar Volume}_{30\,C} \times t$$
$$= 44.4 \frac{mL}{min} \times \frac{mol}{981.9\,mL} \times 60 \frac{min}{hour} \times 3\ \text{hours} = \quad 8.13\ \text{mol}$$

Step 2: Find the number of moles of biodiesel and glycerol that can be produced under maximum flow and assuming 100% efficiency

1 mole oil $\rightarrow$ 1 mole glycerol $\rightarrow$ 3 moles biodiesel
8.13 mole oil $\rightarrow$ 8.13 moles glycerol $\rightarrow$ 24.4 mole of biodiesel

Step 3: Find the total volume produced

$$\text{Volume} = N \times \text{Molar volume}$$

$$\text{Volume}_{\text{glycerol}} = 8.13\ \text{mol} \times 73.1 \frac{mL}{mol} = 594\ \text{mL}$$
$$\text{Volume}_{\text{biodiesel}} = 24.4\ \text{mol} \times 338.5 \frac{mL}{mol} = 8256\ \text{mL}$$
$$\text{Volume}_{\text{total}} = 594\ \text{mL} + 8256\ \text{mL} = 8.850\ \text{mL} \approx 9\ \text{Liters}$$

The volume produced is 9 liters. Given what was available on the market, the best option was to use two containers of 5L each. This is very convenient, suits the purpose, and gives a little security factor.

8. Design Process

8.1 Acquisition of basic knowledge about the design

The first step in any design project is to master the science behind it. Only once it is understood, the design can be of high quality. Considering that biodiesel and bioenergy were not topics familiar to the students, the first necessary step was to do a literature review. This was done in Canada during the month prior to the students' departure. Consequently, the subject was well understood when the students arrived at TNAU in India.

8.2 Meet "customer needs" & elaboration of the project

Parallel to the literature review, first contacts were established with the Head of the BioEnergy Department and the Dean of the Engineering faculty to know which projects would best suit their needs. From those preliminary communications, the BioEnergy Department showed interest in four topics. From there, the literature review was narrowed a little to focus on the topics of interest. After arrival on site, further discussion followed and McGill students felt that the topic of most interest was the recovery of methanol during the process of biodiesel production.

8.3 Preliminary proposal

In addition, prior to the students' departure to India, a preliminary project proposal was submitted to Dr. Raghavan and his team. The purpose of this proposal was to establish a clear understanding of the project among the students, Dr. Raghavan, and his team. Therefore, designers and their McGill supervisors would both have the same understanding of the tasks to accomplish as well as the general structure and the general objectives of the project.

8.4 First design

From all the proposed projects, the one selected consisted in the design of a research unit capable of producing biodiesel under continuous flow conditions that would also allow for methanol recovery. The introduction of continuous flow in the design was the next logical step

since the department was already equipped with a batch type unit. Hence, the first weeks were used to elaborate many different scenarios, create different design ideas, sketch, etc. Once the students decided upon one design, they sized each component of the research unit and did the preliminary drawings. The initial design used pumps and flow meters with very low flows.

8.5 Proposal

A proposal was then submitted to the supervisors of the students: Dr. Venkatachalam (Head of BioEnergy Department), Dr. Sampathrajan (Dean of faculty), and Dr. Raghavan (McGill supervisor). The document included the overall description of the exchange project, an overview of the literature review (mainly on biodiesel production), the objectives of the project, the design specifications, a time schedule, and the estimated project cost.

8.6 Design adjustments

However, soon after handing the proposal, the students realized that the initial design could easily be improved. The desired flows in the system were very small. Therefore, the required flow meter and pump devices had to be extremely precise. Such devices were hard to find in Coimbatore area and more expensive than expected. Purchasing them would exceed the budget allowed by McGill for this project.

Hence, many new design options were now possible. The system was rethought of completely and the idea of using only gravity to drive the flow in the unit arose. This required many major modifications. Once the design of the new system was completed, the students decided to meet with the Dean of the faculty and the Head of the BioEnergy Department to present them three different design scenarios: high cost system (using already existing components designed and fabricated by professional companies), low cost system (using gravitational flow and 'home made' components: designed by the students and fabricated by machinists and glassblowers around Coimbatore), and medium cost system (using a combination of gravity flow and a distillation column bought on the market). Those scenarios are presented in section 9.

Hence, the option to have a reliable system with higher precision was offered to the university. Such a choice would however make them responsible for the increase in price. Finally, the selected design was the one with the lowest cost.

Looking at this design from the overall picture, the modifications take all their meaning since they allow for much lower energy input into the system for a given energy output from the biodiesel produced.

8.7 Design realization

The next step was to start the fabrication of the unit. Giving the time constraint, the priority was to find glass blowers and stainless steel machinists that would do the work for the minimum price. Within two weeks, two glass blowers and one stainless steel machinist were found, quotations had been written, and orders were passed. Meanwhile, connections for the unit were bough, along with the piping system. A rack to hold the entire unit was also designed and built at the BioEnergy workshop, with the help of the shop workers. Chemicals were also ordered so that experiments could be run.

Finally, all the components were placed on the rack and the whole unit was assembled. The time remaining for the final assembly was very short and the students could not run a full test with Jatropha oil and methanol. Only placebo experiments were done in order to verify that the unit functioned well.

9. Economics

9.1 Three possible scenarios

The design takes into account the cost of constructing the unit, but also the cost of running the unit. To minimize the cost, the unit does not use any expensive piece of equipment and requires very little power to run.

Prior to the construction of the research unit, the students presented three design scenarios to their supervisors at TNAU (Dean of the Agricultural Engineering College and Research Institute, and Head of BioEnergy Department): there was a high, a middle, and a low cost scenario.

9.1.1 Option A - High cost scenario

This option consists of purchasing all the system components that would optimize the precision of the system and would ensure a high reliability. Hence, the reactor is bought, along with peristaltic pumps and flow meters. This ensures a better control of the system parameters since all components will work as specified and therefore biodiesel quality production will be closer to predictions. However, the cost associated with it is very high compared to option B. Lower maintenance and less equipment problems are to be expected with this option.

Table 9.1: Approximate surplus cost associated with buying the system components

Component	**Company**	**Model**	**Price (Rp)**
Static mixer	Cole-Parmer	K-04669-87	3 750
Distillation Column	Alder-Sigma	Z175714	78 000
Peristaltic Pumps	sdfine-chem limited	---	± 200 000
Flow meter	sdfine-chem limited	---	> 75 000
	Overall estimated cost:		**356 750**

Advantages:

- More reliable
- Higher material quality
- More precise
- Fewer problems with the equipment
- Lower maintenance

Disadvantages:

- Higher cost
- Higher power input required
- Material may not be delivered prior the students departure

9.1.2 Option B - Low cost scenario

This is the reviewed design, which is a simplification of option A. It uses simple principles to perform the same tasks as option A. Since gravity is used to drive the flow, it requires very little energy input in order to perform. Moreover, the pumps are of no use.

All equipments required for the system are designed by the students on site and would be built upon the plans that would be provided to local manufacturers. This would reduce the price of the unit. However, the flow of this unit might not be constant at all time and a little more difficult to adjust.

In addition, it is important to understand that the designers have little knowledge in chemical engineering and did the design based on their best knowledge. Concerns were raised about clogging, oil flowing through the plates in the reactor, number of holes per plate required for the optimal vapor flow, holes diameter, and pressure build up. Therefore, unexpected reactions and problems might be encountered with the usage of the "home made" reactor.

Advantages:

- Less expensive
- Lower power input required
- Can deal with small flow without the associated high cost for precise pumps and flow meters

Disadvantages:

- Possible problems with the reactor (distillation column)
- Flow not constant – harder to control and adjust
- Higher incertitude with the parameters
- Longer time to set up the system

9.1.3 Option C - Middle cost scenario

This is an intermediate solution that combines option A and B together. For example, one could buy the reactor but keep the gravity system. Also, one could buy two peristaltic pumps for a better control of the feed flows and still use the components designed on site and a gravity flow system. This option offers many different possibilities.

The most viable option suggested by the designers would be to buy a reactor available on the market and keep the gravity system. Even tough this would increase the price significantly; it would discard all possible doubts concerning the actual functioning of the reactor and its influence on the system efficiency.

9.2 Cost of building the unit

The students decided to manage the building process themselves, instead of asking to one supplier like is usually done by people on the campus. Hence, glassblowers and stainless steel machinists were found, drawings of the components were explained to them, quotations were obtained and orders were passed. Connections, heating coils, slotted angle rods, and pipes were also purchased in Coimbatore.

This process was time demanding since the students often had to go in town to meet with the fabricators, find and get the missing required pieces, ask questions to some suppliers, etc. People involved in the building process were very collaborative and curious about the project.

An excel sheet was built to keep track of the expenses relative to the project. Hence, the total cost of building the unit was 82,600 Indian Rs, which represents about 2,230 Canadian dollars.

Table 9.2: Cost of building the unit

Biodiesel Project		
Company	**Purchase**	**Cost**
Winners	Slotted Angle & screws	3350
Saberval Surgicals Co. Limited	plastic / urine bags, seringes	480
Anandan Dr.	I.V. tubing system	150
Shibam Eng &-Pneumatics	Fittings for unit (mostly SS), coupling, cross, T, hoze, bolts, small clamps, U clamps, nipples, silicon pipe, union, seals, bush, teflon	18506
Sri Jaikrishna metals	Pipes, 10 x SS circular plates (1.2mm thick)	2933
Dianaa Hardwares	Bolts, nuts, washers	481
Heatran Eng. Corporations	Heating mantel, ceramic paper, 200W coil, no.10 ceramic beads	1969
The precision Scientific Co.	Stirring bar (x3), glass ware components (decanters, burettes, condenser, heating mantles, clamps)	19874
Safire Scientific Company	Glass ware components (pre-mixer, evaporator, glass tube, heating plate)	6042
S.R. Industries	Oil Container and Reactor	14664
Anant Hardware Machine Tools Corporation	Braided nilon tube 20mm dia., PVC tube, brass nozzle	384
Sri Meenakshi Electricals	3 power plugs	1310
Noor Traders	Teflon tabe 1/2", Hoze clumps (3/8, 3/4, 1")	497
Shri Mahalakshmi Industries	Stainless Stell plate punching (0.5mm thick)	1375
The I.L.E. Co.	Absolute Methanol, 500ml	2200
Orient Hardware	glass glue	17
J.S. Aluminium (P) Ltd.	Alunimium ladder	2812
Displacements in Coimbatore to get material		
mostly done with Kumaran Arul Travels		5553
		Total Cost
		82597

9.3 Fixed & variable costs

The building process was completed while the students were in India. Therefore, there should be no more fixed cost, which mainly consists in expenses relative to the construction of the unit. Hence, the only remaining expenditures are the fees related to experimental trials. Those variable costs are small and mainly consist of power input, methanol supply, oil supply, and labor.

The collaboration between McGill and TNAU allowed to equip the BioEnergy Department with a working unit to produce biodiesel under continuous flow as well as the workshop with some useful additional tools. The unit will of course allow for further research on the subject. Once the process will be mastered and the unit not needed anymore, all the material can be reuse to build other units.

10. Recommendations

10.1 Unit in short and long term

The present unit was designed and built with the aim of pursuing many different experiments. Every component is easily by-passed and most of the necessary measuring equipments are installed. At the moment, there are six thermocouples. Also, if desired, a manometer can be inserted to measure the pressure build-up in the reactor. In addition, the frame of the unit is done with slotted angles. This allows for easy repositioning of some components if required for future experimental set-ups. Ideas for future experimentations are presented in the design section of this report (*refer to section 6.3 - Future experimental set-ups*).

In the short term, the optimization and full understanding of the unit can be a master level research project. On the longer-run, the unit could eventually be scaled-up to the pilot plant size.

10.2 Usage recommendations

- Never use tap water in the system. This water contains salts which stick on the glassware and can not be removed. Use mineral or distilled water only.
- When the unit has not worked for a long period of time, prior to usage, run a trial with mineral water to ensure there is no leakage and the heaters as well as the thermocouples are working properly. Water with dissolved soap can be applied on the structure to verify for vapour leakage.
- Before allowing methanol to flow in the unit, make sure there is oil in the pre-reactor. This will limit the methanol emanation. Also, warm up the pre-reactor, reactor and evaporator with oil in them until the desired temperatures are obtained.
    - Pre-reactor (Thermocouple 1): 55°C
    - Evaporator (Thermocouple 3): Above 65°C
    - Reactor (Thermoregulator): Above 55°C

- The temperature inside the reactor should not be above 65°C, otherwise reactive distillation process will not work at its full potential.
- Use clean and filtered oil, otherwise reactor is likely to clog.
- Extreme precaution should be taken when moving glassware or any items connected to glassware. Those are fragile and not available on the market. They were designed and built especially for this unit.
- Do not climb on the rack to work, this will bend it. Always use the ladder provided.
- It is preferable to use a pump to bring the water to the condenser located at the top of the unit. Make sure the flow of water is sufficient to fill the condenser.
- After each usage, verify and clean the plates located inside the reactor. To do so, it might be preferable to heat the outer shell of the reactor in order to dilate the metal.

10.3 Safety

This system is working with methanol vapor that is highly inflammable and explosive. Consequently, it may lead to risk of fire or explosion if appropriate precautions are not previously taken. In addition, methanol vapor is known to be a mild irritant for the eyes and can cause irritation of mucous membranes when present in relatively small concentration (1000 ppm). When present in higher concentration (5000 ppm), it can cause stupor or sleepiness (Technical Information & Safe Handling Guide for Methanol, Sept. 2006, Version 3, publication from Methanex corporation).
Special care needs to be taken while working with the system: there could be unexpected pressure build up and potential risk for explosion.

Here are the safety recommendations:

- Place the unit in a well aerated space
- Ensure the unit is placed in a spark and flame free environment
- Dry chemical extinguishers need to be easily accessible
- Electrical equipments must be explosion-proof or be breaker protected and placed in a safe position, a little away from the system
- System operators should wear at least safety goggles

- System operators should have access to a respiratory mask for organic vapor and wear it as soon as the operator feels it is necessary

10.4 Maintenance

In order to ensure ~~the future good~~ adequate functioning of the unit, a good maintenance is required. When several trials are done to test the unit, a minimum cleaning should be done between each trial. This includes:

- Cleaning all components of any remaining liquids and particles with distilled or drinking water. It is important to never use tap water due to its high salt content.
- Completely empty methanol and oil containers (using the burettes, so there is no mixing) and dispose of it appropriately.
- After each usage, verify and clean the plates located inside reactor.

10.5 Unit improvements

10.5.1 Immediate improvements

Since the students had to assemble this unit in a very short period of time, some modifications and improvements are still possible in order to make the unit even more functional. Such modifications imply:

- To replace the braided nylon pipes with silicone pipes of ¾ inch and 1 inch respectively. The braided nylon pipes are very stiff and do not adhere well to the glassware. Thus there is a higher chance for leakages and to break the glassware. Silicon is more flexible and would adhere better.
- To install a pump to bring the water to the condenser located at the top of the unit.
- The evaporator heating mantle might need to be replaced by a more powerful one.

10.5.2 Future improvements

As mentioned earlier in the document, this unit is done using the least expensive equipment as possible. Also, only basic physic principles are used to drive the flow. Consequently, the unit can easily be improved in terms of accuracy and efficiency. All the components have been

designed by the students and were made in Coimbatore. By changing some of the components for more accurate ones designed and built by professional firms (mainly the reactor), the unit would gain in efficiency. Also, more constant and precise flows could be obtained using pumps.

In the preliminary design, the pre-reactor consisted of a static mixer. However, in order to have appropriate mixing using such a device, a higher pressure was required. Since no pump is used, the idea of using a static mixer was replaced by a simple mixer. Therefore, one major change to bring if pumps are eventually installed is the use of a static mixer instead of a simple mixer.

11. Conclusion

Two students from the Bioresource Engineering Department from McGill University, Thomas Fortin-Chevalier and Pénéloppe Thériault, got the chance to do their undergraduate design project at Tamil Nadu Agricultural University on a bioenergy related topic. Prior to their departure, a literature review was done on the various possible projects that they could undertake during the summer.

During the first week at TNAU, the students met with the Dean of the Agricultural College of Engineering and the Head of the BioEnergy Department to agree on the official project on which they would dedicate their design project. A continuous flow biodiesel production project which includes methanol recovery was chosen.

A first proposal was presented to the Dean of the Agricultural College of Engineering and the Head of the BioEnergy Department. Based on this proposal, the students started their design work. The preliminary design generated discussion between the students and their supervisors, which gave rise to new design ideas. Hence, the flow could be increased while the energy input decreased. This led to the elaboration of three different design scenarios. Finally, the Dean of Agricultural College of Engineering chose the least expensive option.

The construction of the unit started short after the design was approved by supervisors from TNAU and McGill. Different manufacturers and suppliers were found in Coimbatore. A stainless steel machinist built the reactor and the oil container, while two different glass blowers built the pre-reactor, the evaporator, the tube leading to the decanters, and the decanters. The remaining pieces and unit components were also purchased in Coimbatore. Those include the slotted angles, the condenser, the methanol containers, the different type of pipes, the heating coils, etc. The unit was assembled by the students and some workers from the BioEnergy workshop, under a very short time period.

Although the students did not have the time to perform tests with the unit, the procedure was clearly explained to Ms. P. Chitra from the BioEnergy Department. It is expected that the

BioEnergy Department of TNAU will pursue research with the unit in order to better understand it and to assess its potential for future commercial utilization.

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Appendix 1. List of the suppliers

Supplier	Components
Winners	Slotted angles to build the frame
Saberval Surgicals Co. Limited	Urine bags to contain methanol, flow regulator for methanol
Shibam Eng &-Pneumatics	Fittings, couplings, cross, T, nipples, silicon hose, bolts, small U clamps to hold rods, union, Teflon
Sri Jaikrishna metals	Stainless Steel pipes, SS circular plates
Dianaa Hardwares	Bolts, nuts, washers, PVC pipe, tap valve
Heatran Eng. Corporations	Reactor heating mantel, ceramic paper, thermoregulator, condenser heating coil, electrician service (Electrician : T. Ramchandran at 98431-44871)
The precision Scientific Co.	Glassware components (decanters & burettes), clips, evaporator heating mantle, magnets for magnetic stirring Glassware made by *Ashok Scientific Glass Work's* company
Safire Scientific Company	Glassware components (pre-reactor, evaporator, glass tube to decanters) and hot plate
S.R. Industries	Reactor and Oil container
Shri Mahalakshmi Industries	Plates punching
Anant Hardware Machine Tools Corporation	PVC tube (20mm diameter)
Sri Meenakshi Electricals	Power plug
Noor Traders	Teflon tape, hose clumps
The I.L.E. Co.	Absolute Methanol
Orient Hardware	Glass Glue
J.S. Aluminium (P) Ltd.	7'' aluminum ladder, 2mm thickness

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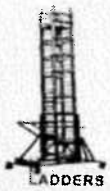
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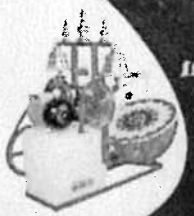

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Appendix 2. List of important meetings

End of April
Dr. Sosle - Preliminary project: production of biogas for hay drying purposes.

Beginning of May
First contact with the Dean of Engineering College of TNAU. There is mention of three areas in which the university would like to conduct research:

1- Methanol recovery from biodiesel production
2- Glycerol recovery from biodiesel production
3- Detoxification of Jatropha cake

May 1st, 2007

- Meeting with Dr. Raghavan and Dr. Orsat
- Preliminary discussion about the potential projects
- Possibility to complete design project course (BREE-491) for Pénéloppe & Thomas over the summer
- Talk about possible Ph. D for Guillaume and Master for Pénéloppe & Thomas
- Idea of using microwaves for biodiesel production
- Idea of research on motor performance with Jatropha oil
- Guillaume raises the possibility to research on pyrolysis

Middle of May

- Meeting with Dr. Sosle
- Talk about the different possibilities: continuous flow biodiesel production, biodiesel production using microwaves, pyrolysis, and gasification.
- Drop the idea of research on microwaves due to safety and equipment considerations
- Talk about preliminary list of materials to bring from Canada (thermocouples, datalogger, etc.)

End of May

- Meeting with Dr. Raghavan for Thomas & Pénéloppe

June 7th, 2007

- Meeting with Sir Vankatachalam, Head of the BioEnergy Department
- Presentation of the potential projects: continuous flow biodiesel production, pyrolysis, biogas production from Jatropha cake
- Sir Vankatachalam introduced the idea to use ultrasounds in the biodiesel production process

June 8th, 2007

- Meeting with Dean Sampathrajan
- Presentation of the potential projects: continuous flow biodiesel production, pyrolysis, biogas production from Jatropha cake
- The project on continuous flow biodiesel production would allow methanol recovery, a topic in which the department showed interest in. It was agreed that the team would work on this project. The mandate is to first design and build a lab scale unit. Then, if time allows, the unit might be scaled up.

June 15th, 2007

- Meeting with Heatran supplier service
- The project is not ready yet and needs further work.

June 27th, 28th, 2007

- Presentation of the proposal
- Dean of Agricultural Engineering College: Approval of the proposal, discussion about the time schedule
- Dr. Raghavan: Presentation of the proposal for the course BREE-491 and discussion about available budget for the project.
- Head of BioEnergy Department: Not met. The proposal is given to his assistant, P. Chitra, who read it and gave him feedbacks.

July 6th 2007

- Presentation of the calculations
- Dean of Agricultural Engineering College: After a quick overview of the calculations, confirms that we should go ahead and purchase the required material.
- Head of BioEnergy Department: Not met. The document is given to his assistant, P. Chitra, who reads it attentively and gives the team many feedbacks.
- Dr. Sosle: Warns the team that flows calculated were extremely small and that there would be no pump able to provide such small flow to his knowledge. (If there were, they would be very expensive.) He suggested to use gravity and a mixer container to overpass this technical challenge.

July 19th, 2007

- Presentation of the reviewed design
- Dean of Agricultural Engineering College: Understands that flows were too small; gives his okay to purchase the material; the students clearly explain their concern about the distillation column and other components that may not work appropriately → designed by U.G. students versus specialists who have knowledge that the students do not have. The safety considerations included in the design are also presented to him.
- Head of BioEnergy Department: Not met; rapid presentation of the new design concept to his assistant, P. Chitra.

July 20th, 2007

- Safety considerations: an email is sent to McGill supervisors about concerns the students have.
- Dr. Orsat: Quick reply in which she answers the students' concerns and suggests them ways to proceed about those.
- Dr. Raghavan: Quick reply in which he answers the students' concerns and suggests them ways to proceed about those. One important suggestion is to perform tests with water prior to use alcohol.

July 27th, 2007

First meeting with SaFire Scientific Company

- Preliminary explanation of the design.
- The initial idea was to do all components in glass. However, after this meeting, the students realize that oil & methanol containers as well as the static mixer can not be done in glass.

July 28th, 2007

State Level Technical Symposium

- Presentation of the design project
- Win second prize in the energy category

Meeting with Dr. Sosle

- Suggested that mixing with static mixer would not work
- Start thinking about a new system to mix the reactants

July 30th, 2007

First meeting with Precision Scientific Co. (glassware supplier)

- The service is quick and the sales executer has access to a lot of material
- The students agree on sending an e-mail to indicate the desired material
- A bid is expected within the next three days

July 31st, 2007

Second visit to SaFire Scientific Company

- Clear presentation of the material the students want from him
- A bid is expected within the next two days

August 1st, 2007

- Visit of Jatropha plantation at the TNAU Forest Institute
- Guillaume gives a presentation at an engineering college close to Coimbatore
- Bid is received from Safire Scientific Company

August 2nd, 2007

- Look around Coimbatore for stainless steel machinists - with M.Thomas from the Food Processing Engineering Workshop
- Visit a stainless steel fabricant – unfortunately, he does not understood technical drawings

August 3rd, 2007

- Bid is received from Precision Scientific Co.
- Order is passed to Safire Scientific Company
- Order is passed to Precision Scientific Co.

August 8th, 2007

The students find a machinist that can undertake the fabrication of the stainless steel components (S.R. Industries)

August 10th, 2007

- A bid is received from S.R. Industries
- Order is passed to S.R. Industries

August 13th, 2007

- The order from Safire Scientific Company is received

August 17th, 2007

- The order from Precision Scientific Co. is received

August 18th, 2007

- The order from S.R. Industries is received
- An electrician from Heatran Engineering Corporations (T. Ramchandran – mobile: 98431-44871) installed the thermoregulator for the reactor

August 20th, 2007

The students give a clear presentation on how to use the unit to Ms. P. Chitra and Dr. Angeeswaran.

August 21st, 2007

- Meet with the Head of BioEnergy Department for official good bye
- Meet with the Head of Post-Harvest Technology Center for official good bye
- It is impossible to meet with the Dean of Agricultural Engineering College since he is away from the campus

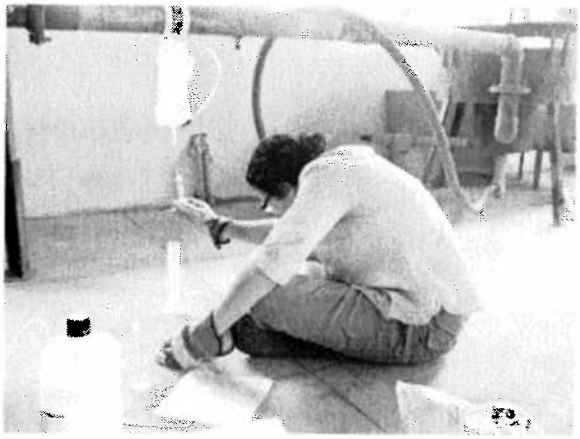
Appendix 3. Project's photos

Pictures taken during the design and construction process.

1. Testing how the mixture will mix in the pre-reactor.

2. Making CAD drawings and testing the solution

3. Testing flow variation with change in head.



4. Testing methanol flow with I.V. valve system.

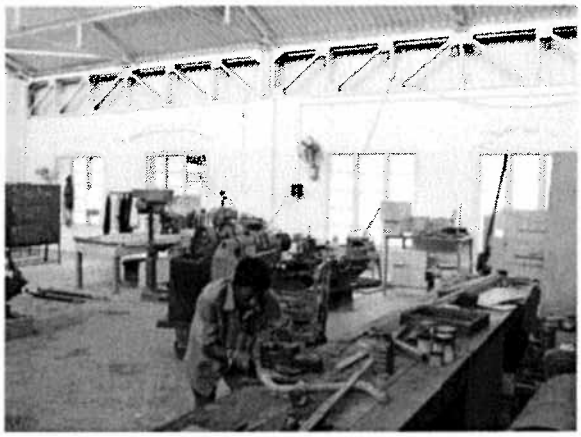
5. Finalizing the list of all required fittings and connections.

6. Shibam Engineering & Pneumatic – Getting some fittings and connections.

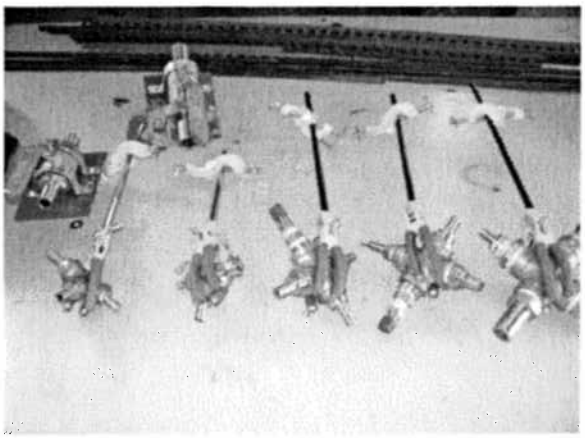
7. Getting some tools at Orients Hardware store.

8. Meeting with a stainless steel manufacturer.

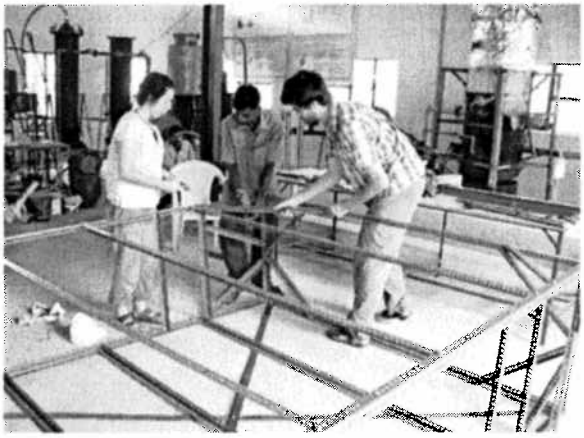
9. Getting pipes and valves at Sri Jaikrishna Metals.



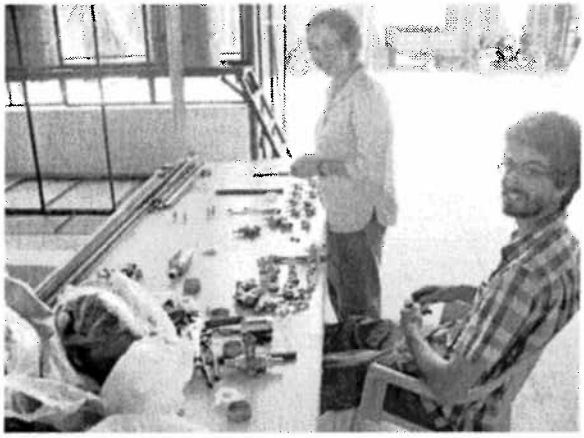
10. Kaliswaran helping us in the BioEnergy workshop.



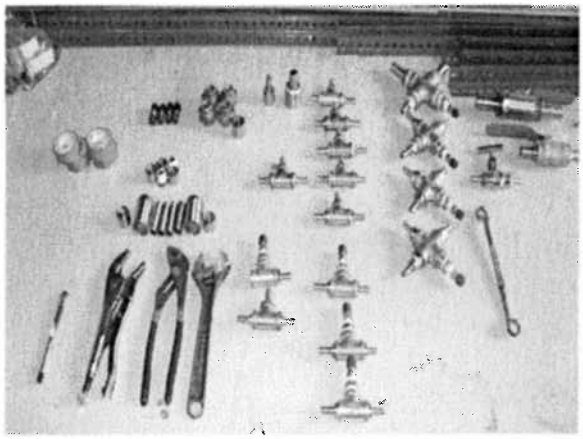
13. Clamps to hold the connections.



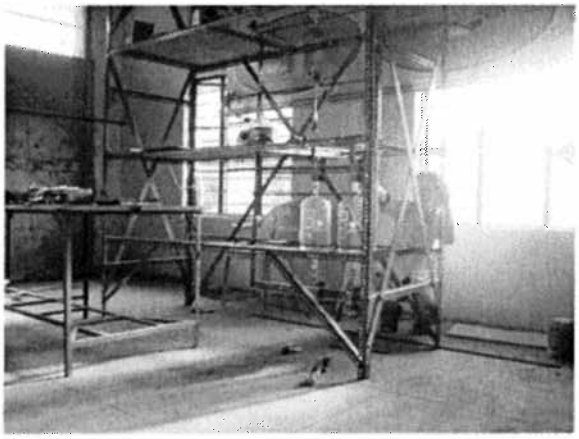
11. Starting to build the frame.



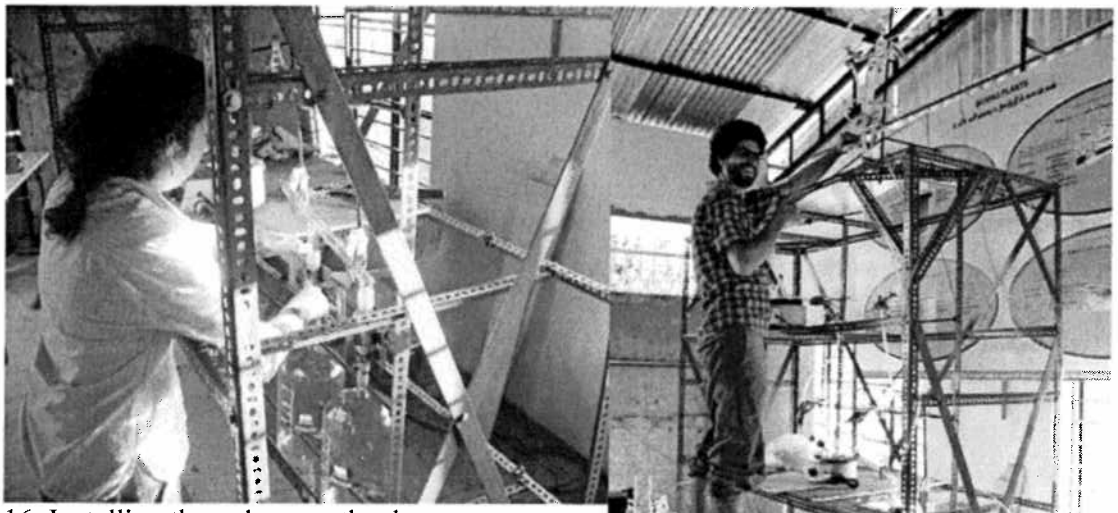
14. Assembling the connections using teflon tape.



12. Connections used for the research unit.



15. Installing the decanters on the system.

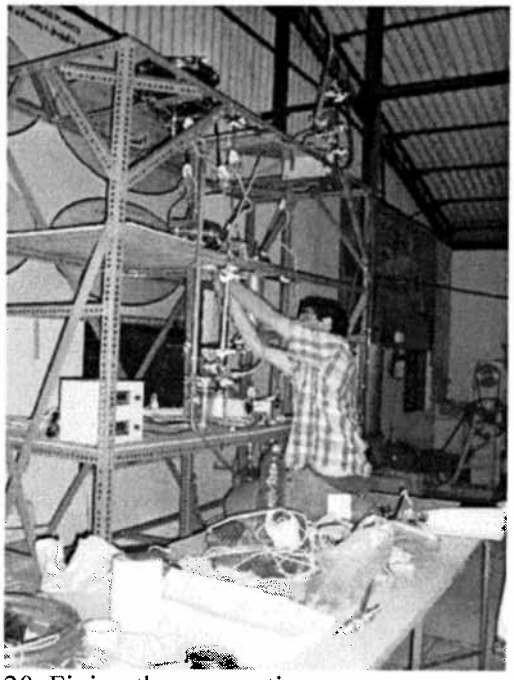


16. Installing the valves on the decanters.

17. Fixing the methanol flow controller.

18. Installing the condenser.

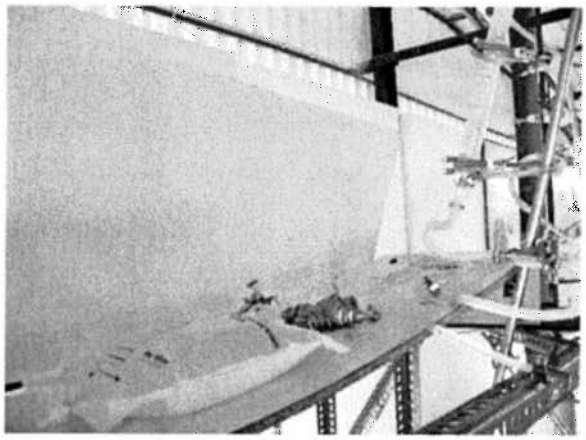
19. Calibrating the thermocouples.



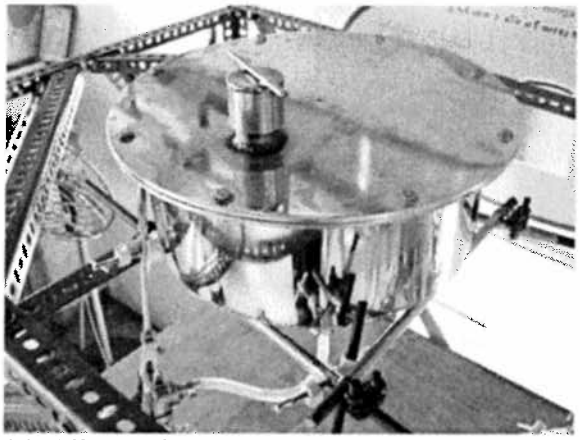
20. Fixing the connections.

21. Building the shelf for the unit.

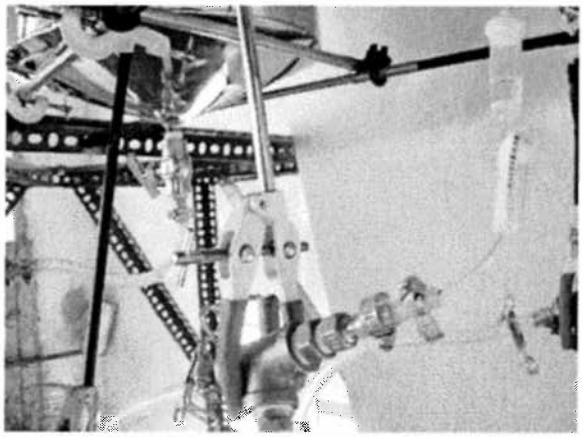
22. The students with P.Chitra and workers of the BioEnergy workshop.



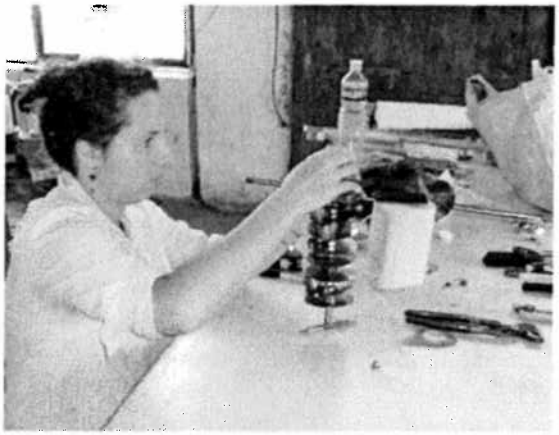
23. Methanol containers and condenser



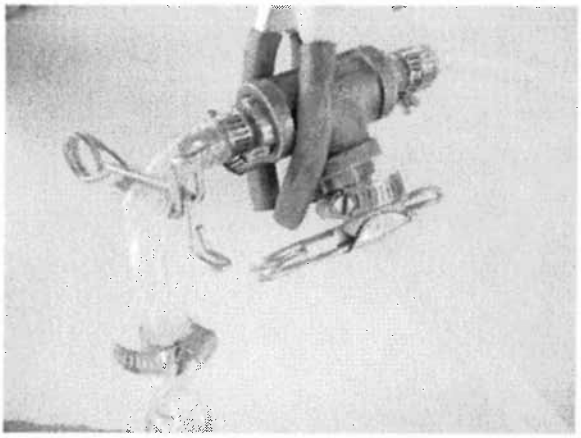
24. Oil container



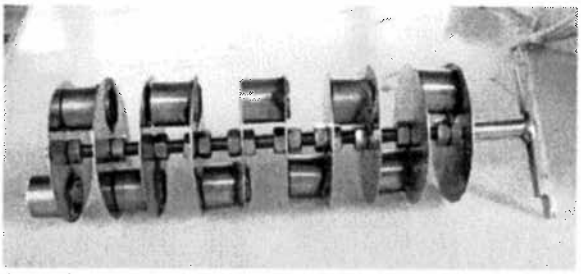
25. Valves to regulate the methanol and oil flows.



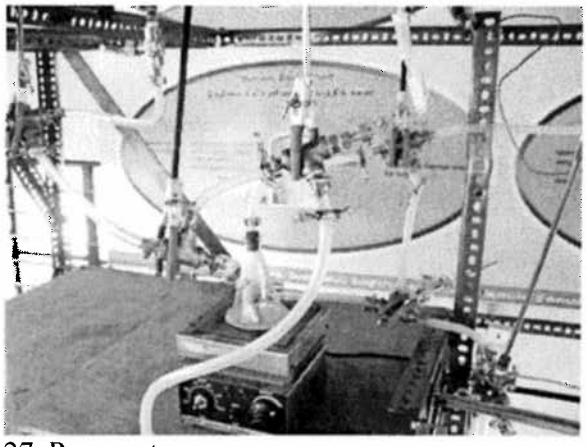
28. Assembling the plate system that goes inside the reactor.



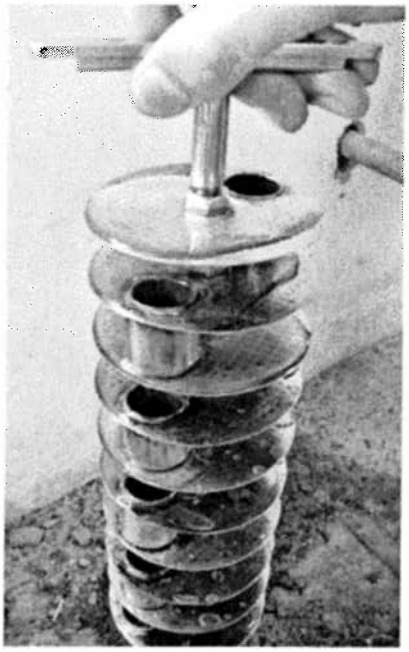
26. Connections, with stoppers to divert the flow.



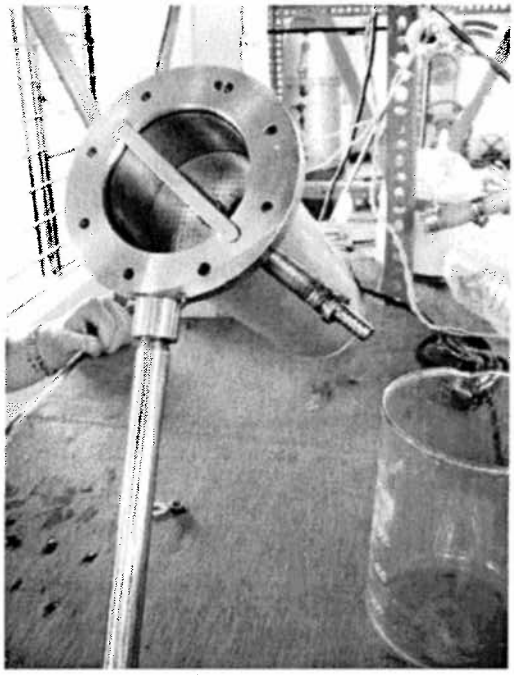
29. Plate system.



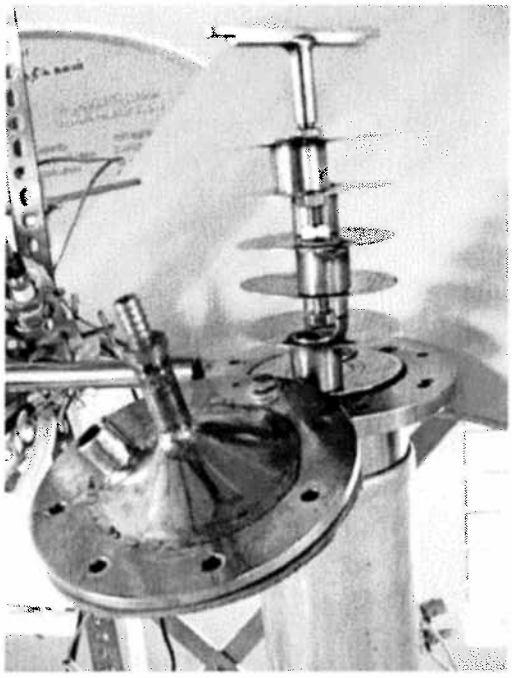
27. Pre-reactor.



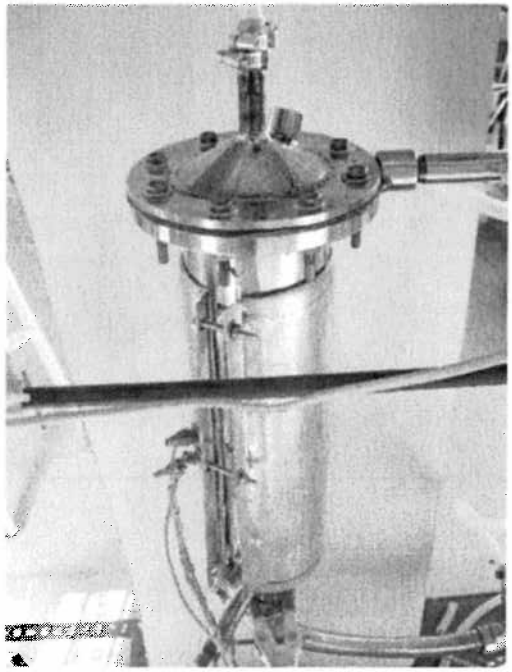
30. Plate system with water holding on each plate.



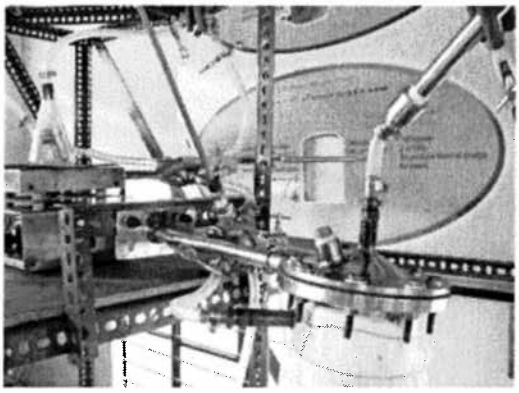
31. Top view of the reactor with the inserted plate system.



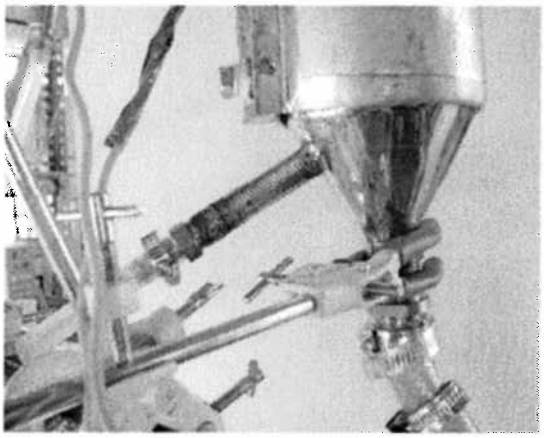
32. Top of the reactor.



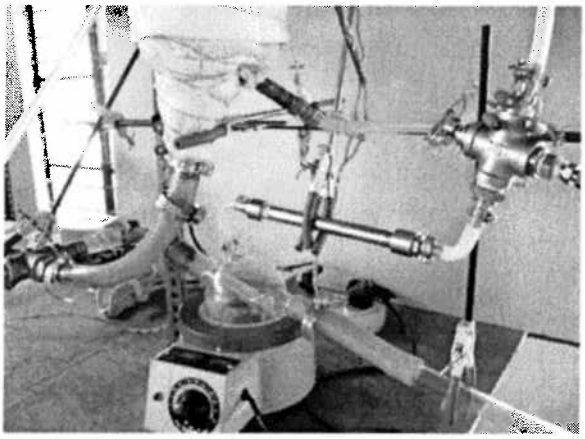
33. Heating mantle around the reactor.



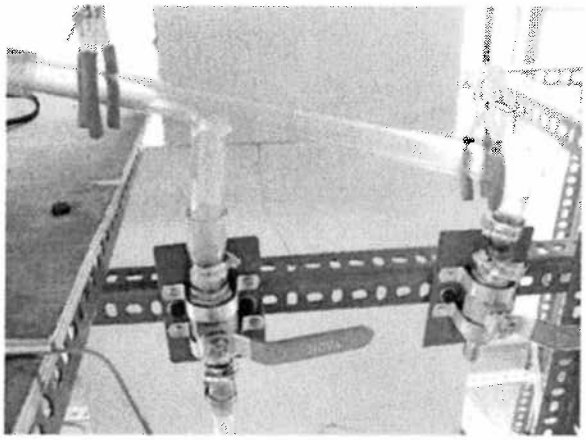
34. Rod to fix the reactor, with liquid inlet and vapor outlet. The reactor is insulated with ceramic paper.



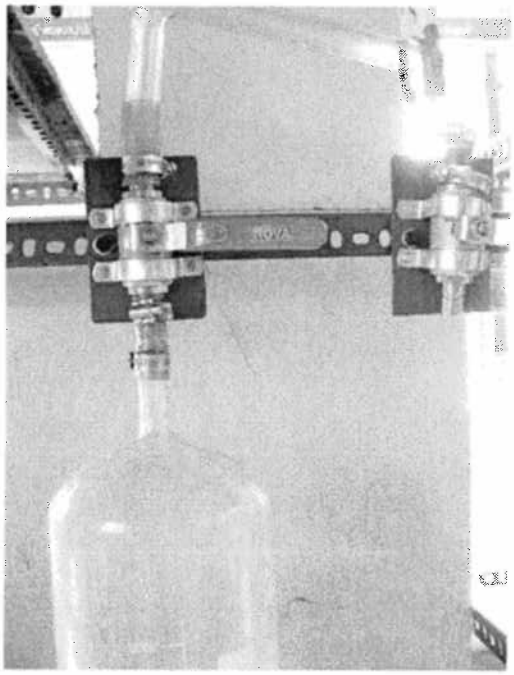
35. Bottom part of the reactor, with liquid outlet and vapor inlet.



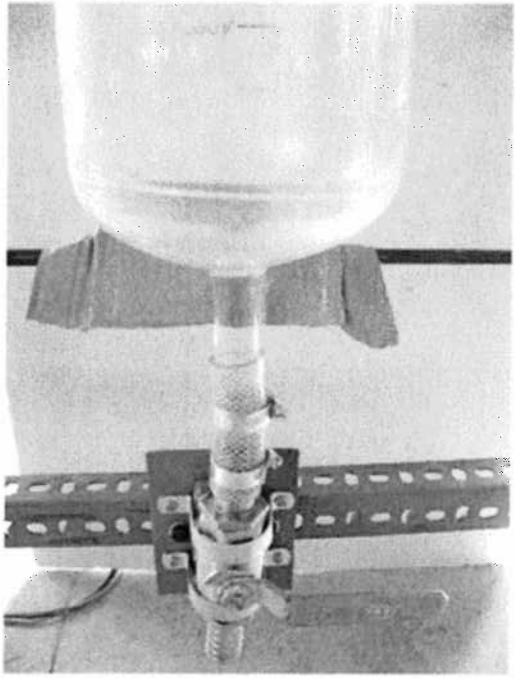
36. Evaporator.



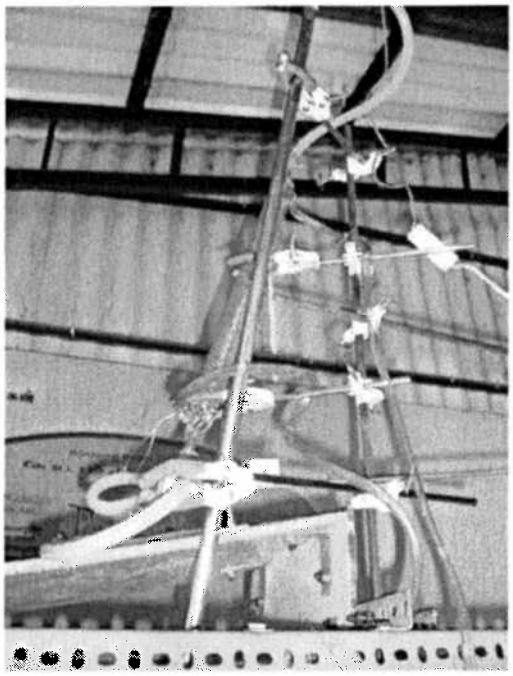
37. Glass tube that connects the evaporator to the decanters.



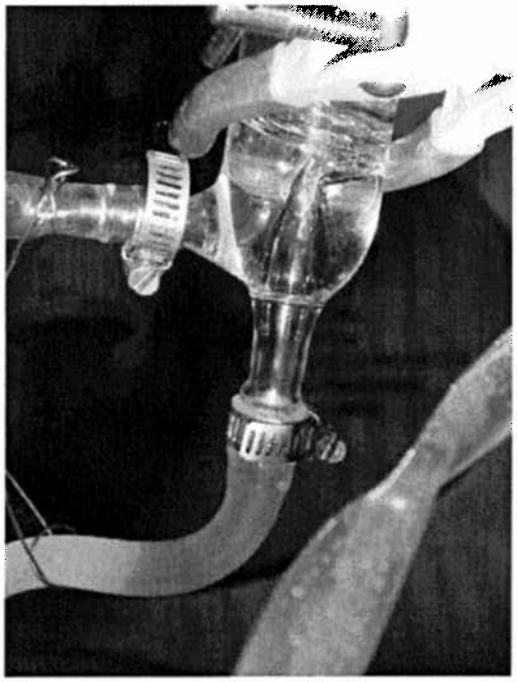
38. Decanter and valve.



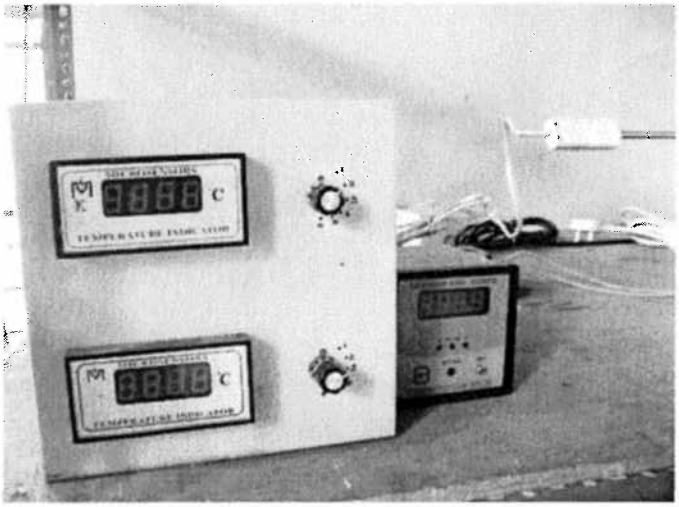
39. Valve to close the decanter.



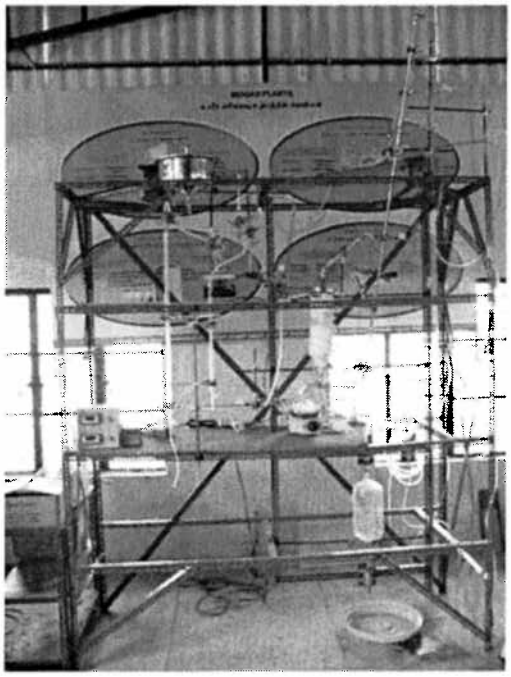
40. Condenser with methanol vapor tube.



41. Condenser connections.

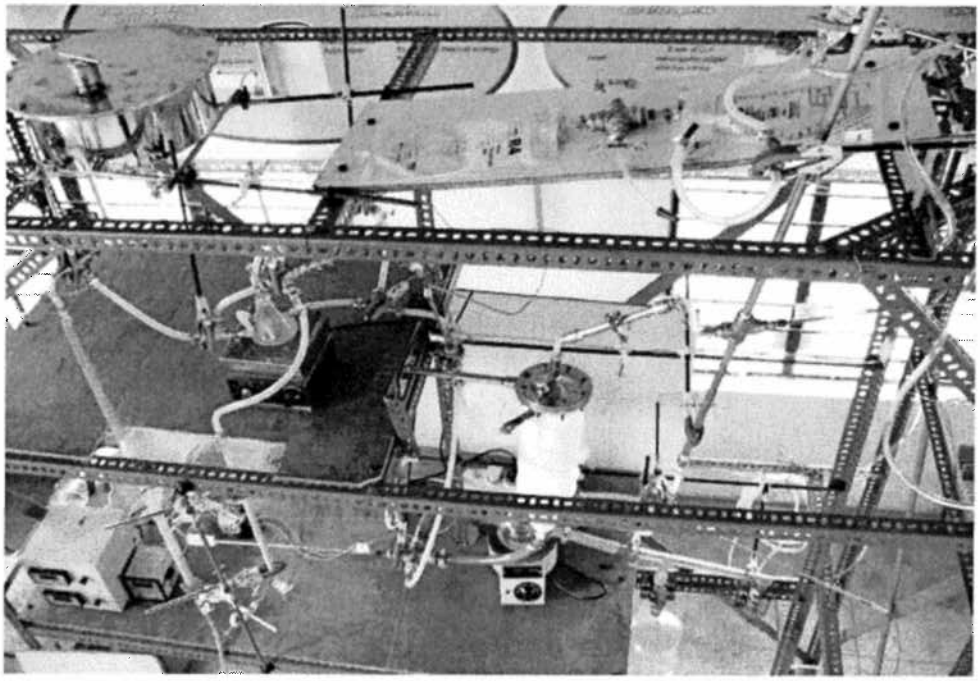


42. Thermo indicator and Temperature controller.



43. Complete unit

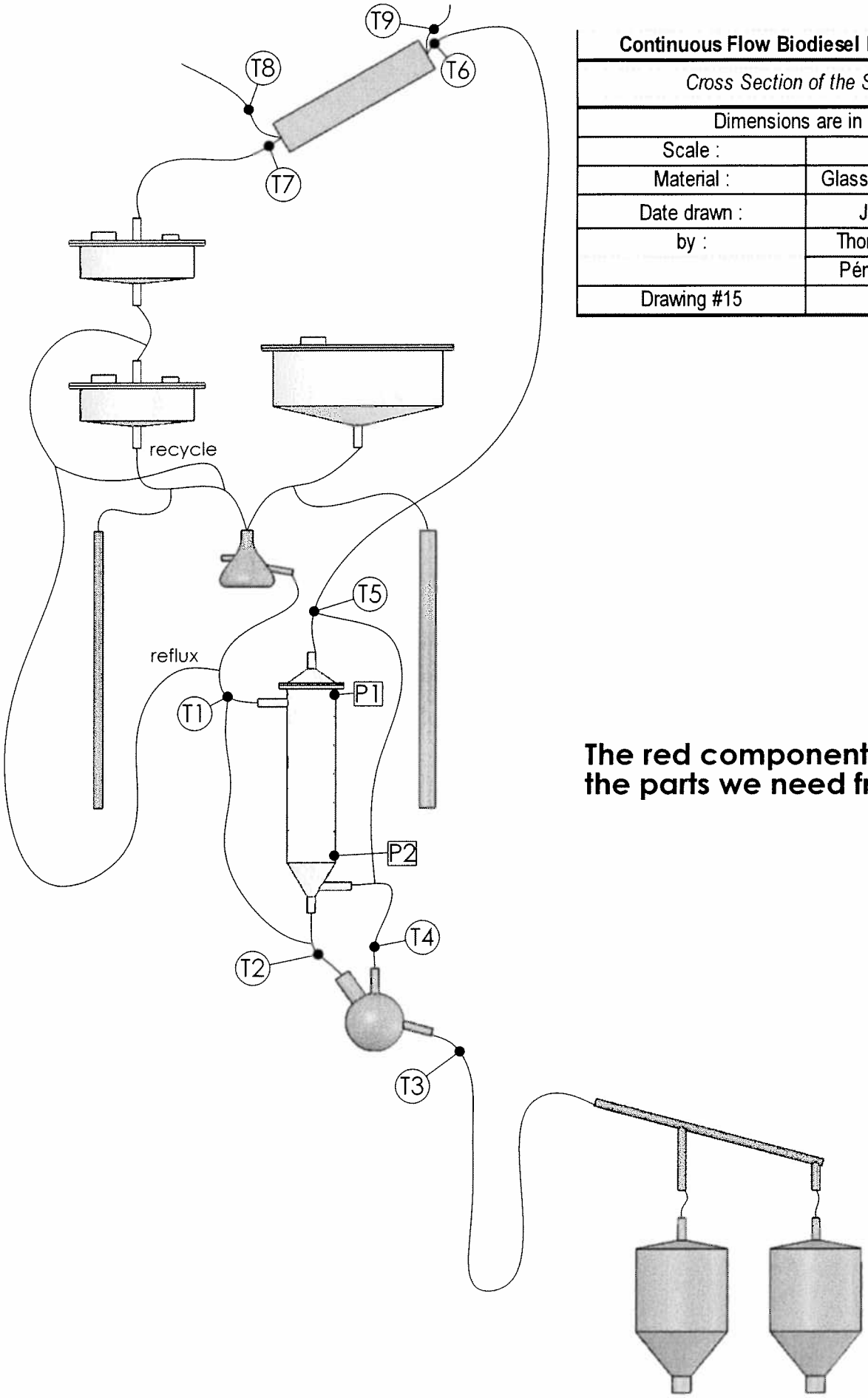
.



44. Top view of the unit.

44. Complete unit with the designers, Thomas and Pénéloppe, and their supervisor, Guillaume.

Appendix 4. Technical drawings



Continuous Flow Biodiesel Research Unit	
Cross Section of the System	
Dimensions are in mm	
Scale :	1:9.5
Material :	Glass & Stainless Steel
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #15	Version 3

The red components are the parts we need from you.

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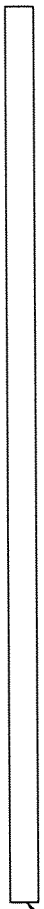
Burette #1



Specifications:

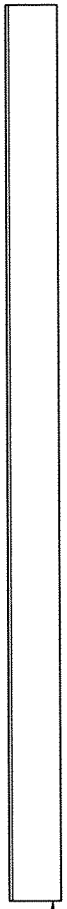
Volume = 50ml

Height = 50 cm

Precision = 0.1ml

A stop cock valve needs to be installed here

Burette #2



Specifications:

Volume = 200ml

Height = 50 cm

Precision = 1ml

A stop cock valve needs to be installed here

McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
Burette	
Dimensions are in mm	
Scale :	1:4
Material :	Glass
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #10	Version 3

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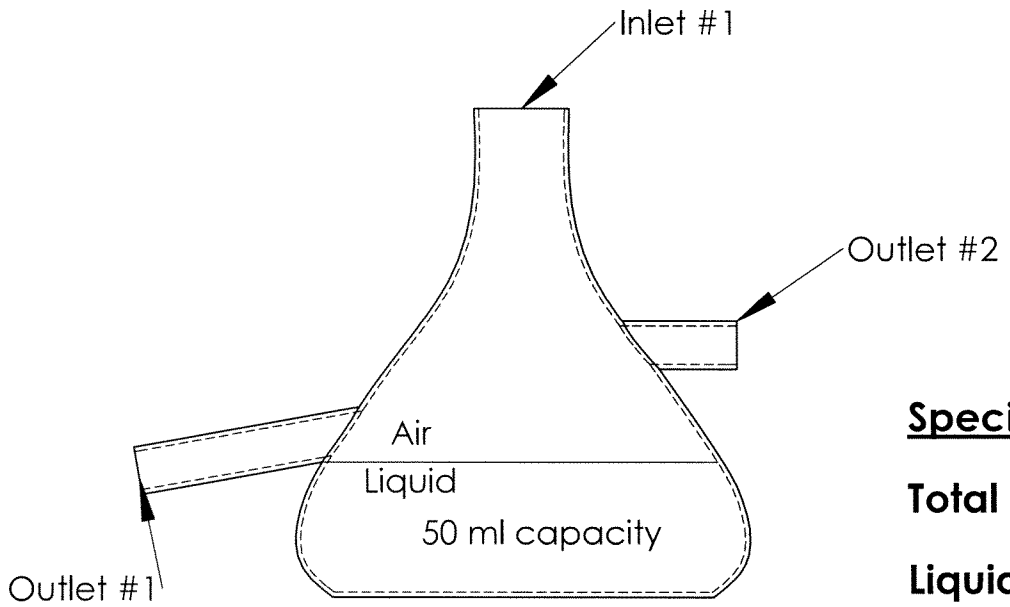
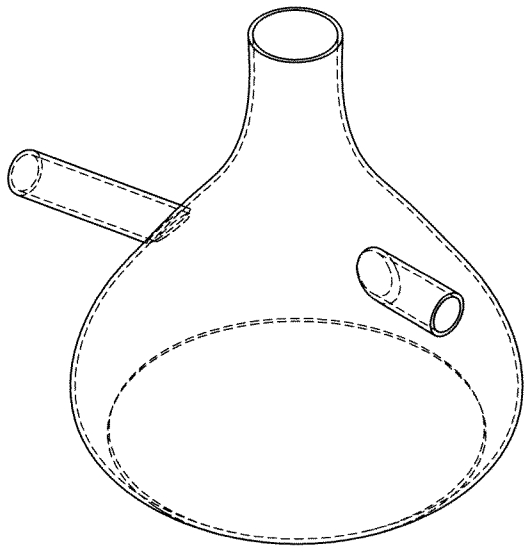




Specifications:

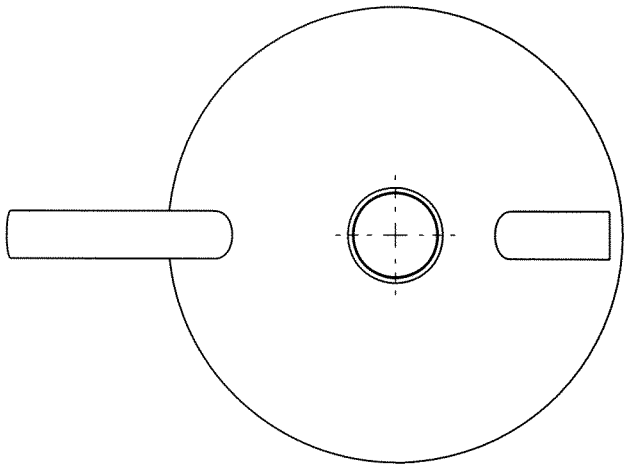
Total volume = 250ml

Liquid volume = 50ml

Inlet #1 = 20mm O.D.

Outlet #1 = 10mm O.D.

Outlet #2 = 10mm O.D.



McGill - TNAU Collaboration Project **Continuous Flow Biodiesel Research Unit**	
Pre-Reactor	
Dimensions are in mm	
Scale :	1:1.5
Material :	Glass
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #6	Version 1

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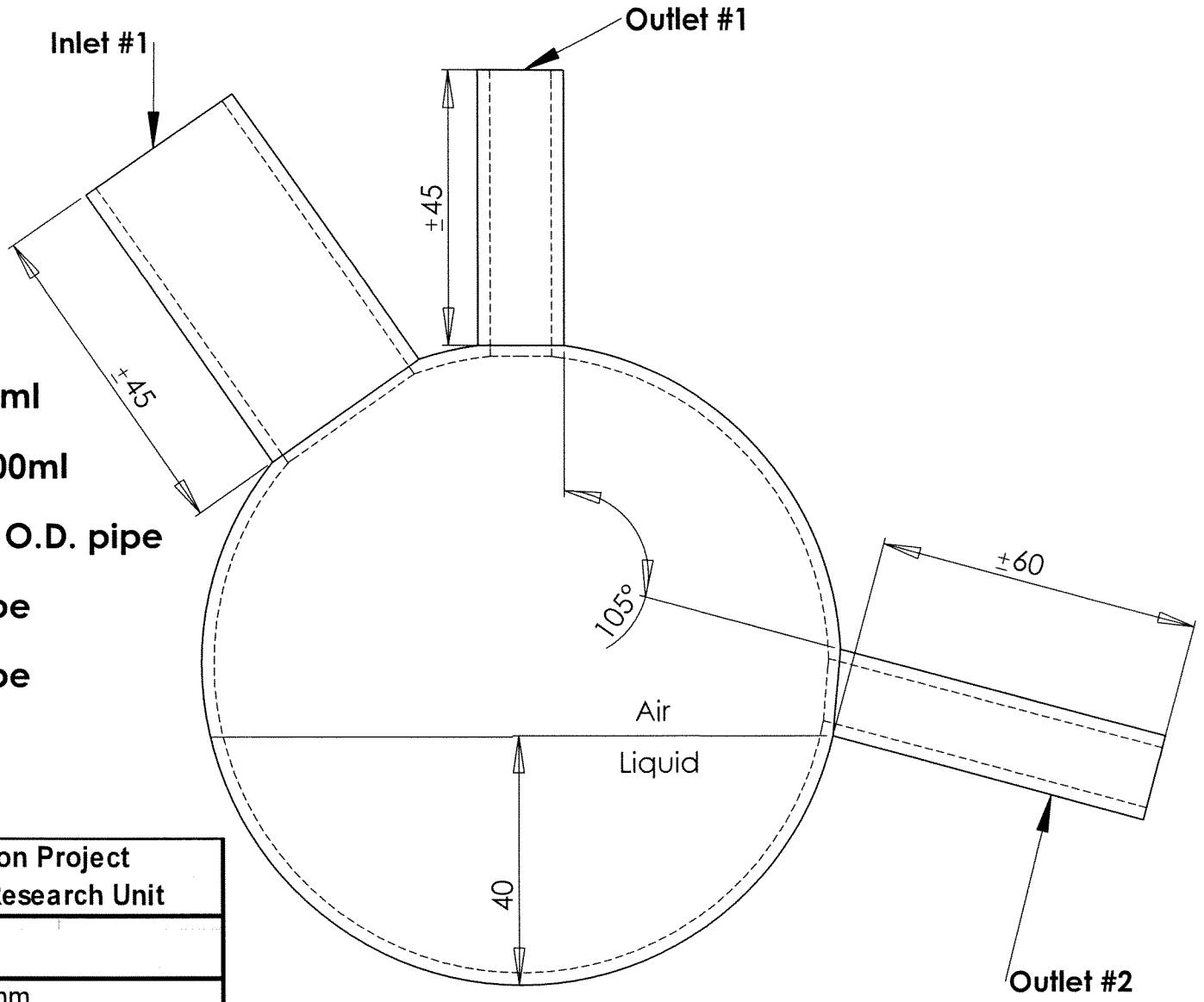
Side View



Specifications:

Total ballon Volume = 500ml

Working Volume max = 200ml

Inlet #1 = cork with 20mm O.D. pipe

Outlet #1 = 10mm O.D. pipe

Outlet #2 = 10mm O.D. pipe

McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
Evaporator	
Dimensions are in mm	
Scale :	1:1
Material :	Glass
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénélopne Thériault
	3

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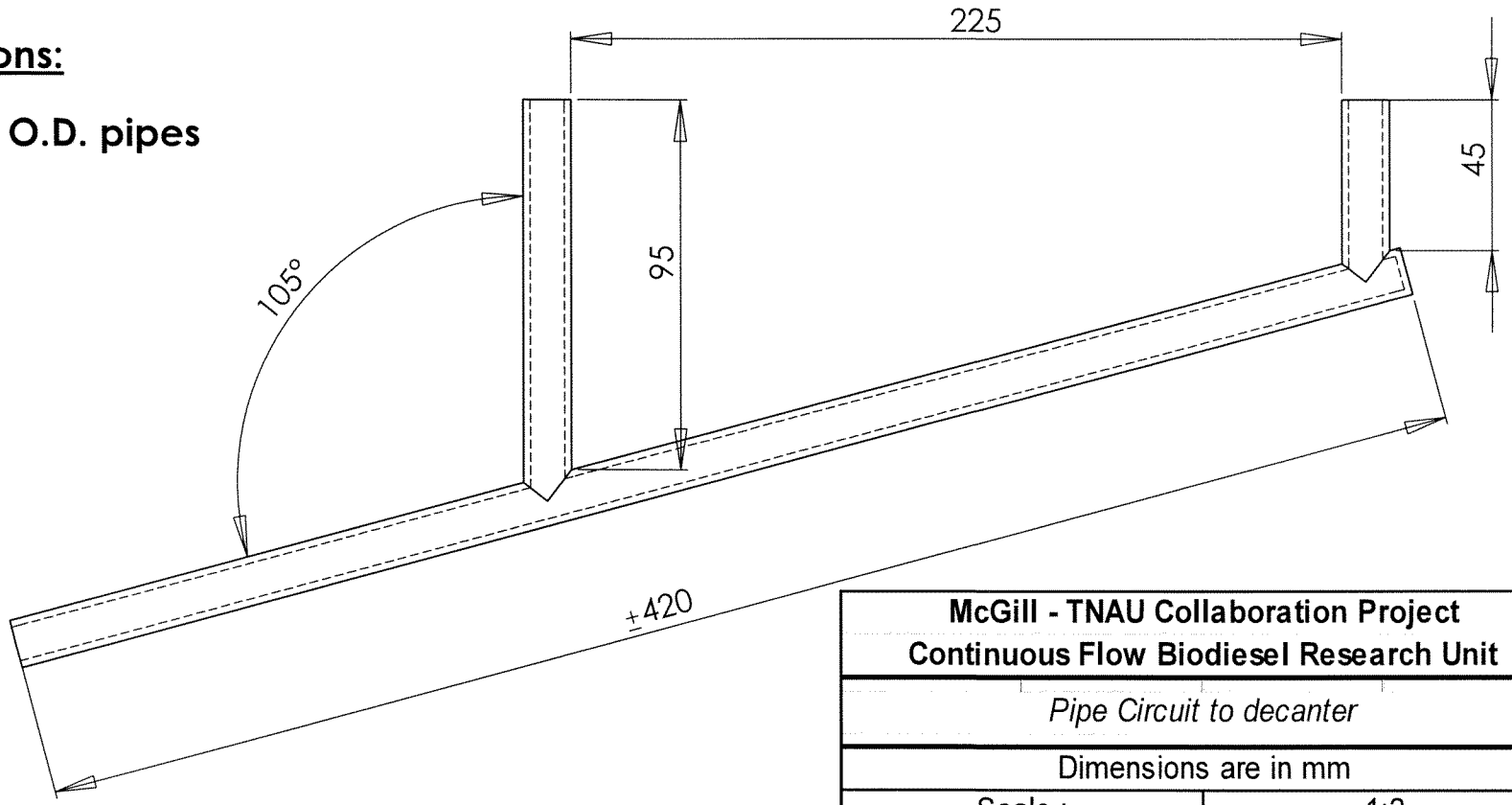
Specifications:

Use 20 mm O.D. pipes



McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
Pipe Circuit to decanter	
Dimensions are in mm	
Scale :	1:2
Material :	Glass
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #13	Version 3

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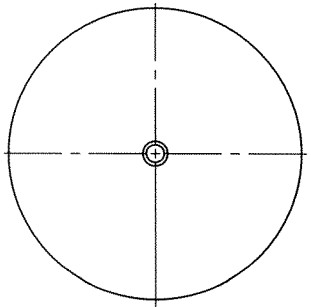
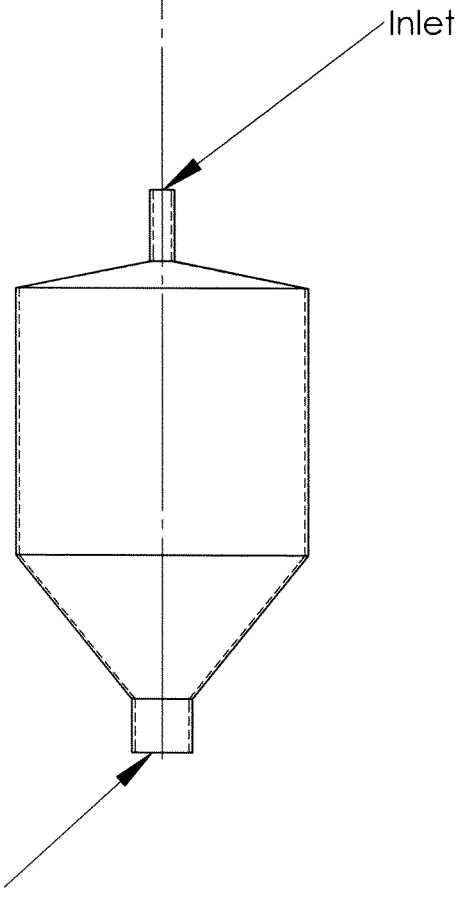
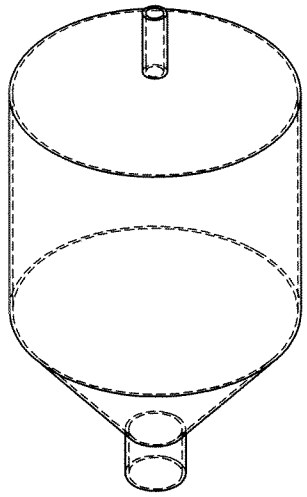
Top View



Side View





Specifications:

Volume of container = 5L

Inlet = 20 mm O.D. pipe

Outlet = 25.4 mm (1") O.D. pipe

McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
Decanter	
Dimensions are in mm	
Scale :	1:4
Material :	Glass
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #14	Version 3

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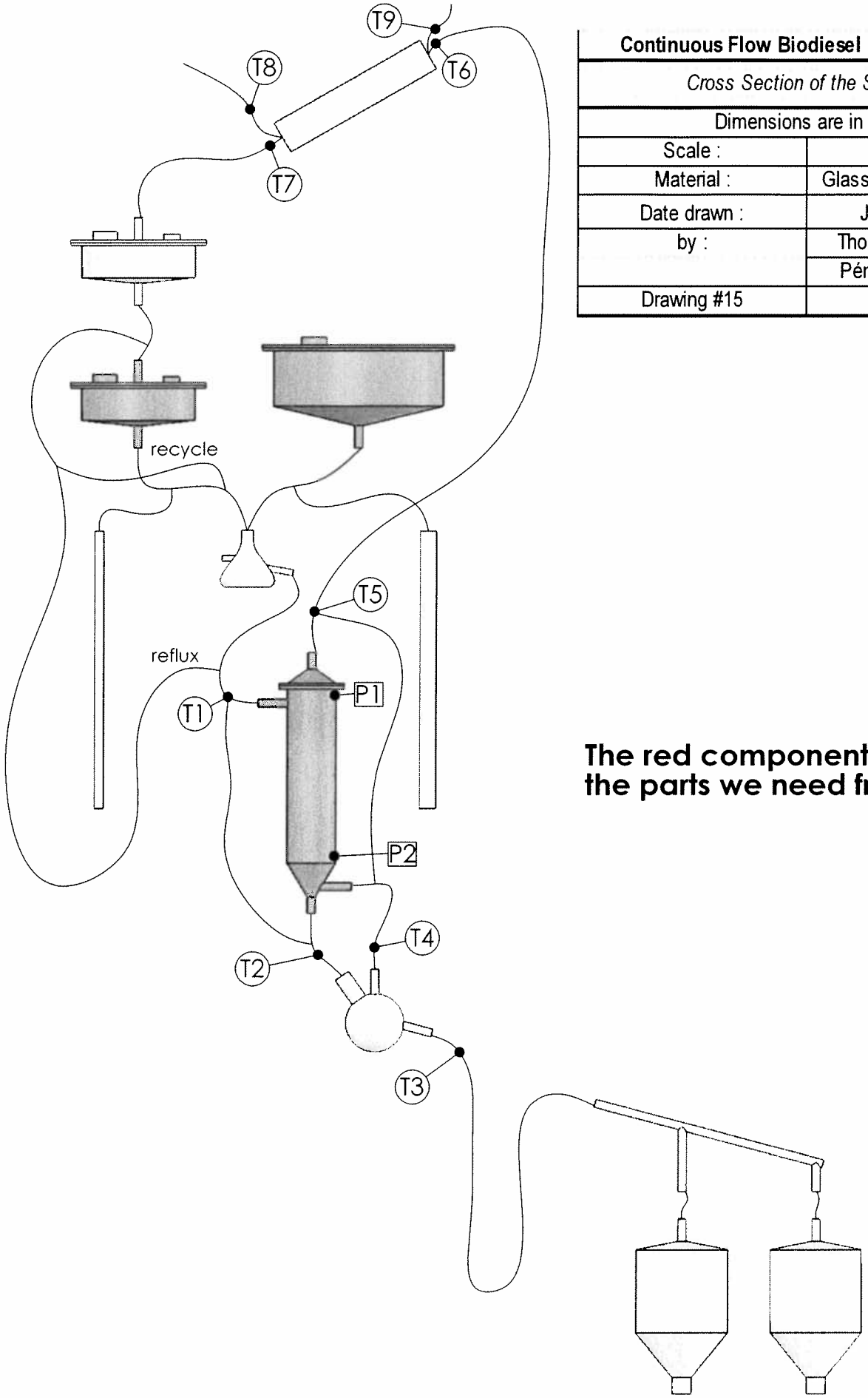

Continuous Flow Biodiesel Research Unit	
Cross Section of the System	
Dimensions are in mm	
Scale :	1:9.5
Material :	Glass & Stainless Steel
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #15	Version 3

The red components are the parts we need from you.

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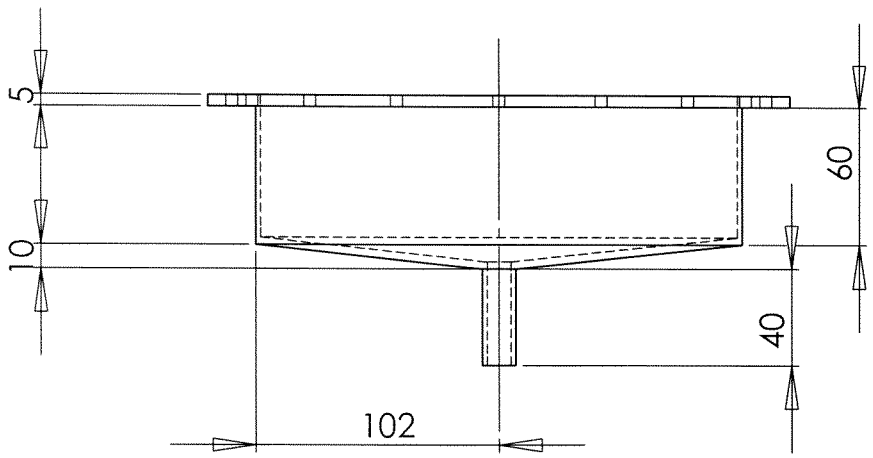
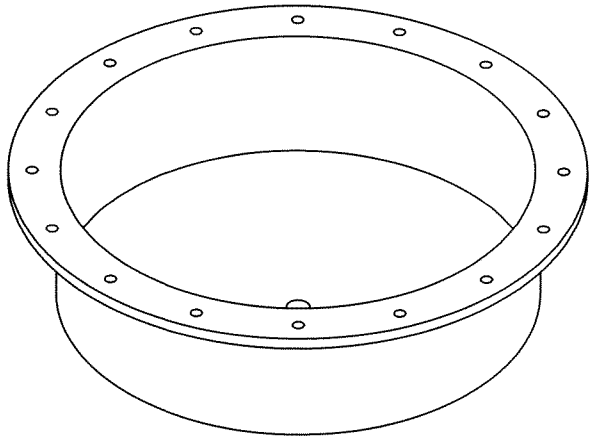
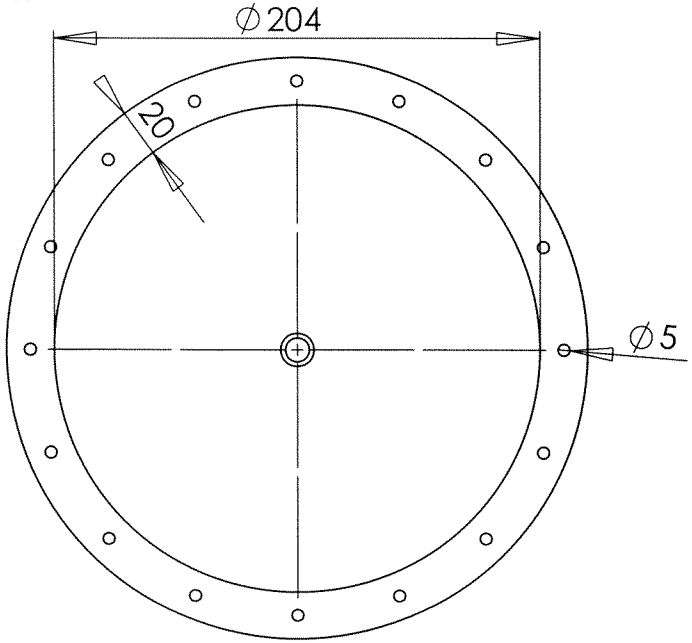
Side View





Female connection
3/8", BSP

Bottom View



Specifications:

Minimum Volume = 1.8L

McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
Methanol Container	
Dimensions are in mm	
Scale :	1:3
Material :	Stainless Steel
Date drawn :	July 17th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing # 1	Version 2

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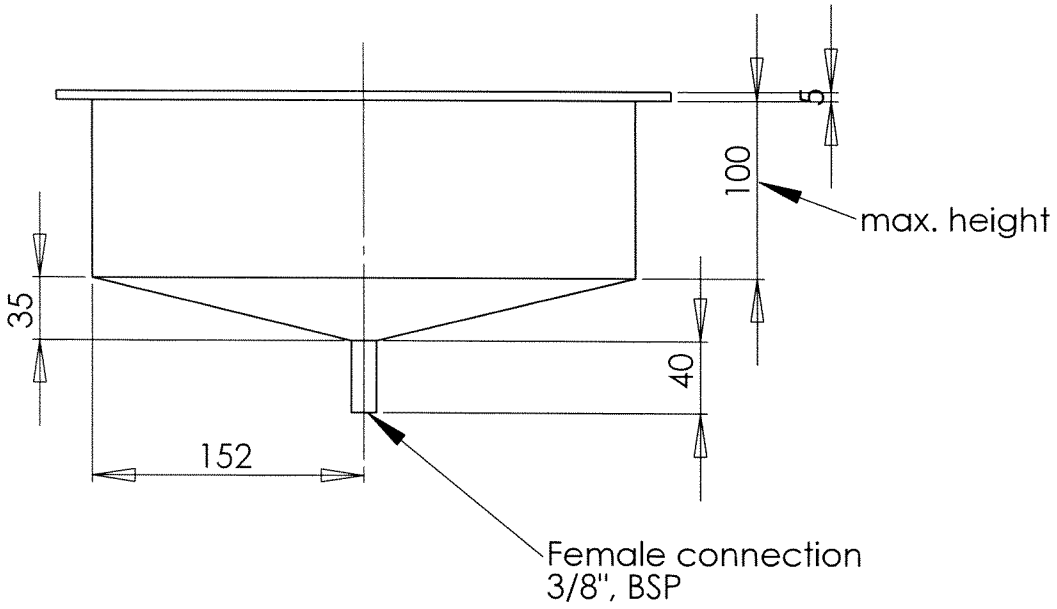

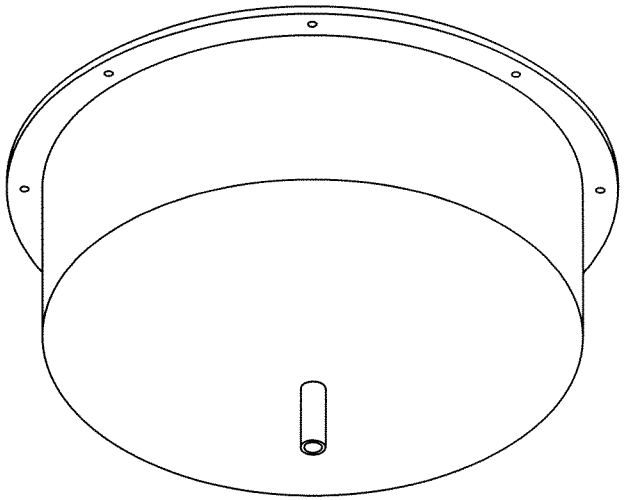

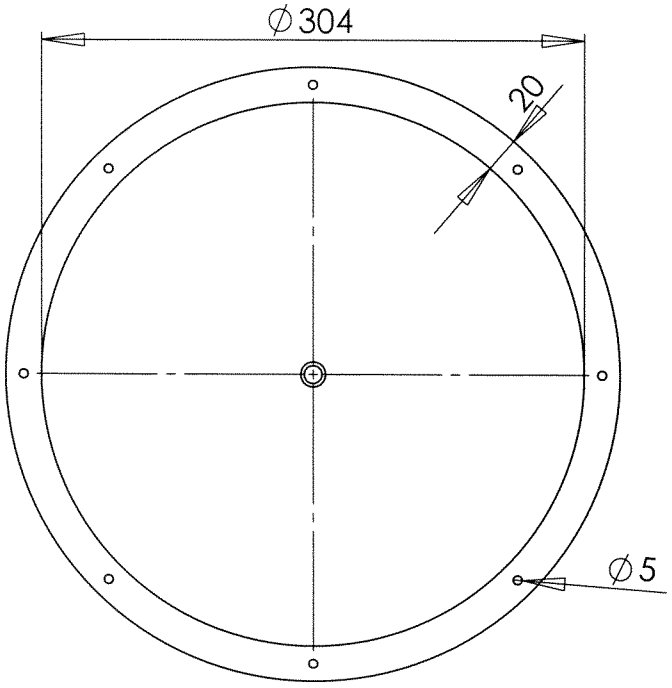

Specifications:

Minimum Volume = 1.8L

Maximum cylinder height = 100mm

McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
Oil Container	
Dimensions are in mm	
Scale :	1:4
Material :	Stainless Steel
Date drawn :	July 17th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #2	Version 2

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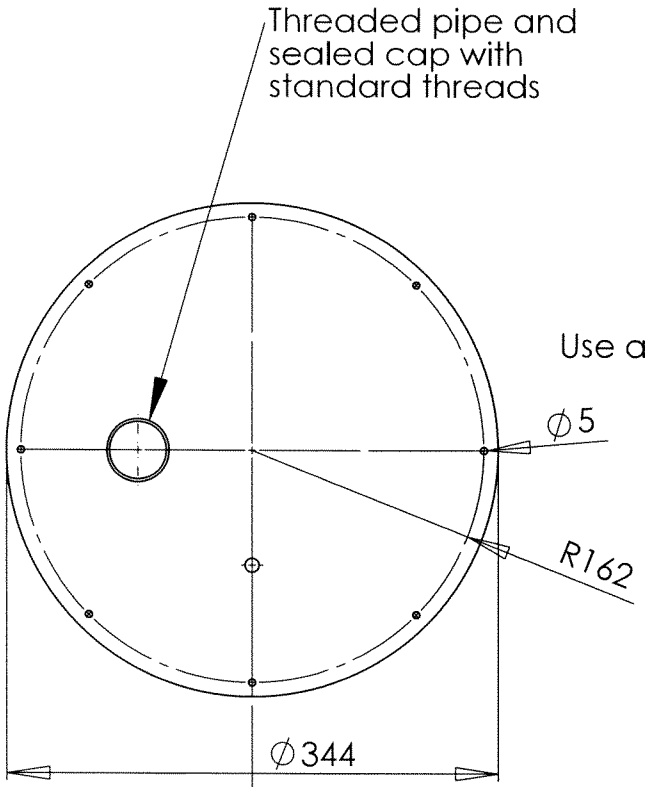
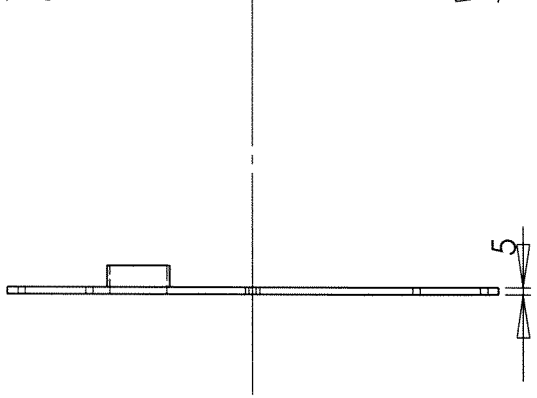
Oil Container Top

Top View

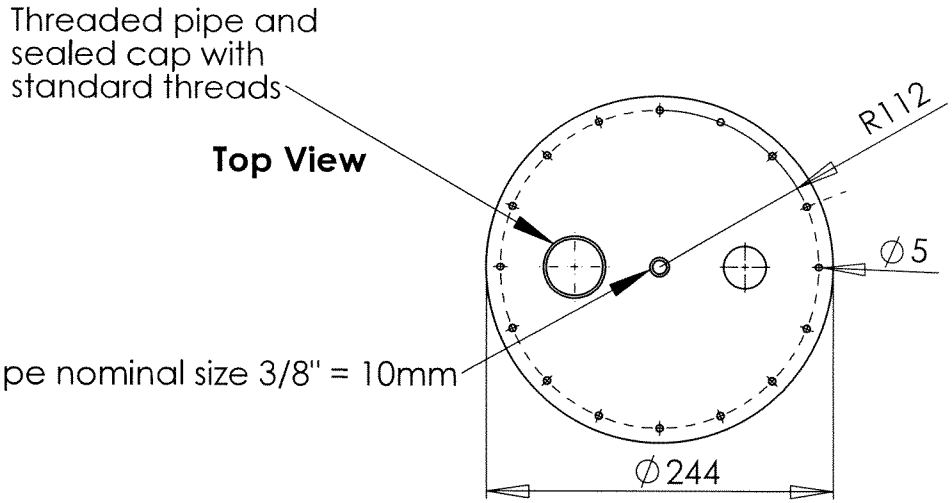


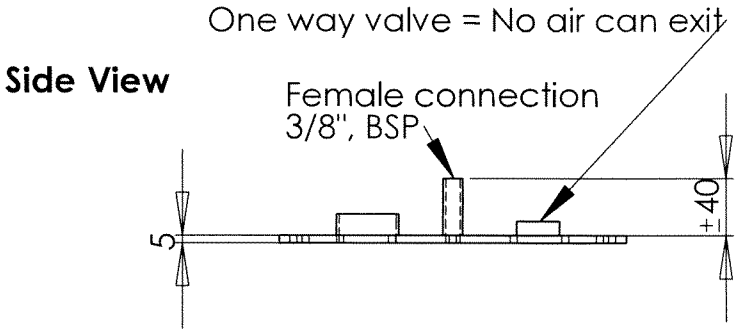
Side View



Scale 1:4

Methanol Container Top





Scale 1:5

Continuous Flow Biodiesel Research Unit	
Oil and Methanol Container Tops	
Dimensions are in mm	
Scale :	1:4 & 1:5
Material :	Stainless Steel
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #3	Version 3

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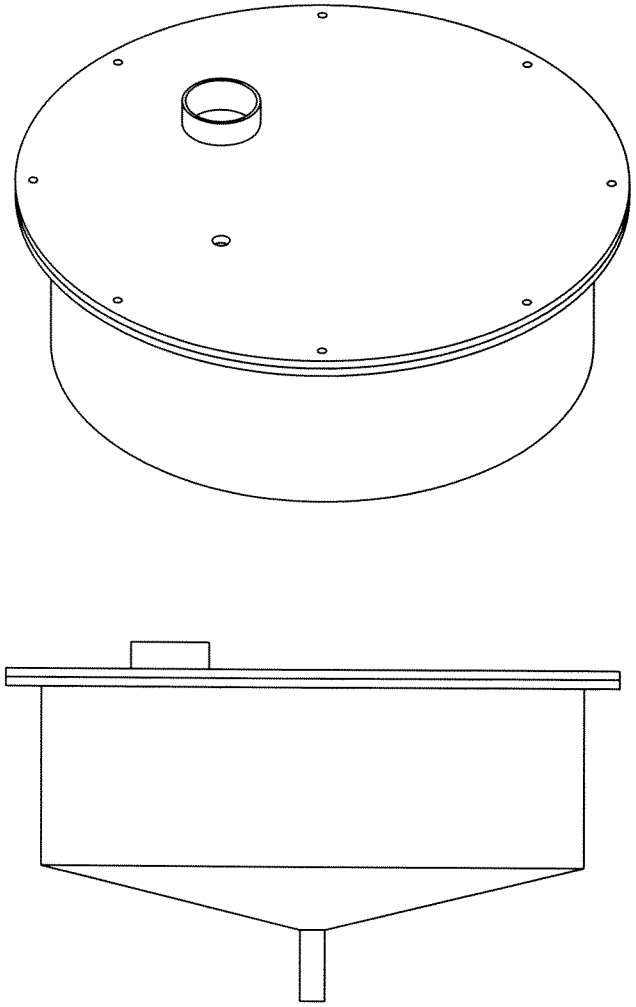
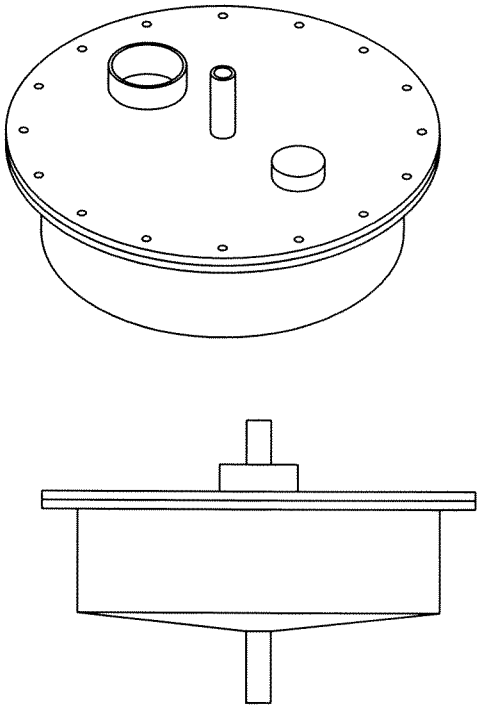
Oil Container - Assembled



Methanol Container - Assembled



Continuous Flow Biodiesel Research Unit	
Oil and Methanol Containers	
Dimensions are in mm	
Scale :	1:4
Material :	Stainless Steel
Date drawn :	July 19th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #4	Version 2

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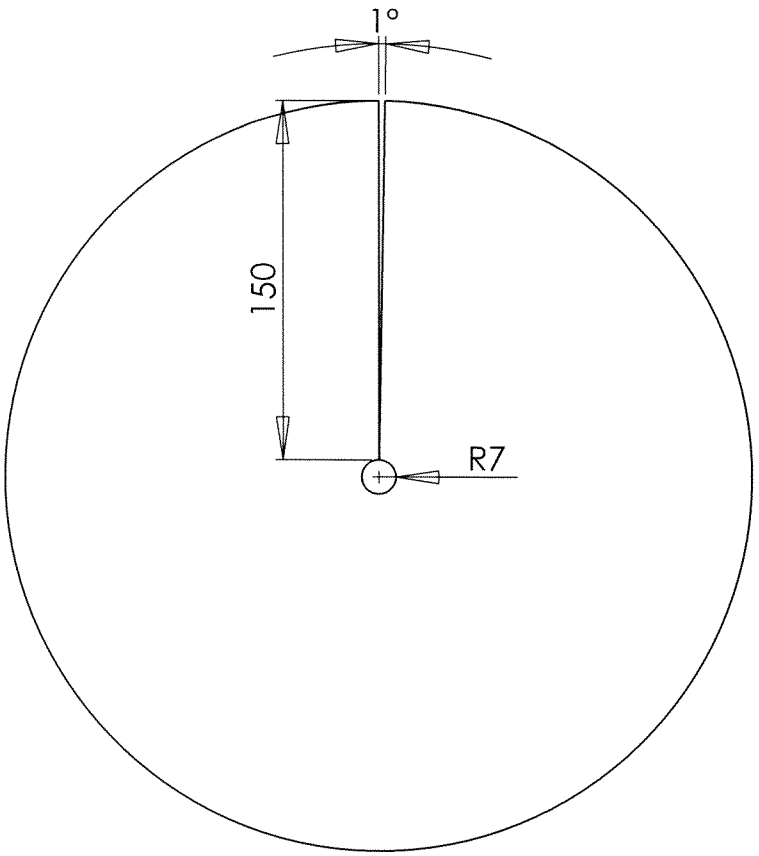
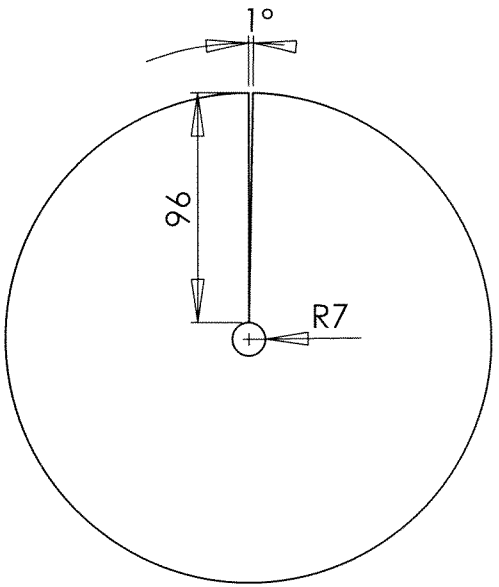
2-D plate - bottom Oil Container



2-D plate - bottom Methanol Container



McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
2-D views - bottom Methanol & Oil containers	
Dimensions are in mm	
Scale :	1:3
Material :	Stainless Steel
Date drawn :	July 31th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #5	Version 1

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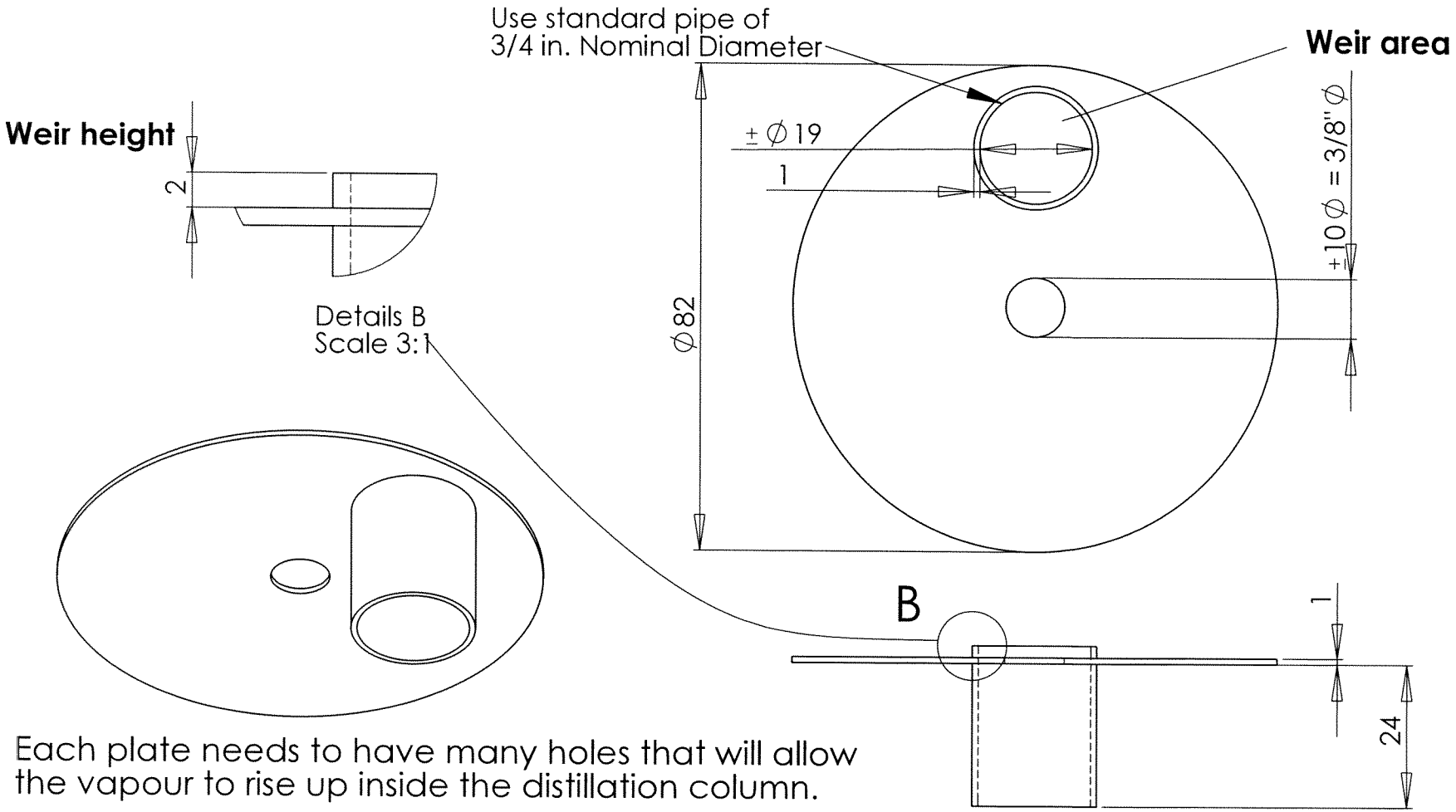

Each plate needs to have many holes that will allow the vapour to rise up inside the distillation column.

The diameter of each hole is **0.75mm** and the distance between the holes is **2mm**.

Make the maximum number of holes per plate as possible. Use square pattern.

The holes need to be pierced from the bottom of the plate.

McGill - TNAU Collaboration Project **Continuous Flow Biodiesel Research Unit**	
Plates (inside the distillation column)	
Dimensions are in mm	
Scale :	1:1
Material :	Stainless Steel
Date drawn :	July 12th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing # 7	Version 2

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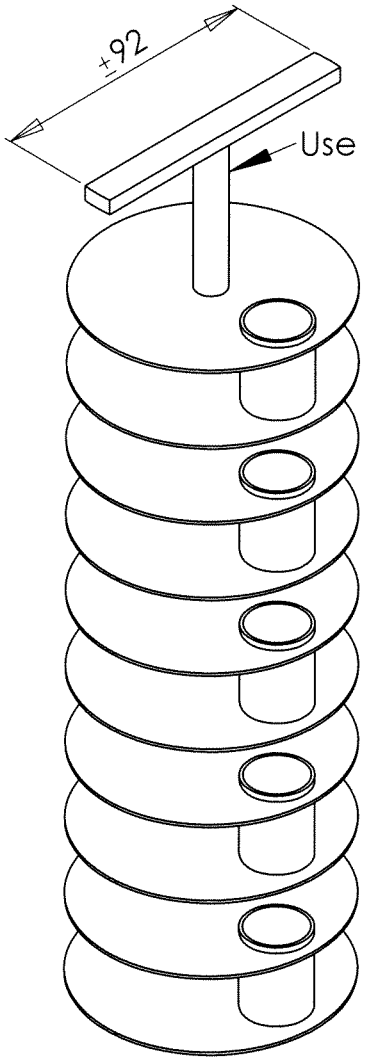

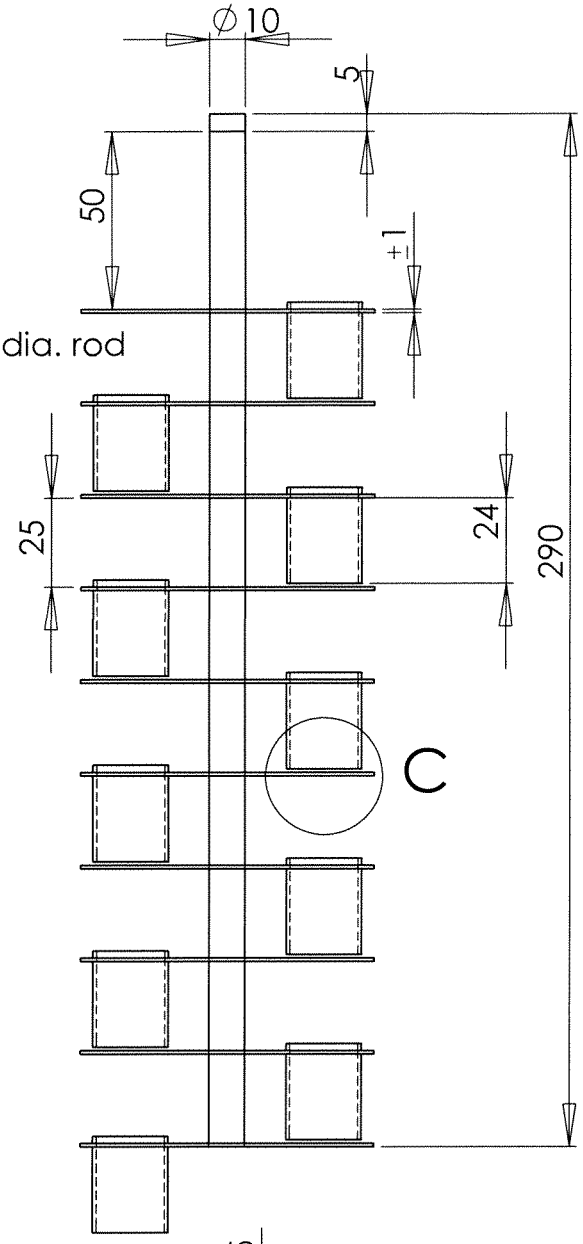

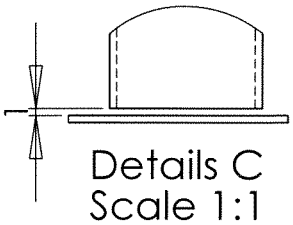

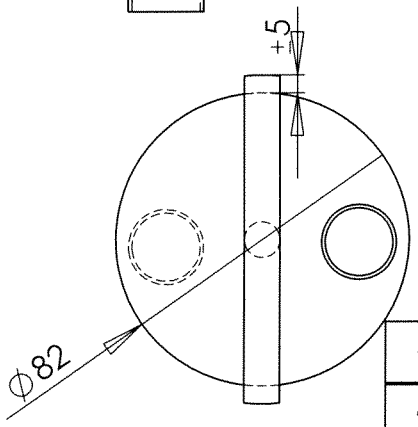

McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
Plates arrangement inside the distillation column	
Dimensions are in mm	
Scale :	1:2
Material :	Stainless Steel
Date drawn :	July 12th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing # 8	Version 2

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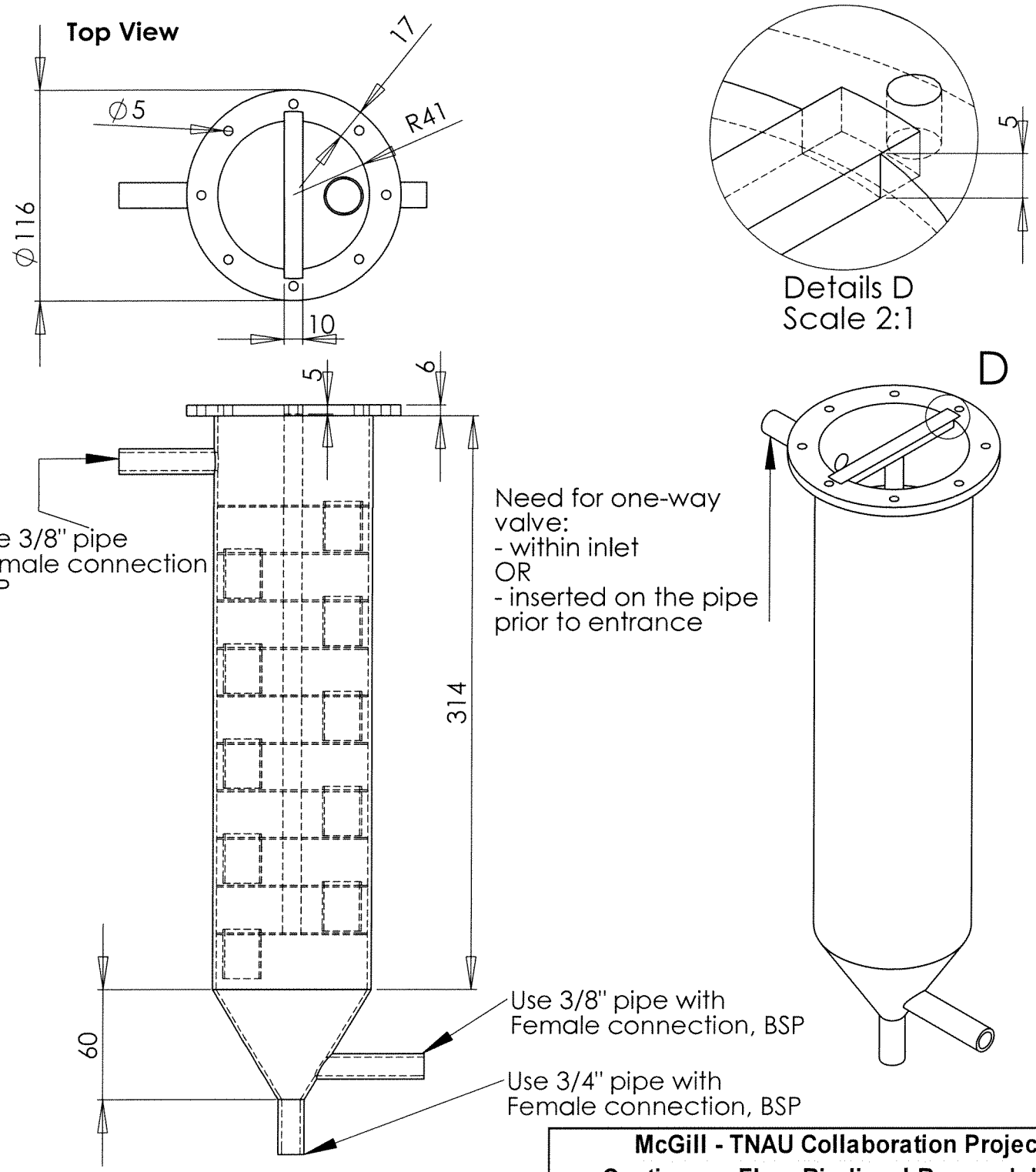

McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
Distillation Column - Outside shell	
Dimensions are in mm	
Scale :	1:3
Material :	Glass
Date drawn :	July 12th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #9	Version 2

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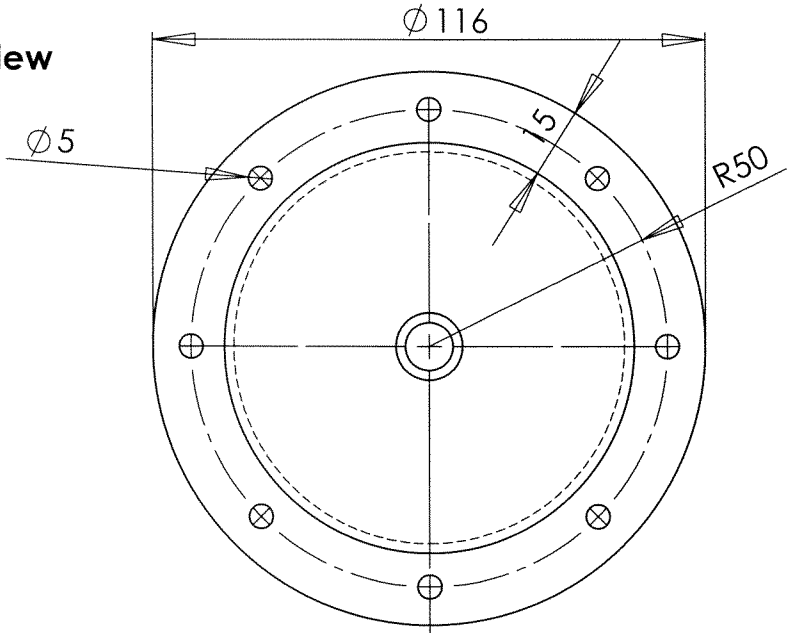
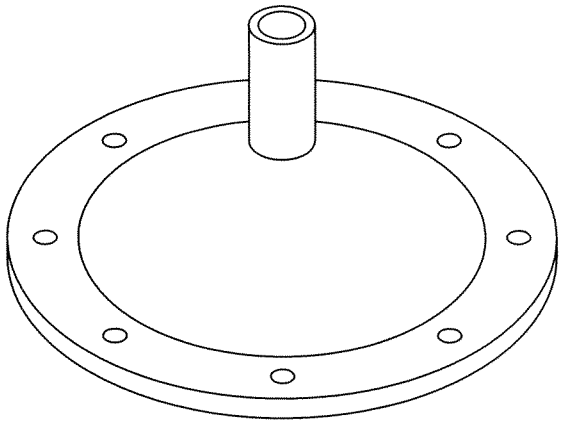
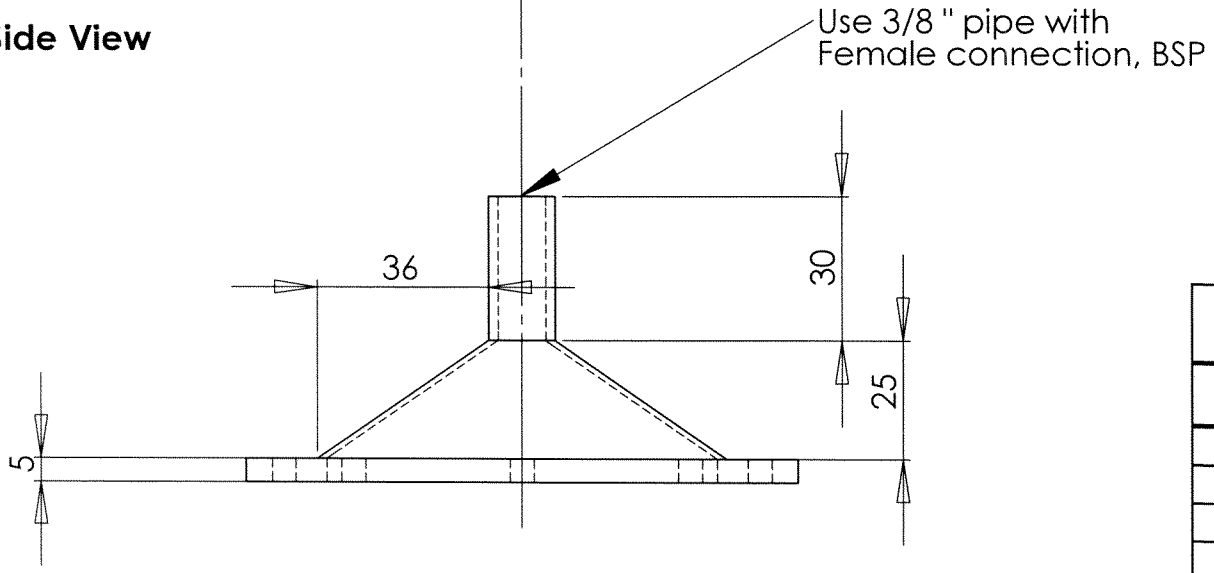
Top View





Side View



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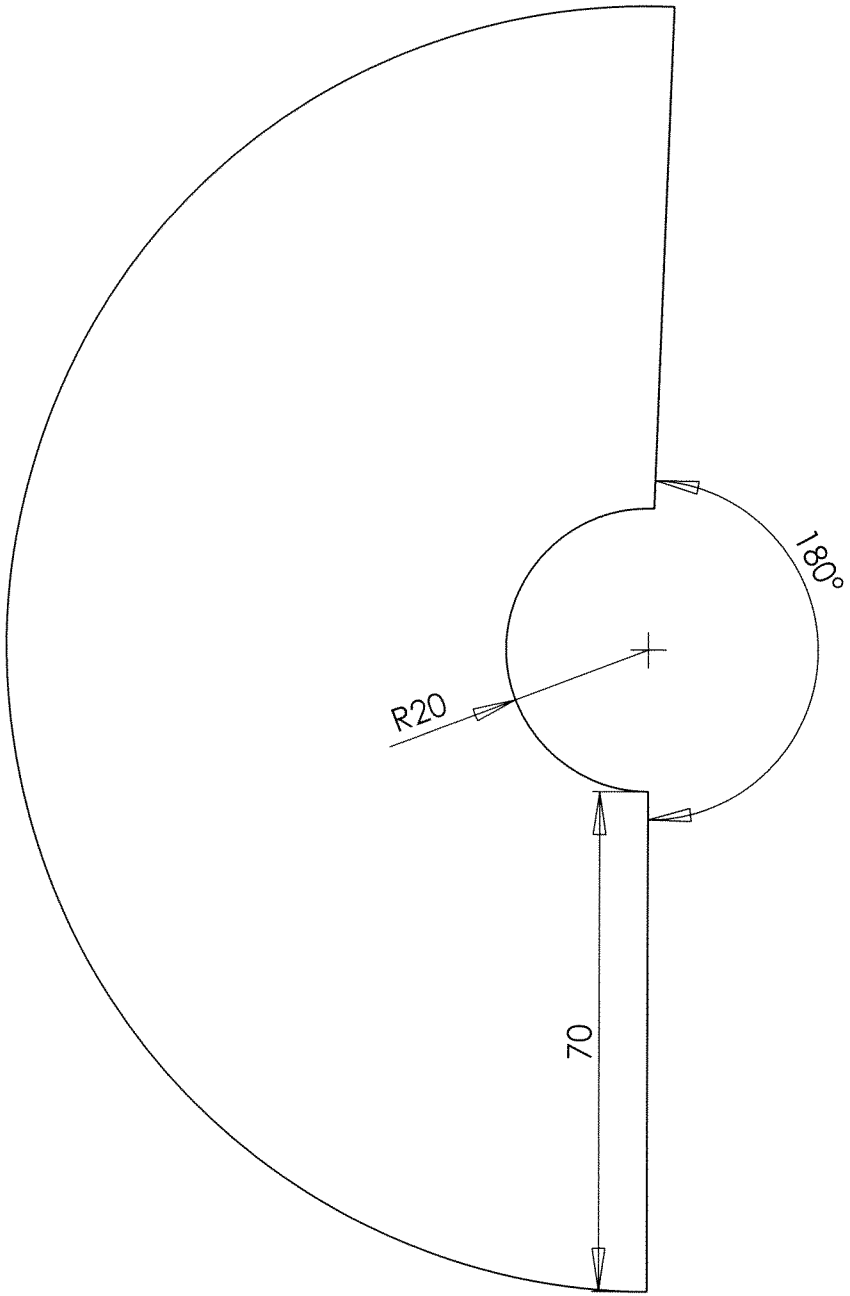
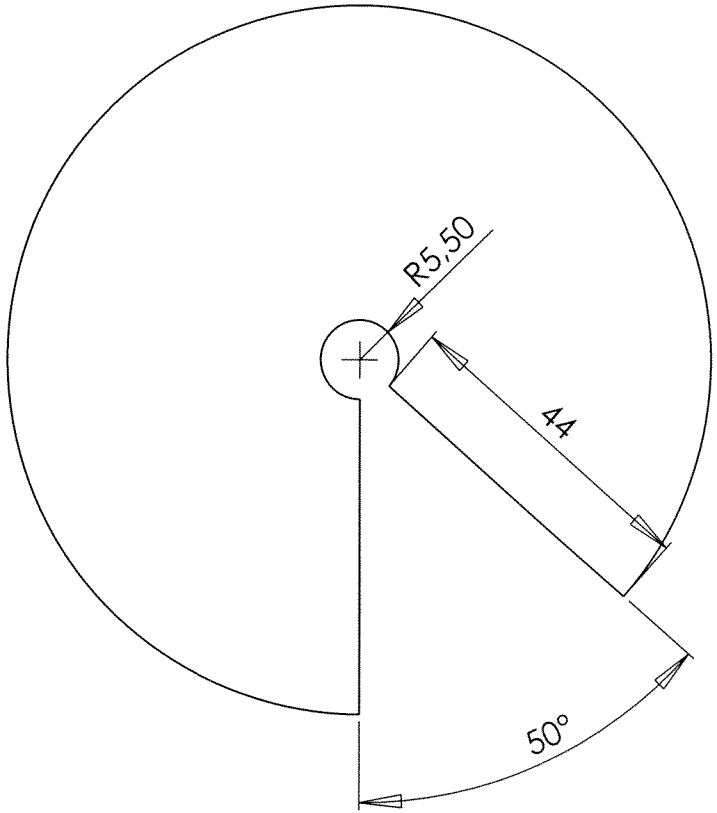
McGill - TNAU Collaboration Project **Continuous Flow Biodiesel Research Unit**	
Top of distillation column	
Dimensions are in mm	
Scale :	1:1.5
Material :	Glass or Stainless Steel
Date drawn :	July 20th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #10	Version 2

2-D plate - bottom Reactor



2-D plate - top Reactor



McGill - TNAU Collaboration Project Continuous Flow Biodiesel Research Unit	
2-D views - bottom & top Reactor	
Dimensions are in mm	
Scale :	1:1
Material :	Stainless Steel
Date drawn :	July 30th, 2007
by :	Thomas F.-Chevalier
	Pénéloppe Thériault
Drawing #11	Version 2

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