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Design and modeling of a vacuum drying system for a biodiesel pilot plant

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Design and modeling of a vacuum drying system for a biodiesel pilot plant

by

Kirk Stephen Menges

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
Jon Van Gerpen (Major Professor)
Gregory Maxwell
Brent Shanks

Iowa State University
Ames, Iowa
2003

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Graduate College
Iowa State University

This is to certify that the master's thesis of

Kirk Stephen Menges

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy

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ABSTRACT

The purpose of this research was to investigate the removal of water from oil and biodiesel fuel using a vacuum drying system. Water left in the oil will cause an incomplete reaction when producing biodiesel. The water can hydrolyze the triglycerides to diglycerides and form a free fatty acid. Also, water left in the biodiesel will cause fouling of the fuel handling system for diesel engines and corrosion of tanks and equipment. This research project examines the performance of the drying system at different vacuum settings, fluid temperatures, throttling pressures, and condenser flow rates in order to determine minimal conditions for meeting fuel moisture specifications. This meant performing preliminary research into current vacuum drying systems and consulting vendors on chosen equipment based on initial research and modeling. A biodiesel vacuum drying system was constructed and built at the Biomass Energy Conversion (BECON) Facility in Nevada Iowa.

A model of a vacuum drying system was developed in order to determine the proper equipment needed for the desired moisture removal at various conditions. Modeling of the vacuum drying system consisted of an energy and mass balance around the important components of the system, along with important assumptions and theories such as, the theory of ideal solutions and thin film theory. The model of the vacuum drying system and the actual system were compared, while determining the limits and assumptions of the model and drying system.

The tests were carried out in a vacuum drying system at various conditions as the moisture percentages of the fuel and oil were monitored in order to determine the system performance. A series of experiments were conducted in order to investigate the effects of

varying conditions on the drying system. The important factor investigated in these experiments was the moisture of the oil and fuel as the following conditions were varied.

1. Flash tank vacuum pressure
2. Flash tank input fluid temperature
3. Throttling pressure of input flash tank fluid
4. Condenser flow rate

The results from these tests provide important information for the prediction of drying system performance at various conditions. The data from the tests will help determine what system settings are needed to achieve the maximum efficiency of the drying system in terms of moisture removal.

1. INTRODUCTION

The current pilot plant at the Biomass Energy Conversion (BECON) Facility in Nevada, Iowa produces biodiesel from vegetable oil feedstocks, animal fats, and other oils or greases. Moisture removal from the oil is needed in order to convert the feedstock into a quality and desirable fuel. A feedstock with a high level of moisture can result in an incomplete reaction when producing fuel. “Drying is a thermal process in which a material is stripped of its moisture content by means of heat supplied to it” according to Bilgin Kisakurek [1].

The current ASTM Specification D 6751 – 02 sets the fuel specifications for biodiesel [2]. Standard D 6751 – 02 references ASTM D 1796 – 02, Test Method for Water and Sediment in Fuel Oils by Centrifuge Method, and requires the moisture level for biodiesel to be less than 500 parts per million (ppm) [3]. Increased fuel system corrosion and fouling of fuel-handling equipment can result from water levels higher than what the ASTM specification requires for biodiesel fuels. Water in fuel storage tanks can also cause problems such as corrosion and emulsions [3].

1.2 Objective

There were two objectives for this project, the first being to design and build a drying system suited for the biodiesel pilot plant at BECON. The second objective was to determine the conditions where the drying system must run at to meet the required moisture percent levels for oil and fuel. Experimenting with different operating conditions and recording the results of these experiments was used to establish the relationships required for predicting

drying system correlations. These correlations will help in obtaining the best moisture removal for other similar drying systems.

1.3 Scope

The intent of this study was to investigate the conditions that affect the characteristics and moisture removal efficiency of the drying system. With these relationships it was expected that one could determine the characteristics of a similar drying system that might not be able to operate at the most efficient or desirable set points. The variables explored in this study were the heater temperature, flash tank pressure (vacuum), heater pressure (throttling pressure), and condenser flow rate. A vacuum drying system was chosen over an atmospheric drying system because to achieve the separation of the oil and fuel from moisture without vacuum would require higher quantities of input energy. The higher input energy would result in longer process times, increased cost, and would possibly affect the quality of the oil and fuel itself due to the higher temperatures required for moisture removal in an atmospheric drying system.

2. BACKGROUND

In this chapter, the history and past research on drying systems that are appropriate for biodiesel production will be described, along with a brief background on biodiesel as an alternative fuel. This will include a basic description of the biodiesel reaction and how water interferes with this reaction. Different drying processes such as rotary and conveyor dryers will be compared to vacuum dryers, along with the advantages and disadvantages of each drying process.

2.1 Background on Biodiesel

“Biodiesel is an alternative fuel for diesel engines consisting of the alkyl monoesters of fatty acids from vegetable oils or animals fats”, as stated by Canakci and Van Gerpen [4]. The advantages of biodiesel are reduced emissions, non-toxicity, biodegradability, it is renewable, and has improved properties such as the cetane number. Biodiesel can be made from potentially any oil-seed feedstock, along with waste greases and fats, as long as the appropriate recipe of alcohol and catalyst are used for the process and the feedstock is properly prepared. Most of the biodiesel currently made in the United States is soybean oil-based biodiesel [5]. There is a lot of research currently being done in the area of producing biodiesel from other potential feedstocks besides soybean oils.

Transesterification is the chemical process whereby vegetable oils or animal fats are reacted with specific amounts of alcohol and a catalyst to make biodiesel. The transesterification reaction is shown in Figure 2.1.

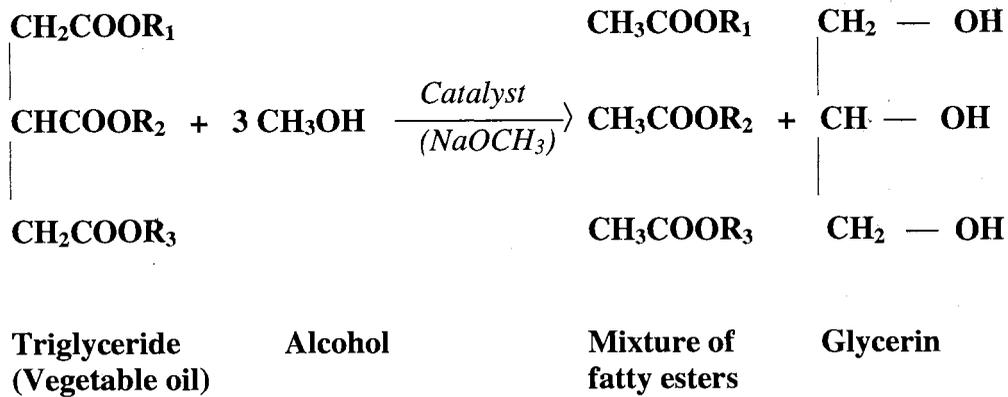


Figure 2.1 Transesterification Reaction.

In this reaction, a triglyceride is reacted with an excess of the stoichiometric amount of alcohol and a catalyst, which splits the triglyceride molecule into glycerin and a mixture of fatty esters. For the biodiesel pilot plant in Nevada Iowa, methanol and sodium methoxide are the main alcohol and catalyst used for the transesterification reaction. Other catalysts and alcohols can be used in the transesterification reaction, such as potassium hydroxide and ethanol. The esters are then named according to the alcohol that is used in the reaction, and “biodiesel” is the general term for the fuel created from the transesterification reaction. Other competing reactions that could take place instead of the reaction in Figure 2.1 are shown in Figures 2.3 and 2.4. Oleic acid, shown in Figure 2.2, is typical of the free fatty acids that can be found in vegetable oils that have not been refined. These free fatty acids can also be present in lower quality oils and greases.

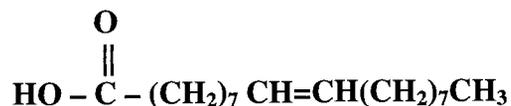


Figure 2.2 Oleic Acid.

Free fatty acids will react to form soap when oleic acid is present in a reaction involving alkali catalyst. An example of this competing reaction can be seen in Figure 2.3.

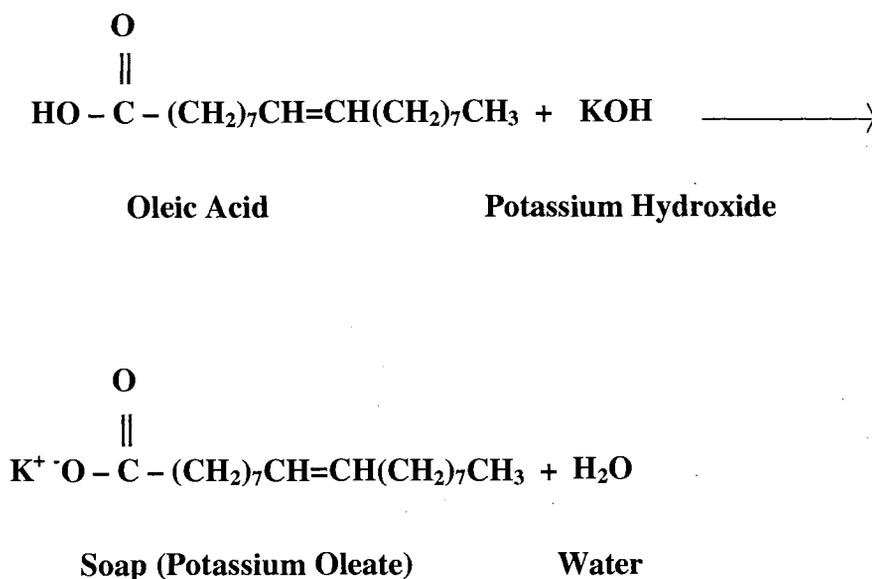


Figure 2.3 Competing Reaction with Soap Formation.

This reaction binds the catalyst into a form that is no longer capable of accelerating the reaction and produces soap. The soap can then interfere with glycerol separation and water washing after the reaction is completed. This reaction also leads to water formation, which can hydrolyze the triglycerides to diglycerides and form additional free fatty acid as shown in Figure 2.4

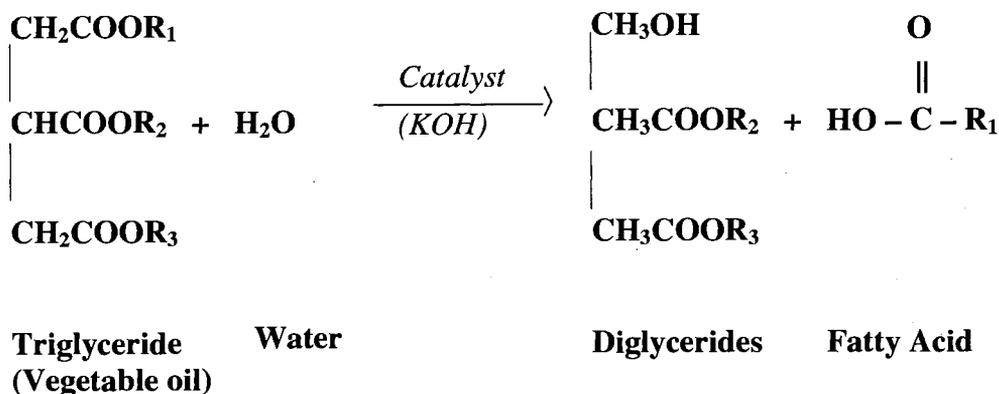


Figure 2.4 Competing Reaction with Water Formation.

The free fatty acid will form excess soap in the presence of an alkali catalyst according to the reaction above. This reaction is undesirable, and this is why it is important to remove the water from the oil before starting the transesterification reaction. Not removing the required amount of water when producing biodiesel can lead to saponification. Saponification is the process of fats being converted to soap because of the water present during the transesterification process.

Removal of water from the oil needs to be done in order to achieve a quality fuel. The water is even more crucial when the feedstock is restaurant grease or waste greases, which can typically contain higher amounts of water.

For the transesterification process to proceed properly, the feedstock, (oils, fats, and glycerides), must be anhydrous. Water in the reaction produces soap, hinders the separation of the ester and glycerol, reduces the yield of the esters, and makes the water washing process difficult [6]. The moisture percent for oils should be kept low in order to achieve the

best conversion of glycerides into esters. According to Ma and Hanna, “the water content of beef tallow should be kept below 0.06% w/w” [6]. Canakci and Van Gerpen concluded that “if the water concentration is greater than 0.5%, ester conversion rate may drop below 90%” for high free fatty acid feedstocks such as restaurant and waste greases [7].

2.2 History and Past Research

Biodiesel is a relatively new fuel for the consumer market even though fuels created from non-petroleum based oils have been around a long time, at least since the days of Rudolf Diesel. Rudolf Diesel demonstrated his engine at the World Exhibition in Paris in 1900 using fuel oil extracted from peanuts [8]. Until recently, there has not been much research and information into the production of biodiesel as compared to petroleum-based fuels. This limits the information on past research for water removal from biodiesel. Some processes that have been used for water removal are centrifuges, gravity separation with time, and heating the fuel or oil to drive off moisture.

The advantage of using a centrifuge is that it is not as time consuming as gravity separation, but both centrifuges and gravity separation cannot get out dissolved water. Free water is the water that can be removed from the fuel or oil using centrifuges and gravity separation. The dissolved water can be removed using heat, but it is very energy intensive and time consuming. Heating the fuel to drive off moisture requires temperatures well above the boiling point of water unless vacuum is applied to the process. Each of these processes results in a fuel that may or may not meet the required moisture level for use in diesel engines as called out in the ASTM fuel standards. Another potential source for information

on water removal is the processes used in the petroleum refining industry for moisture removal.

Refineries use either atmospheric distillation columns at high temperatures or high vacuum distillation columns at lower temperatures to remove most of the moisture according to the required specification [9]. The diesel fuel then goes through other processes, but moisture removal will have been taken care of in the distillation columns. A lot of information is available on drying processes using vacuum (less than atmospheric pressure), but air is the medium in most of the processes used in industry. Drying can be done with air, heated air, and drying under vacuum, as in the biodiesel pilot plant case.

Examples of drying using air are rotary dryers and conveyor dryers. Rotary dryers are also sometimes called drum dryers because of the “drum” used in the drying process. Figure 2.5 shows a heated rotary dryer, while air that is not heated can be also used in the process. Rotary dryers use a drum that can range in sizes from 0.3 meters to 5 meters, and lengths of 2 meters to 90 meters [1]. The drying medium, either ambient air or heated air, flows concurrently or countercurrently through the center drum section of the rotary dryer.

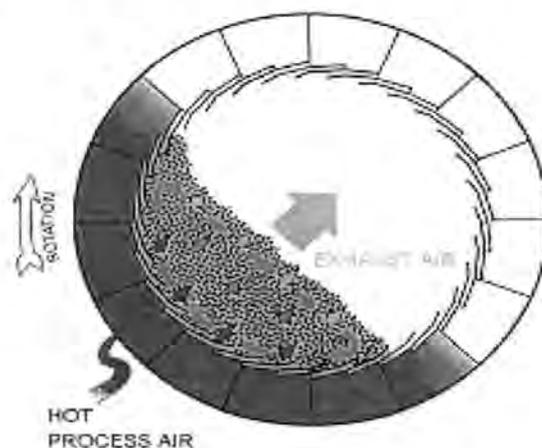


Figure 2.5 Rotary Dryer – Heated [10].

“Wet” material flows in one side of the drum while a “dryer” material flows out the other end. The drum is inclined from 1 to 4 degrees to promote the flow of the material through the drum along with drum rotation. Mounted lifting flights are used to tumble the wet material and expose it to the drying medium as it passes through the dryer. The advantages of rotary dryers are that they can handle large amounts of wet material with high moisture content. The disadvantages are that they cannot reach low levels of moisture without vacuum, and they require high residence times along with small particle diameters for the wet material in order to remove as much of the moisture as possible. Wet material also has to be robust in order to take the physical tumbling of the rotary dryer, which can damage material that is sensitive to forces being applied to the material from tumbling.

Conveyor dryers are another alternative to rotary dryers, which can use air or heated air and are a little gentler on the wet material. Figure 2.6 represents a single stage conveyor dryer using hot air. Again, air that is either heated or not heated can be used along with multiple stage conveyors in order to obtain the required amount of moisture removal.

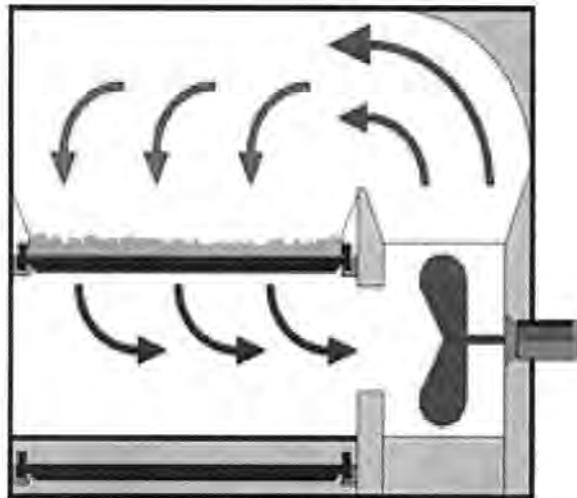


Figure 2.6 Conveyor Dryer – Heated [11].

Conveyor dryers can range in sizes from 1.0 to 4.5 meters wide and the product can be carried through insulated housings that are 3 to 60 meters long, where air is forced through the material [1].

Some products require gentle handling during the drying process; because of this conveyor drying is used as opposed to rotary drying. Conveyor drying usually uses a perforated bed where the wet material is spread over the bed and air is passed up or down through the bed. The bed can be on a moving belt that is passed through a tunnel-like structure in which vertical air flow is closely controlled [1]. The individual wet particles remain fixed in position except for the occasional transfer process from one conveyor to another. An advantage to the fixed position is that each particle has the same residence time in the dryer, which is important for uniformity of moisture for downstream operations in some processes. Another advantage is that the material is not exposed to the violent tumbling that occurs in a rotary dryer. Multiple conveyors can also be used to obtain the desired moisture level in the drying operation. Some disadvantages to conveyor dryers are the long residence times required for drying, along with high temperatures that might be required to reach certain moisture levels. These high temperatures can affect material that is sensitive to the high levels of heat, and maintaining a vacuum on a conveyor dryer in order to operate at lower temperatures can be a little more difficult. Operating a drying system under vacuum results in lower temperatures required for the drying process. This is especially important for heat sensitive material plus the process can require less energy due to the lower temperature operating conditions.

Figure 2.7 shows a vacuum drying process where a vacuum pump is used to reach pressures less than atmospheric.

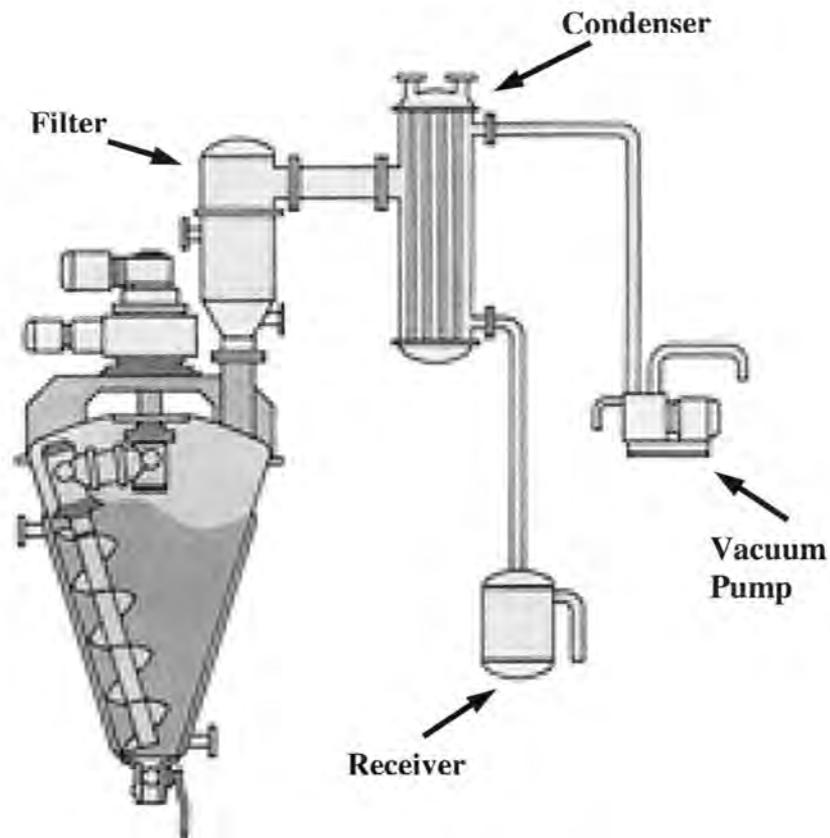


Figure 2.7 Vacuum Dryer [12].

The primary advantage of vacuum drying processes is the lower operating temperature, which means less energy is required for the process. Vacuum drying systems also have shorter residence times for the drying process, and can reach lower moisture levels without affecting heat sensitive material. One disadvantage of vacuum drying systems, such as the one used for the biodiesel pilot plant, is the requirement of maintaining a uniform thin film layer inside the flash tank. Another disadvantage is the low volume of wet material a vacuum system can handle, which is small in comparison to rotary and conveyer dryers. Vacuum drying systems are best suited for very low levels of moisture, such as levels close to a few percent. While rotary and conveyor dryers can handle wet material with high levels

of moisture. Rotary and conveyor dryers also are meant for solid material, while the vacuum drying system at BECON is designed for liquid material

Vacuum systems can be broken down into two categories, one is mechanical methods for vacuum production and the second is physico-chemical methods of vacuum production [13]. Some examples of mechanical vacuum pumps for drying processes are rotary, dual rotary, conveyors, and ejector pumps. Some examples of physico-chemical methods of vacuum production are ion pumping, chemisorption pumping, cryocondensation pumping, and cryoadsorption pumping.

Physico-chemical vacuum pumps allow for better working pressure ranges when compared to mechanical vacuum pumps because they preclude pollution of the vacuum chamber with vapors of working liquids that are used for sealing or lubrication [13]. Ion pumps generally work on the principle of direct movement of previously charged gas molecules in an electrical field [13]. Chemisorption pumping is the sorption of active gases on the surface of a getter [13]. A getter is a substance introduced into a vacuum tube or electric lamp to remove traces of gas, Titanium, Zirconium, and Tantalum are some metals that can be used as getters. Cryocondensation is the removal of gases from a vacuum system by means of their condensation on cooled pump surfaces. Light gases such as Hydrogen, Helium, and Neon cannot be pumped by condensation and must be adsorbed, which is cryoadsorption pumping. Cryoadsorption pumping takes place when a gas molecule landing on the surface of an organic material loses kinetic energy as it cools and rapidly diffuses into the inner volume of the organic material [13]. All of these processes mentioned are specific to certain applications and are not appropriate for application to the vacuum drying process

used in the biodiesel plant pilot. In a vacuum drying process, evaporation is the main phenomena responsible for the removal of moisture from the wet material.

Evaporation processes such as rising film and falling evaporators are similar to what is taking place in the flash tank of the vacuum dryer for the biodiesel plant. In all of these systems a thin film forms on the inside surface, which provides for rapid and near complete vapor removal.

In a falling film evaporator, as seen in Figure 2.8, liquid flows down multiple tubes where heat is applied to the outside surface of the tube [14].

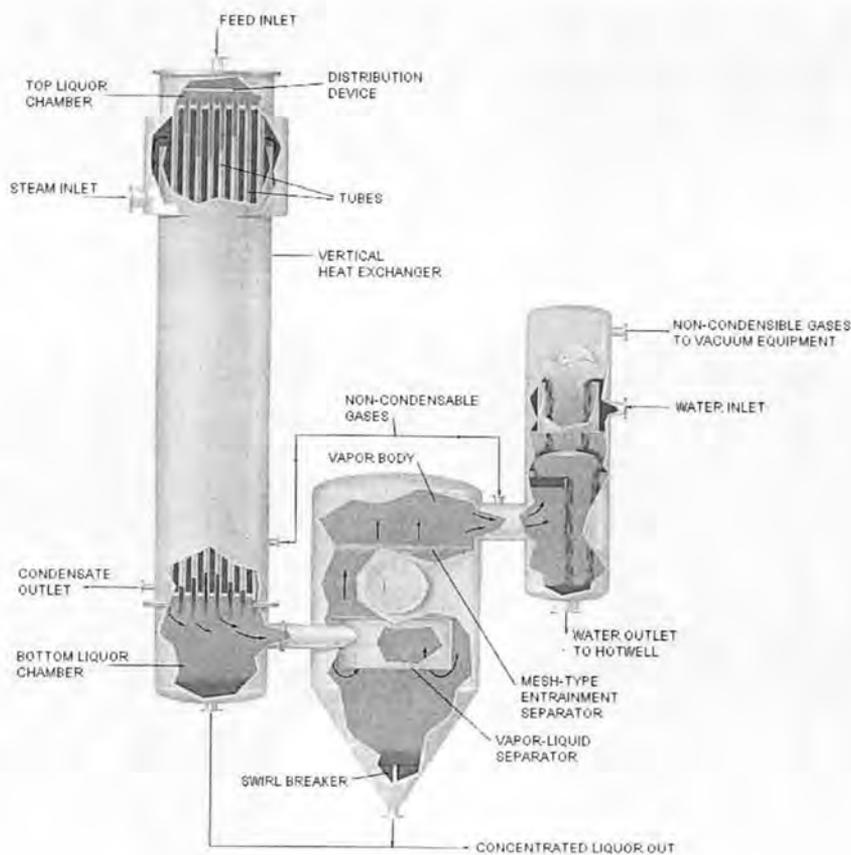


Figure 2.8 Falling Film Evaporator [15].

The applied heat causes the evaporation of the liquid film as it travels down the tubes. The liquid film is accelerated by the vapor passing down the center of the tube because of the drag effect [14].

This drag effect is due to gravity and the high velocity vapor at the vapor-liquid interface accelerating the liquid while the vapor loses momentum at the interface due to the drag force. The two-phase mixture then enters a vapor body where the liquid can drop to the bottom, while the vapor can rise to the tube of the vapor body.

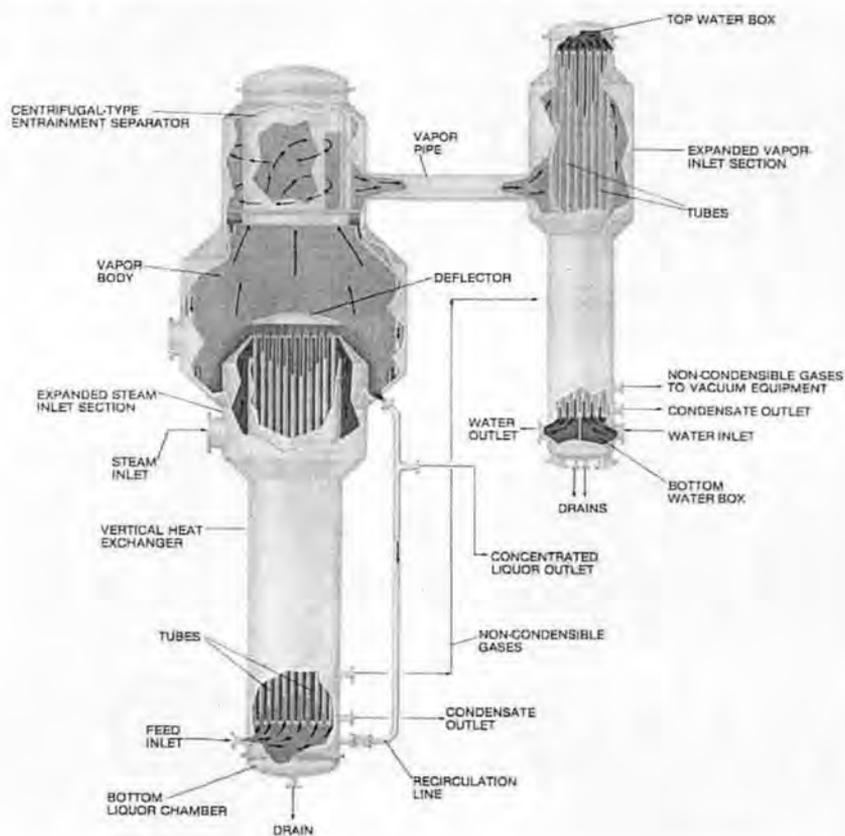


Figure 2.9 Rising Film Evaporator [16].

The advantages of a falling film evaporator are that it operates in applications where the driving force in temperature differences between the heat transfer medium and liquid is low.

Another advantage is that it operates at short residence times compared to the rising film evaporators. A disadvantage is that it is not suited for highly fouling products.

Figure 2.9 represents a rising film evaporator, where the feed is pumped into the bottom of the evaporator and the feed pressure forces the liquid up the tubes where it is heated until it reaches its boiling point [14]. The vapor rises in the center as the liquid boils and is distributed in the form of a liquid on the tube wall. The film and vapor accelerate as they move up the tube due to the formation of additional vapor and the drag effect on the liquid of the vapors moving at higher velocities [14]. The vapor and liquid enter the vapor body where the vapor is removed and the liquid is trapped and removed as a product.

3. MODEL DEVELOPMENT

This chapter describes the model development used to simulate the performance of the vacuum drying system. It contains three sections; the first section explains the theory used to model the drying system. The second section deals with the ideal solution theory and how it was used to complete the model. The third section examines the computer program that was used to solve the model created of the drying system.

3.1 Model and Theory

The drying system for the biodiesel pilot plant consists of two identical systems, one drying system is for oil and the other is for biodiesel. The actual equipment and piping will be described in the next chapter. In this section, the process steps undergone by each fluid are described. Oil or biodiesel enters into each respective side of the drying system where it was first pre-heated by an economizer heat exchanger, and then heated to the main operating temperature before being throttled just before the flash tanks. Each fluid flows through an orifice-type nozzle where it was sprayed tangentially into the flash tank. This creates a swirling thin film on the inside of the flash tank, while water was vaporized and removed from the flash tank by vacuum. The vaporized water was condensed in a heat exchanger and pulled through the vacuum pump where it was discharged to the drain. After leaving through the top of the flash tank, the fluid exiting the bottom of the flash tank, which now contains very little water, was pumped through the economizer heat exchanger and then was either recirculated through the system again or sent to a storage tank. The recirculation was needed to warm-up the system before continuous operation can begin. What was modeled using the

following equations and theory was the moisture removal phenomenon inside the flash tank. This was done by drawing a control volume around the system and writing mass and energy balance equations. The two separate systems will result in the same equations for the different fluids, oil or biodiesel.

First, an energy and mass balance were performed around the schematic shown in Figure 3.1, which represents one side of the vacuum drying system. The same schematic will be used for the other side of the drying system. Fluid represents either oil or biodiesel in the schematic.

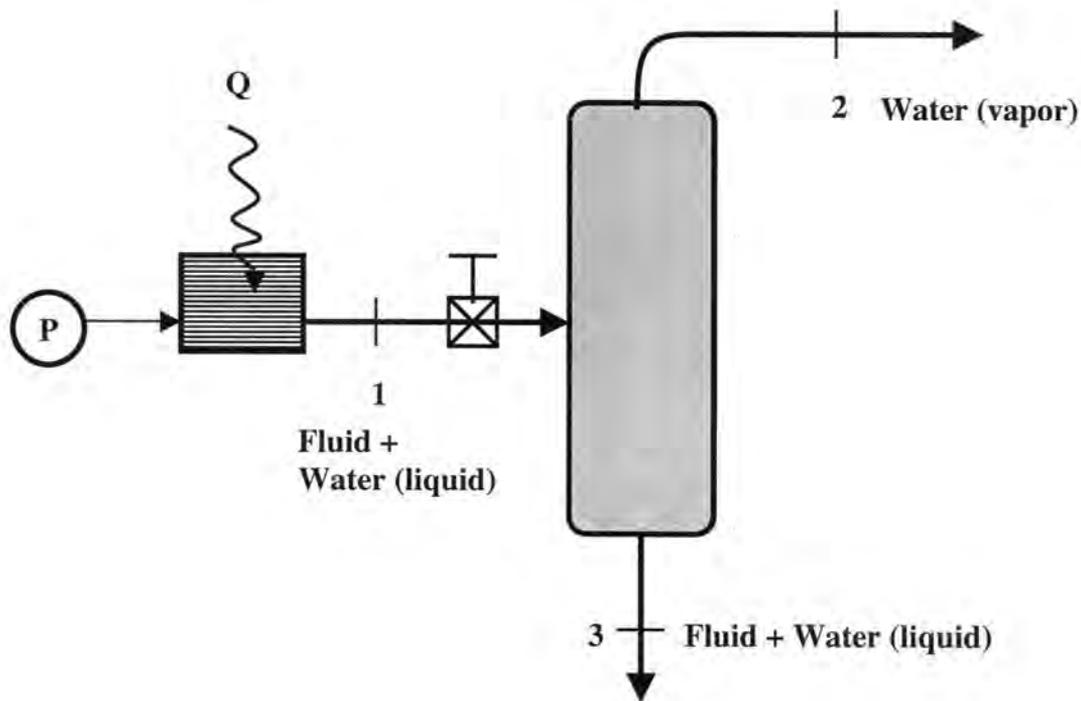


Figure 3.1 Drying System Schematic (Mass & Energy Balance).

State 1 is just before the throttling valve and contains fluid (either the oil or biodiesel) plus its corresponding water, in liquid form. State 2 represents the water vapor removed from the liquid. State 3 is the fluid with much less water (in a liquid state) present than in the initial state. The equation developed from the energy balance is as follows:

$$\begin{aligned} & \dot{m}_{SO,1} h_{SO,1}(T_1) + \dot{m}_{H_2O,1} h_{H_2O,1(liq)}(T_1) \\ & = \dot{m}_{SO,3} h_{SO,3}(T_3) + \dot{m}_{H_2O,2} h_{H_2O,2(vap)}(T_2, P_2) + \dot{m}_{H_2O,3} h_{H_2O,3(liq)}(T_3) \end{aligned} \quad (1)$$

where:

$\dot{m}_{SO,1}$ = the mass flow rate of soybean oil from state 1

$\dot{m}_{SO,2}$ = the mass flow rate of soybean oil from state 2

$\dot{m}_{H_2O,1}$ = the mass flow rate of water from state 1

$\dot{m}_{H_2O,2}$ = the mass flow rate of water from state 2

$\dot{m}_{H_2O,3}$ = the mass flow rate of water from state 3

$h_{SO,1}(T_1)$ = the enthalpy of soybean oil at state 1

$h_{SO,3}(T_3)$ = the enthalpy of soybean oil at state 3

$h_{H_2O,1(liq)}(T_1)$ = the enthalpy of water at state 1

$h_{H_2O,2(vap)}(T_2, P_2)$ = the enthalpy of water at state 2

$h_{H_2O,3(liq)}(T_3)$ = the enthalpy of water at state 3

Equation 1 uses the Law of Conservation of Energy equation to sum the “energy in” and “energy out” of the system shown in Figure 3.1.1. The Law of Conservation of Energy states that the amount of energy remains constant and energy is neither created nor destroyed [17].

Equation 2 represents the overall mass entering and exiting the flash tank as seen in Figure 3.1. Note that this energy balance assumes that the oil (or biodiesel) and water in the incoming flow can be included with separate terms. This assumes there are no special attractions or interactions between the two substances and is a key element of the ideal solution theory to be discussed later. The balance equation for this system is as follows:

$$\dot{m}_{SO,1} + \dot{m}_{H_2O,1} = \dot{m}_{SO,3} + \dot{m}_{H_2O,2} + \dot{m}_{H_2O,3} \quad (2)$$

According to the Law of Mass Conservation [17], the mass flow rate of the soybean oil at state 1 has to equal that at state 3, so the notation for state 1 or 3 can be dropped since they have to equal each other, as shown in Equation 3.

$$\dot{m}_{SO,1} = \dot{m}_{SO,3} = \dot{m}_{SO} \quad (3)$$

In theory there could be some soybean oil, or biodiesel if performing the analysis on the other drying system, in state 2 exiting the flash tank. For all practical purposes this will be ignored because the oil, or biodiesel, in state 2 is very small and considered negligible because of its small amount. So, to simplify the model and equations, it is assumed that no oil, or biodiesel, exits at state 2.

Again, because the Law of Mass Conservation, the flow of water into the flash tank has to equal the flow out of water out of the flash tank. Equation 4 represents the sum of the water entering and exiting the system shown in Figure 3.1.

$$\dot{m}_{H_2O,1} = \dot{m}_{H_2O,2} + \dot{m}_{H_2O,3} \quad (4)$$

Dividing equation (1) by the mass flow rate of soybean oil simplifies the equation and leaves the mass ratios shown in Equations 5 and 6, which will be used in the second part of the model.

$$y_1 = \frac{\dot{m}_{H_2O,1}}{\dot{m}_{SO}} \quad (5)$$

$$y_2 = \frac{\dot{m}_{H_2O,2}}{\dot{m}_{SO}} \quad (6)$$

Assumptions made in order to further simplify the model were that T_2 and T_3 were equal and P_2 and P_3 were also equal. These two assumptions are valid since it is assumed that there is negligible heat transfer from the flash tank, the water vaporization process takes places quickly, and that the liquid and vapor phases are in equilibrium.

Equation 3 can be substituted into Equation 1, eliminating the mass flow rate at state 3, giving Equation 7.

$$\begin{aligned}
& h_{SO,1}(T_1) - h_{SO,3}(T_3) \\
& = y_2 h_{H_2O,2(vap)}(T_2, P_2) - y_1 h_{H_2O,1(liq)}(T_1) + [y_1 - y_2] h_{H_2O,3(liq)}(T_3)
\end{aligned} \tag{7}$$

Then the assumption of constant specific heats for the soybean oil (or biodiesel) can be used to simplify Equation 7 using Equation 8.

$$\Delta h = Cp\Delta T \tag{8}$$

The specific heat of soybean oil is about the same for biodiesel, so in the EES program the same value was used for both cases, which was 0.55 Btu/lb_m-°F [18].

With this, the enthalpy for soybean oil, or biodiesel, can be substituted with temperature at the respective state along with the specific heat, which leads to Equation 9. The enthalpy of water at each respective state can be obtained from the EES computer program to solve the equations and determine the residual water at various conditions. The EES computer program is given in Appendix C of this thesis. Equation 1 above for the energy balance around the system then can be simplified to Equation 9.

$$Cp_{so}(T_1 - T_3) = y_1(H_x - H_y) + y_2(H_z - H_x) \tag{9}$$

where:

Cp_{so} = the specific heat of soybean oil

H_x = the enthalpy of water at state 3

H_y = the enthalpy of water at state 1

H_z = the enthalpy of water at state 2

The vapor pressure of the water at state 2 can be found using T_3 and applying the Ideal Solution theory, which will be discussed later in this thesis. EES has an automatic property table built into it as long as the appropriate thermodynamic properties, such as temperature and pressure are specified. Once the vapor pressure is known, then the pressure at P_2 can be found, again, remembering the assumption that P_2 equals P_3 , and knowing the mass ratio of liquid in state 3. The mass ratio at state 3 is equal to the difference between the ratios at state 1 and 2, as shown in Equation 10, because the Law of Mass Conservation.

$$y_3 = y_1 - y_2 \quad (10)$$

Once the mass ratio at state 3, y_3 , is known then the residual water in the liquid leaving the bottom of the flash tank can be determined.

The first part of the model was made up of the mass and energy balances based on the first three assumptions, T_2 and T_3 are equal, P_2 and P_3 are also equal, and constant specific heats for the soybean oil (or biodiesel). The second part of the model was where the assumption of ideality of a solution comes into play.

3.2 Ideal Solution Theory

The concept of an Ideal Solution was an important assumption when trying to model the drying system using a simplified model. The theory of ideal solution implies the complete uniformity of cohesive forces [19]. This means intermolecular forces between the

species in a binary system are essentially the same. It also implies that the volume of the solution varies linearly with composition. There is no absorption or evolution of heat in the mixing of the species, and the total vapor pressure of the solution varies linearly with mole fraction composition [20]. This is based on Raoult's Law, which states that the partial pressure of the solute in the vapor will be directly proportional to its mole fraction in the liquid phase. Equation 11 represents Raoult's Law.

$$P_A = X_A P_A^o \quad (11)$$

where:

P_A = the partial pressure of species A in the gas mixture above the liquid

X_A = mole fraction of species A in the liquid mixture

P_A^o = the saturation pressure of species A in the mixture

The total pressure for a binary system can be found using Equation 12.

$$P = P_A + P_B = X_A P_A^o + X_B P_B^o \quad (12)$$

where:

P = the total pressure of the mixture

P_B = the partial pressure of species B in the gas mixture above the liquid

X_B = the mole fraction of species B in the liquid mixture

P_B^o = the saturation pressure of species B in the mixture

It is assumed that when using ideal solution theory that the liquids are behaving similar to the how gases would behave in the Ideal Gas Theory. This is that each species behaves the same in the mixture with different species as it would with only the same species in the mixture.

The vapor pressure of a given species in a solution that is considered ideal is a fair measurement of the tendency of the species to escape from the solution into a vapor state [19]. Applying ideal solution theory to the modeling of the drying system implies that the oil or fuel can be treated separately from the water. This means, the oil or biodiesel can be separated from the water in the equations used to model the drying system. Treating the fluids separately in the equations and models means one is assuming that the oil or biodiesel behaves the same whether or not the water is present in the mixture. The same can also be said for the water. The assumption of an ideal solution is also made because the solute is very dilute in the solvent. The solute being the water moisture and the solvent is either the oil or the biodiesel.

Investigating the vapor pressure of a solution as a function of temperature, pressure, and concentration leads to a good picture of the solution properties. According to Moore, only a few liquid solutions exhibit the concept of ideality, and most solutions deviate from ideality [19]. The theory of an ideal solution is better suited for dilute solutions. A dilute solution is made up of a high concentration of one species, B, while another species, A, exists in a very small concentration in the solution. Figure 3.2 will be used to explain ideal solution and deviations from ideality.

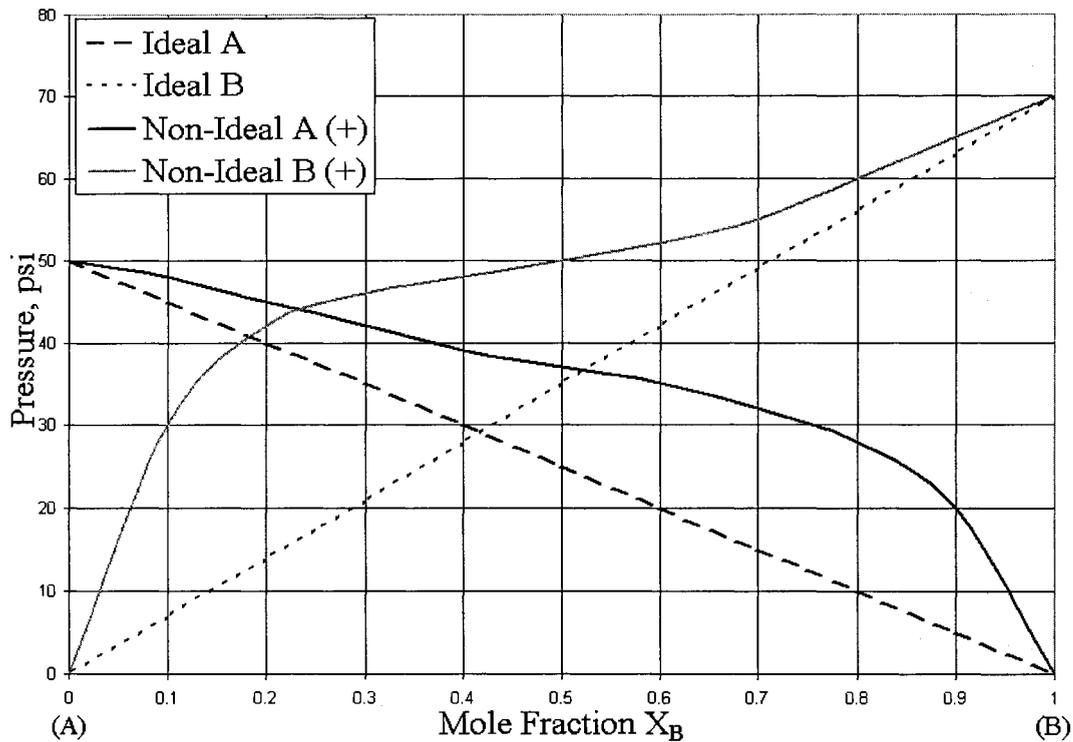


Figure 3.2 Vapor Pressure – Ideality.

Figure 3.2 represents a fictitious pressure versus mole fraction diagram for a binary mixture of species A and B. The very right of the x-axis where species B is 1 represents 100 percent B in the mixture, with no species A present in the mixture. So, the vapor pressure of the mixture is only dependent on species B since it makes up 100 percent of the mixture. For this example it would be 70 psi. The very left side of the x-axis represents a mixture containing no species B and 100 percent species A. Then, the vapor pressure of the mixture would be 50 psi since there is no species B present to affect the vapor pressure. Figure 3.2 could be used to determine the total vapor pressure of the mixture if given the mole fraction

of one of the species and knowing that the total mole fraction of species A plus species B must equal one.

The dashed lines in Figure 3.2 represent Raoult's Law for Ideal Solutions, which is that the vapor pressure varies linearly with composition expressed in mole fractions as shown in Equations 11 and 12. The solid lines above the two dashed lines represent positive deviations from ideality. This happens when the mixture total pressure is greater than what is predicted by ideality. Negative deviations from ideality would result in the curves being located below the dashed lines, and the total pressure of the system being less than what was predicted by ideality. The Results section of this thesis will discuss whether or not the assumption of ideality is valid or not for this model based on experimental results and the model itself.

3.3 Thin Film Theory

A film forms when a fluid flows past a vertical solid surface, where the fluid velocity is zero at the surface and then increases as it gets farther away from the surface. In the case of the drying system, the fluid is swirling around the inside of the flash tank, where a thin film develops on the flash tank wall promoting the evaporation of the moisture from the oil or biodiesel. Figure 3.3 depicts the falling thin film inside the flash tank, and is the last part of the model used to tie the ideal solution, mass and energy balances together for a simple representation of the drying process.

As seen in Figure 3.3, the film develops on the inside of the tank, and it is assumed that the film is of uniform thickness as it extends down the wall of the flash tank. Although the diagram shows a temperature and concentration gradient in the film, it is also assumed

that the temperature profile of the liquid and the concentration profile of the water in the liquid are uniform due to the short residence time inside the flash tank for the equilibrium case. The concentration of water is uniform at the top at its incoming concentration, and then decreases from the vapor-liquid interface to the wall as the film travels down the inside surface of the flash tank. Also, the temperature profile actually decreases from the wall to the vapor-liquid interface, and the film will grow in thickness as it travels down the surface. The temperature and water concentration gradients were not included in the model. The validity of these assumptions for the equilibrium case and the actual case will be discussed in the Results and Discussion section of this thesis, and whether or not the assumptions were valid when developing the model for the drying system.

It is assumed that there was no heat transfer into the wall of the flash tank because of insulation on the flash tank and piping. This means the main driving force for moisture removal inside the flash tank was the vapor pressures, which was higher at the vapor interface and lower in the vapor region of the flash tank. The pressure in the vapor region of the flash tank is maintained at a constant pressure by the condenser and vacuum pump. The difference in pressure from the vapor region to the film causes the vaporization of the moisture. There are some potential problems with the actual falling thin film versus the ideal thin film that was in equilibrium. One of the problems was the local cooling at the surface due to evaporation, which slows down the vaporization of the moisture in the film. There is also resistance due to mass transfer, diffusion of water to the vapor-liquid interface to replace the water that has been vaporized. As a result of this resistance to mass transfer, the concentration of oil or biodiesel at the interface is greater than it would otherwise have been [21], as can be seen in Figure 3.3.

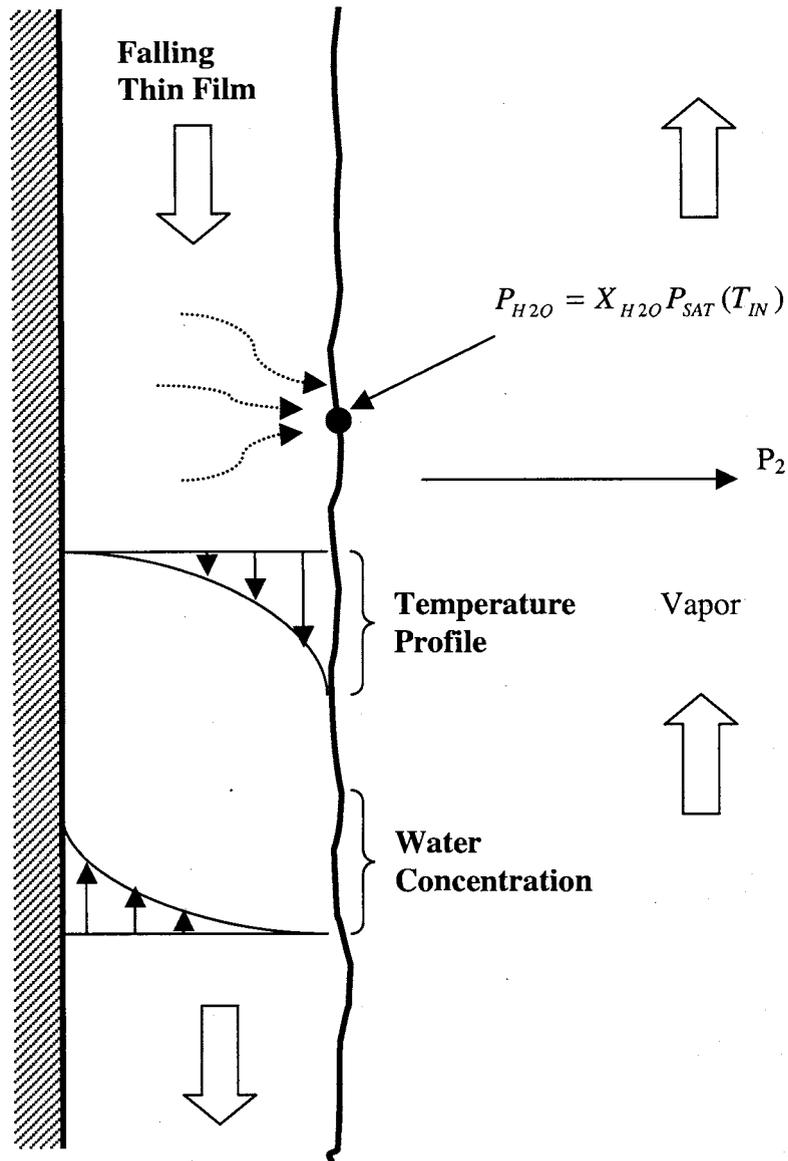


Figure 3.3 Falling Thin Film.

The thermodynamic model does not account for the gradients where the concentration of water at the interface is lower than at the surface, or the temperature profile, which decreases from the wall of the tank in the film to the interface. Whether or not they

affect the correlation between the experimental data and the theoretical model will be discussed in the Results and Discussion section of this thesis.

3.4 Engineering Equation Solver (EES) program

Engineering Equation Solver (EES) is a software package that solves n non-linear equations for n unknowns given initial estimates as inputs [22]. Some advantages of EES are its built-in look-up tables for the thermodynamic properties of certain fluids, along with its ability to solve problems requiring iterative solutions or parametric problems [22]. EES was used to solve the algebraic equations developed while creating the model of the drying system. It was also used to predict what values for certain conditions would result in a given moisture percent in the fluids. A separate EES program was also created to solve the algebraic equations from the model of the condenser heat load for the outlet coolant temperatures versus fluid flow rate.

4. EXPERIMENTAL EQUIPMENT AND TEST PROCEDURES

This chapter describes the equipment and test procedures used for this study and is divided into three sections; the first section discusses the vacuum drying system used in this study. The second section describes the system validation tests, and the third section discusses the equipment used to determine the moisture percent of the samples taken for the dryer system evaluation.

4.1 Vacuum Drying System

The pilot plant drying system consists of two identical systems located next to each other in the drying system support structure. One side of the drying system is for oils or fats, such as soybean oil or animal fat, and the other side is for the biodiesel fuel. The piping, components, routing, etc. are identical for both systems. The reason for building two identical systems is so the oil and fuel could be processed at the same time, and also to prevent the contamination of oil or fuel when switching from one fluid to the other in a single drying system. The systems are identical in design and components because both the oil and fuel have similar properties, and each fluid also will need to reach similar values for moisture removal in order to be used for their intended purpose.

Figure 4.1 presents a schematic of the drying system for both the oil and biodiesel systems. Fluid (oil or biodiesel) enters the drying system from either the glycerol separation tank (biodiesel) or the staging tank (soybean oil), where it is pumped into the system using pump (2) or (3) and then it is pumped through the economizer heat exchanger (6). The economizer heat exchanger gets its heat from the outgoing fluid, which is emerging from the

The fluid is then sent through the main heat exchanger (7) where it is heated to the required temperature for the drying process using a 50/50 mixture of propylene glycol at up to 240 °F.

The fluid is then throttled in the globe valve (9) before being sent into the flash tank (11) through a 1/8" orifice flow nozzle. The fluid enters the flash tank tangentially. The manufacturer of the flash tank recommended the use of the tangential entry, as opposed to the centerline entry, in order to take advantage of the dynamics of the swirling motion created by the tangential entry. The tangential entry also promotes better warm up and heat transfer in the flash tank due the swirling motion that is more turbulent than the centerline entry. The entering fluid flows tangentially as a thin film around the inside wall of the flash tank, and the vacuum in the flash tank is controlled by the vacuum pump.

Vaporized water is pulled through the demister in the top of the flash tank before being condensed in the vacuum pump heat exchanger (12). Once the moisture is condensed it flows into the liquid ring vacuum pump (5) where it is eventually discharged into the overflow container and pumped to a drain.

Fluid left behind after the vaporization process is pulled from the bottom of the flash tank with pump (1) or (4) and circulated through the economizer in order to take advantage of the energy in the fluid. The fluid can then either be sent back into the drying system on the suction side of pump (2) or (3), or discharged to its specified storage tank. Which way the fluid goes depends on whether or not the fluid is in recirculation mode (system warm-up) or continuous flow mode (steady-state operation). Gate valves (13) and (14) are open or closed according to whether or not the drying system needs to be warmed-up or not.

Figure 4.2 displays the vacuum drying system used at the pilot plant at the BECON Facility. The structure from which the components, piping, and electrical are hung from

consists of 1" x 4" "C" channel iron, with four other pieces of the "C" channel running perpendicular to the main pieces forming anchoring platforms. Unistrut channel measuring ten feet extends upwards from each corner. Support braces tie the structure together, where the liquid ring vacuum pump and four gear pumps are bolted to the "C" channel base. The unistrut used to construct the drying system structure is 1½ inch square channel tubing.

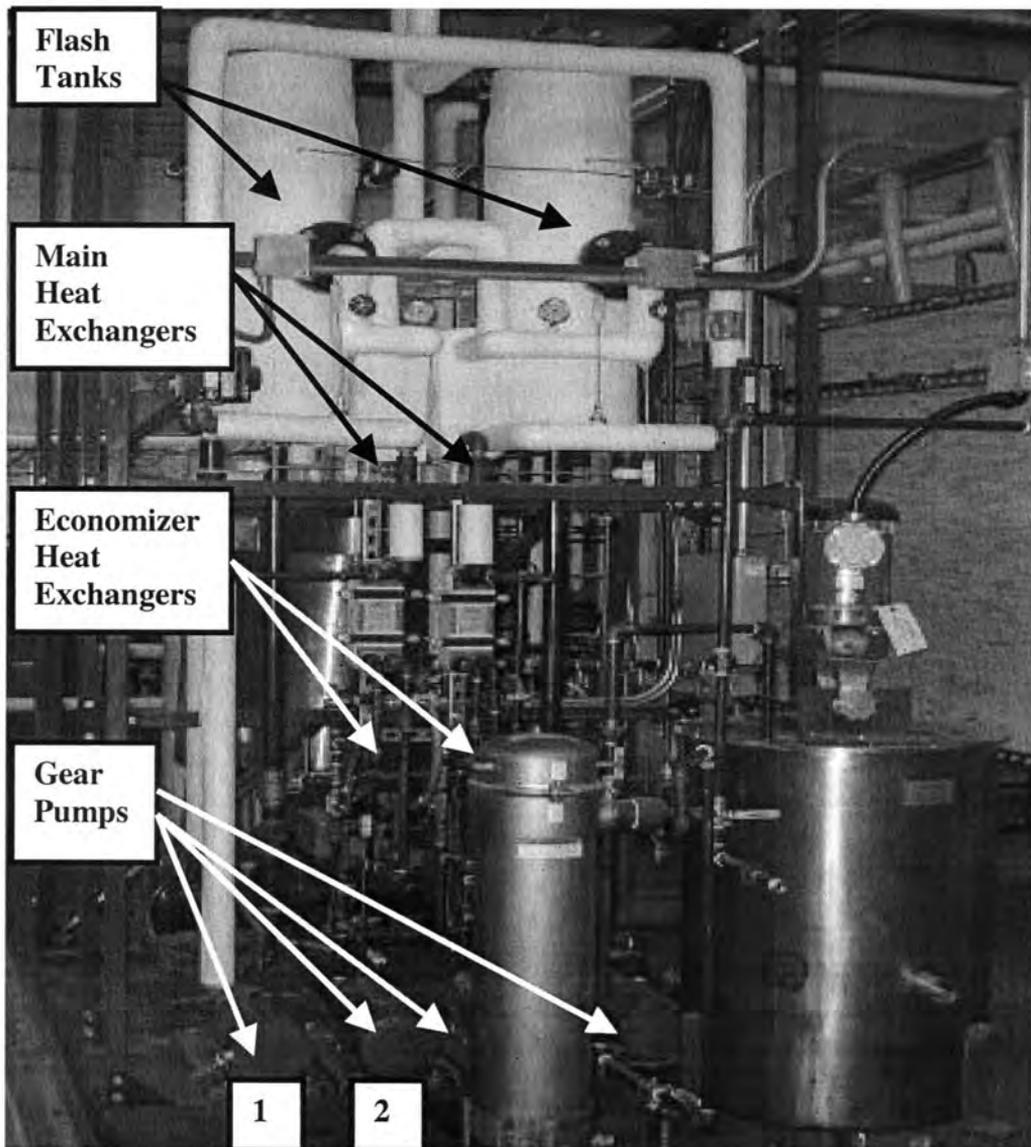


Figure 4.2 Biodiesel Pilot Plant Vacuum Drying System.

The equipment used to build the vacuum drying system is listed in Table 4.1

Table 4.1 Vacuum Drying System Equipment List.

Quantity	Component	Description	Model Number
2	Viking Gear Pump	1/2 hp, 1140 rpm	FH432
2	Viking Gear Pump	1/2 hp, 1725 rpm	FH432
4	Hitachi Variable Frequency Drives	1/2 hp/0.4kW	L100-004HFU
5	ITT Standard Brazepak Heat Exchangers	Compact & counter-flow	5-688-04-030-002
1	Travaini Water Seal Vacuum Pump	7.5 hp, 29.5 inHg, Partial Recovery	TRVB40-110/GH
2	UFM Swinging Van Flow Meters	N/A	MNBSF10GMV-8-32V1.0-AONU-HT
2	Kenco Engineering Sight Gauges	Stainless Steel Body, Viton Seal	T051C05B
2	Cemline Flash Tanks	150 psi, 8 5/8" Diamter, 36" Length	V8FST
5	Omega CN9000A Controllers	N/A	CN9000A
1	Omega Rotary Switch	N/A	SW142-20-B
2	1/8" Orifice Flow Nozzles	Stainless Steel Tube	N/A
1	5 Gallon Polypropylene Tank	N/A	N/A
1	Teel Centrifugal Pump	1/2 hp, 3450 rpm	9R756
2	United Instrument Compound Gauges	4" Display, Glycerin Filled	N/A
2	Ashcroft Gauges	4" Display, Glycerin Filled	N/A
2	Wika Gauges	2" Display, Glycerin Filled	N/A
4	GC Solenoid Valves	Stainless Steel, Viton Seals	S201GF02L7DG4
2	GC Solenoid Valves	Brass, Teflon Seals	S201GF02N5FG9
4	Sharpe Gate Valves	1/2" Stainless Steel	30276
2	Sharpe Globe Valves	1/2" Stainless Steel	40276
1	Carboy 5 Gallon Polypropylene Tank	N/A	N/A

The BECON Facility has a separate heating system, shown in Figure 4.3 that uses a 50/50 mixture of propylene glycol and water to supply heated fluid to the drying system heat exchanger via an insulated piping network.

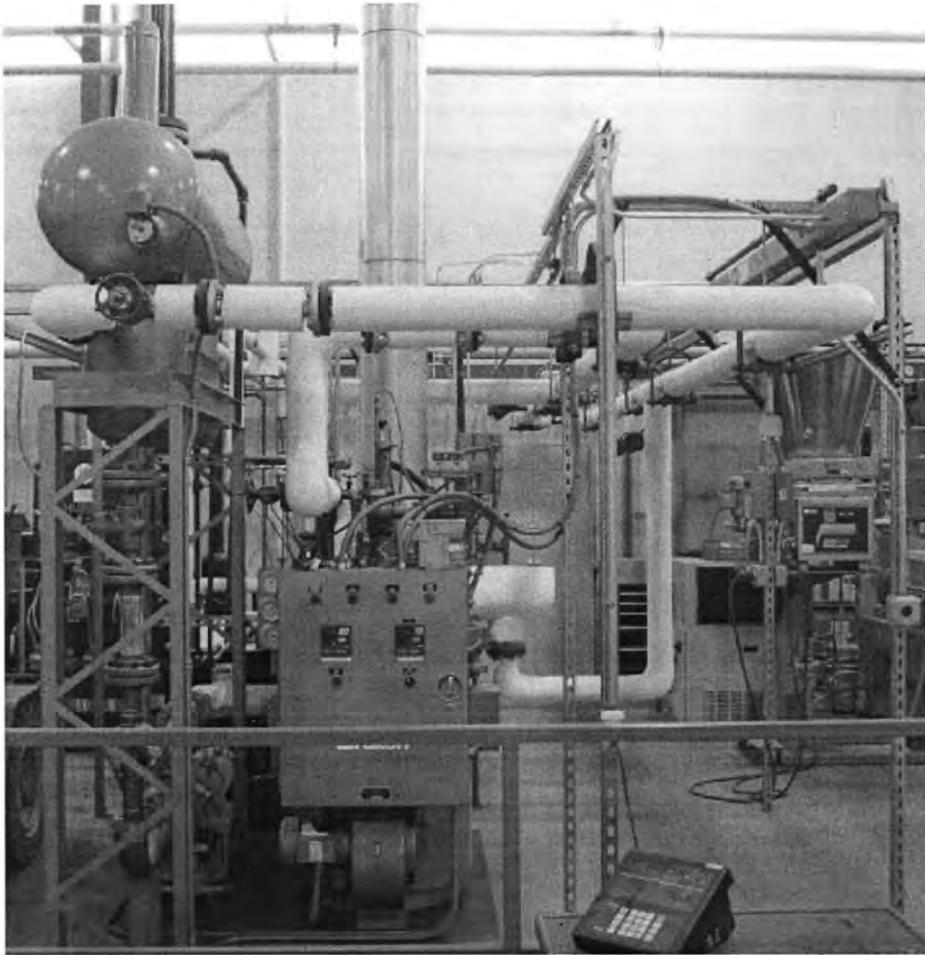


Figure 4.3 Paratherm/Propylene Glycol Heating System.

Propylene glycol was used in the system because of its characteristic of being non-toxic. Paratherm oil was used to heat the propylene glycol in an eight-inch diameter shell and tube heat exchanger. The flow rate of the propylene glycol was monitored and controlled in the drying system flow meters. An Omega CN9000A controller opens a solenoid valve at a specified temperature to control the flow into the drying system flow

meters, while controlling the heat input to the fluids. The piping for the heating portion of the drying system is insulated with one-inch thick insulation. This includes the incoming and outgoing lines to the heat exchangers and the main heat exchangers themselves. This is done in order to maintain the desired temperature from the paratherm heating system to the drying system. The main and economizer heat exchangers are counter flow, compact plate-type heat exchangers. The heating system equipment that supplies propylene glycol to the drying system is listed in Table 4.2. Each flash tank was covered with two-inch thick insulation from the bottom of the tank to the top flange where the demister was located. In the original system, both flash tanks were not insulated, which led to a warm-up problem of the system along with other issues that will be discussed in the Results and Discussion section of this thesis.

Table 4.2 Paratherm/Propylene Glycol Equipment List.

Quantity	Component	Description	Model Number
1	Fulton Coil Design Thermal Fluid Heater	800MBtu/hr	FT-0080-C
1	ITT Standard Shell & Tube Heat Exchanger	6" Diameter, 36" Length	6048
1	Ingersoll-Dresser Pump	5 hp, 3495 rpm	0201-8288

The water sealant temperature was the temperature of the water inside the vacuum pump that was used to create the seal. As the temperature of the water sealant fluid increases, the vacuum created by the vacuum pump is reduced as the vacuum cannot be a lower absolute pressure than the saturation pressure of the sealing water. The vacuum pump pulls down whatever vacuum it can depending on the sealant water temperature, leakage of the drying system, and a controlled vacuum leak in the system.

The cooler the water in the vacuum pump, the lower the pump can pull the flash tank pressure. A bleed valve was used to decrease the vacuum inside the two flash tanks if a different vacuum pressure was desired for the two tanks. The vacuum pressures in the flash tanks were displayed on two glycerin-filled compound gauges. The gauges were glycerin filled in order to reduce the bouncing of the gauge needle, which should help in obtaining more accurate readings. A sight glass was located on the outside edge of each flash tank for level monitoring inside the tanks. It was important to keep the level in the flash tank consistent in order to avoid a high fluid level and the possibility of spraying the vaporized fluid into the fluid that has collected in the flash tank bottom. If the level inside the flash tank increases, then the exposed surface inside the flash tank is reduced. This affects the amount of vaporization that can take place due to the reduced surface area. A thin film covering the inside surface below the spray nozzle was desirable. If the layer becomes thicker or the surface area becomes smaller then the amount of moisture that can be removed is reduced due to the smaller area for mass transfer to take place on the inside of the flash tank. Lower velocities and higher viscosities will cause the layer on the inside of the flash tank to become thicker. The reduced velocities and turbulence can result in less moisture removal than what was considered ideal.

Two Variable Frequency Drives (VFD's) were used to control the level inside the flash tanks by controlling the frequency of the alternating current supplied to the pump motors, hence the speed of the gear pump that pulls fluid out of the flash tank bottom.

Upon vaporizing the moisture in the fluid, the water vapor was pulled through a screen at the top of the flash tank, which acted as a demister. The purpose of the demister was to allow the droplets of oil or biodiesel to accumulate on the screen until the droplets

become large enough that they fall to the bottom of the flash tank. The vapor, after exiting the demister, flowed through piping to the vacuum pump condenser. The moisture entered the condenser and tap water from the BECON Facility was used to condense the moisture. The water flow through the condenser was monitored with a variable area flow meter. There was currently no means of controlling the inlet temperature of the water into the condenser. The condenser heat exchanger was a counter flow, compact plate-type heat exchanger.

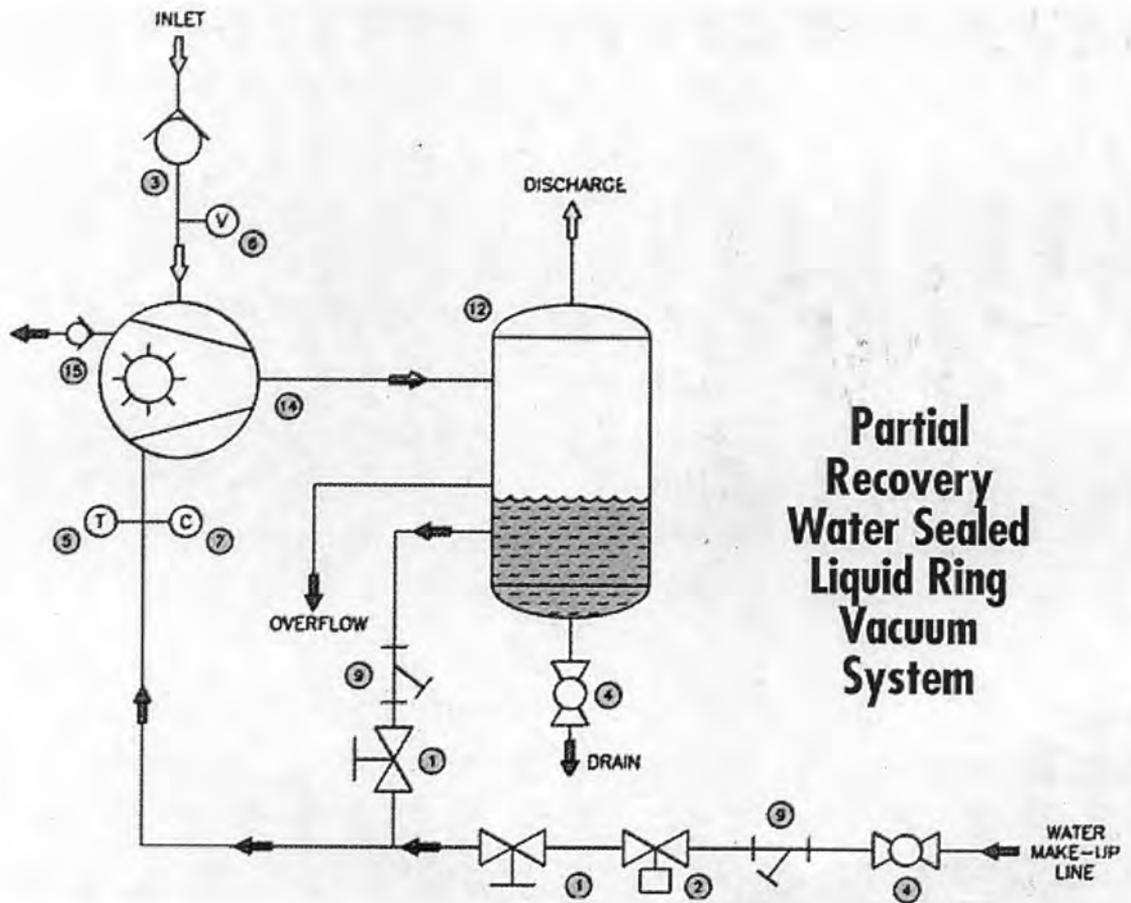


Figure 4.4 Vacuum Pump Schematic – Partial Recovery [23].

Figure 4.4 shows a schematic of the vacuum pump, which illustrates how the various water streams flow into and out of the vacuum pump. The condensed water was pulled into the vacuum pump (12), where it was expelled into a five-gallon polypropylene overflow tank. The vacuum pump receives input water for creating the seal to produce the vacuum from the same tap water line just before the condenser heat exchanger. The vacuum pump was a partially recovering unit, in that a recirculation pipe allows fluid from a lower point in the vacuum overflow tank to enter back into the input water line of the pump. As the vacuum pump overflow tank fills, the water reaches the higher exit port and flows into the five-gallon polypropylene tank. The vacuum pump could be made into a full recovery unit with the addition of a heat exchanger to cool the sealing water before recirculation. Once the water enters the polypropylene tank, it was pumped to the sewer drain via a centrifugal pump once the upper flow switch was tripped to turn on the pump. The pump stays on until the lower float switch turns off the pump when the polypropylene tank was empty. Any vapor in the air above the water in the vacuum pump over flow tank was vented to the outside via a two-inch diameter PVC piping network.

Gear pumps pull the oil or biodiesel out of the bottom of the flash tanks and pump it through the economizer heat exchangers. Once the fluids exit the heat exchangers they can either be recirculated via piping back to the input side of the first gear pump or pumped to the corresponding storage tank. For the soybean oil, this was the 500 gallon soybean oil storage tank. The dried biodiesel can be sent into a staging tank where it can either be pumped to an outside storage tank or into a barrel for transportation to another facility. Recirculation mode was needed in order to warm up the drying system before fluid can flow through the drying system at a continuous flow rate. Solenoid valves have been installed in the system for

future automatic control of the recirculation versus non-recirculation process. An Omega CN9000A controller managed the solenoid valves. The entire system had thermocouples located between each component of the system along with thermocouples on the inlet and exit sides of each heat exchanger. All of the temperatures were displayed on an Omega CN9000A controller, used as a readout, while a rotary switch was used to change from one thermocouple reading in the system to another. A pressure gauge was also located on the exit side of the input pumps for reading the pump pressure. The piping just before and after the main exchanger, along with the piping leading into the flash tank, was covered with one-inch thick insulation. The reason for this was to maintain the temperature of the fluid for proper operation of the drying system. Future plans call for the complete insulation of the entire piping network. Another future item for the drying system was the monitoring and controlling of the drying process using a PLC system. Black carbon steel piping was used through out both drying systems. Brass, zinc, and copper should be avoided with systems containing soybean oil or biodiesel due to oxidation that can take place with any of the three mentioned metals.

4.2 System Validation Tests

This section deals with initial tests that needed to be performed for system verification and testing. The initial tests were on systems linked to the drying system in order to eliminate possible condition changes that would affect the relationships sought for the drying system. These tests consisted of determining the moisture distribution inside the glycerol separation and oil staging tanks, the required warm-up time for the system, the

maximum fluid flow rate for continuous flow operation, and determination of a proper sampling procedure.

4.2.1 Moisture Distribution Test

Various known amounts of water were added to the biodiesel in the glycerol separation tank and to the soybean oil in the staging tank. This was done in order to achieve different initial moisture percents for the warm-up and continuous flow rates, where the flow rates were investigated using a base case condition. The base case condition was 220 °F for the heater temperature, a vacuum of 28 inHg inside the flash tank, 15 pounds per square inch (gauge pressure) for the throttling pressure, and 1 gallon per minute (gpm) for condenser water flow rate. The various initial moisture percents were used in order to investigate what affect they would have on fluid outlet flow rate and final fluid moisture percent readings.

The moisture distribution from top to bottom of the glycerol separation tank was investigated in order to determine if the moisture distribution in the fuel was uniform throughout the tank. An inconsistent moisture distribution within the glycerol separation or staging tank would result in errors in the relationships gathered when evaluating the different conditions of dryer system operation. The various initial moisture percents were used in order to determine how the fluid outlet flow rate and final fluid moisture percent levels were affected by each other. Part of the study for this thesis was to determine what fluid flow rate through the drying system was acceptable for different levels of moisture in the oil and fuel. The results of the tests to determine what flow rates were allowable for different moisture levels will be discussed in the Results and Discussion part of this thesis along with how the moisture level test was performed.

4.2.2 System Warm-Up Test

The drying system warm-up time needed to be determined before any process validation could take place. Multiple warm-up tests were performed on the oil and fuel drying system in order to gain an idea of how long the fluid in each system needed to be recirculated before continuous flow testing could be performed.

The original warm-up for the drying system required 30 to 40 minutes before continuous flow testing could be performed. It was decided that this long warm-up time was due to the flash tanks, piping, and heat exchangers not being covered in insulation. Routing of the drying system was changed at the same time in order to maintain proper throttling pressure before the flash tank. Original routing put the fluid for recirculation on the discharge side of the pump for the incoming fluid. This meant the throttling pressure would decrease when the incoming pump cycled off for recirculation. The new routing and controls allow both incoming and recirculation pumps to run at the same time and constantly to maintain consistent throttling pressure. The final part of the system modification was the addition of the VFD's for level control inside the flash tanks. Inconsistent levels inside the flash tank led to different times for warm-up when no other conditions were changed, along with inconsistent data for determining proper flow rates in continuous flow operation at various moisture levels. The results for the warm-up test, transient, will be discussed in the Results and Discussion section of this thesis.

4.2.3 Continuous Flow Test

After the time required to warm-up the drying system was determined, which was around 16 minutes, then the continuous flow testing was started. The data gathered from

these tests was used to aid in the development of the relationships needed to predict the moisture percent removal for certain system conditions.

First, a base case condition was determined, and then different initial moisture levels and fluid flow rates were investigated. The base condition used for the main testing was 28 inHg of vacuum, 220 °F for heater temperature, 15 pounds per square inch (gauge) pressure for throttling, and 1 gallon per minute (gpm) for the condenser flow rate. The basis for these conditions will be discussed in the Results and Discussion section of this thesis.

4.2.4 Sampling Procedure

The procedures used for sample collection were followed and performed the same for each test in order to minimize errors in the moisture readings. The same stopwatch was used throughout the entire testing procedure and data gathering was performed at consistent time intervals of two minutes. Before each fluid sample was taken, the sampling gate valve located on the recirculation loop was opened, and fluid was allowed to flow from the opening for 5 seconds in order to clear the valve and sampling port from the previous data point. Fluid would be quickly drawn into the sample syringe and air bubbles would be purged from the syringe. Once the sample was taken, the conditions and time of the sample would be noted along with marking the syringe for later analysis.

4.3 Moisture Measurement Equipment

This section describes the equipment and test procedures used to analyze the moisture in the fluid samples taken during the drying system experiments. The first two sections discuss the Karl Fischer Titrator and validation of its values. The next section discusses the

testing procedures for the Titrator, while the section after that talks about the repeatability of the drying system tests. The calibration of the vacuum gauge and why it was needed for the testing is the last section of this chapter. The instrument used for moisture determination in the samples was a Coulometric Karl Fischer Titrator made by CSC Scientific Company, Inc. in Fairfax, Virginia.

4.3.1 Karl Fischer Titrator

A Karl Fischer titration coulometric system was used to determine the moisture level in the oil and fuel samples during the drying system investigations. The Karl Fischer Titrator gives both free and dissolved water in fluid samples. The Coulometric Karl Fischer Titrator can be seen in Figure 4.5.



Figure 4.5 Karl Fischer Titrator.

Coulometric Karl Fischer titration is an accurate method of measuring the moisture content of a sample ranging from 10 parts per million (ppm) to 100% water. Before the actual moisture analysis was performed in the Titrator, a pre-titration test had to be performed in order to give the system a reference state of zero moisture. The equipment used to determine the moisture percent in the fluid samples is given in Table 4.3.

Table 4.3 Equipment List for Moisture Testing.

Component
Karl Fischer Moisture Titrator MKS-500
Hydranal, Composite 5
Hydranal, Methanol Dry
BD Syringe, 3mL 23G Luer-Lok
Mettler AE100 Scale
Fluid Sample
Hazard Receptacle
Personal Protective Equipment

The Karl Fischer Titrator uses the solvent, Hydranal (Methanol Dry), to dissolve the sample being tested, and a reagent chemical, Hydranal (Composite 5), to measure the moisture content. The solvent and reagent used to test the samples taken for evaluating the drying system are given in Table 4.3. The coulometric method uses electricity to produce iodine from the reagent chemical, which reacts with the water in the solution based on the reactions given in Equations 13 and 14 [24].



A microprocessor in the Karl Fischer Titrator system measured the current produced when the reaction endpoint was reached, which was related to the amount of iodine produced and used in the reaction based on Faraday's Law for Electrolysis [25]. Faraday's Law of Electrolysis says that one equivalent weight of a substance is produced at each electrode during the passage of 96,487 coulombs of charge through an electrolytic cell [26]. Water and iodine react on a mole-to-mole basis, hence the moisture percent can be determined from the weight of the iodine found during the titration and the weight of the sample titrated.

4.3.2 Karl Fischer Validation

The validation of the Karl Fischer Titrator will be discussed in this section. Because the moisture levels measured in this study were near the detection threshold of this particular instrument, a number of samples were collected from chemicals that were expected to have low moisture content. Fluids of known moisture percent were tested in order to verify the accuracy of the readings given by the Karl Fischer Titrator. Five different chemicals of known moisture percent, along with an open flask case were tested in the Titrator. Each chemical and case was tested twice in order to confirm the first values obtained from the initial testing. The moisture percent and values determined using the Titrator can be seen in Table 4.4. Each fluid in Table 4.4 was tested using two different syringes, and each syringe contains enough fluid that it can be tested twice, resulting in four measurements for each fluid.

Table 4.4 Karl Fischer Certification Test.

Methanol**			Methanol*			Heptane*		
Moisture Percent			Moisture Percent			Moisture Percent		
First	Second	Average	First	Second	Average	First	Second	Average
0.0173	0.0180	0.0177	0.0143	0.0138	0.0141	0.0085	0.0076	0.0081
0.0161	0.0152	0.0157	0.0124	0.0092	0.0108	0.0091	0.0084	0.0088
Bottle Spec: < 0.01%			Bottle Spec: < 0.01%			Bottle Spec: < 0.005%		
2-Propanol*			N-Heptane*			Open Flask (no sample)		
Moisture Percent			Moisture Percent			Moisture Percent		
First	Second	Average	First	Second	Average	First	Second	Average
0.0158	0.0166	0.0162	0.0040	0.0036	0.0038	0.0000	0.0016	0.0008
0.0135	0.0145	0.0140	0.0039	0.0041	0.0040	0.0011	0.0006	0.0009
Bottle Spec: < 0.02%			Bottle Spec: 0.003%					
Notes:								
*means brand new bottle, never opened								
**means old bottle, all ready opened								

Each chemical was tested and then compared to the moisture percent called out on the bottle content specifications. The purpose of this test was to verify that the Karl Fischer Titrator was producing moisture readings that could be trusted. Another reason for the test was to determine the lower limit of the Karl Fischer Titrator, and see if this lower limit was acceptable for the experiments. If the results from the Titrator were not accurate, then the relationships developed from the testing and EES program could not be trusted due to the incorrect moisture level readings. All chemicals tested were from new, unopened bottles, while an opened bottle of methanol was also tested for comparison. The values given on the bottle specification and the values determined using the Titrator were the same within acceptable reason. The glass Titrator flask plug was taken off for approximately 3-4 seconds each time a sample was injected into the flask for analysis. If the flask was opened to the air for more than the desired time of 3-4 seconds, the moisture readings from the Titrator would slowly creep up in value by thousandths or hundredths of a percent. This 3-4 second time

seemed not to affect the reading as long as it was maintained, as shown in Table 4.4. The open flask test proved that the moisture in the air had a very negligible, if any, affect on the moisture levels when performing an analysis on fluid samples collected from the drying system during tests.

4.3.3 Testing Procedure

The same testing procedure for analyzing the moisture percent in the fluid samples taken from the drying system was used throughout the complete drying system evaluation. Each sample was marked with a corresponding number designating when the sample was taken and under what conditions.

Upon completion of the pre-titration validation check of the Karl Fischer Titrator, a sample of known moisture such as a mixture of water and methanol or pure water was injected into the flask of the Titrator system in order to determine if the unit was producing acceptable and reasonable values. If the Titrator was not producing acceptable values then the procedure called out in the Karl Fischer Titrator manual, along with the self-diagnostic mode, had to be followed in order to calibrate the unit. If this still did not correct the problem, then the unit would have needed to be sent to the manufacturer for calibration, but the Titrator readings were never out of specification enough that it could not be corrected. Sample testing could begin once it was determined that the Karl Fischer Titrator was reading correctly.

First, the sample was wiped off any excess fluid on the outside of the syringe. This was done in order to prevent decreasing weight measurements while the syringe was sitting on the scale. Next the syringe was evacuated of any air bubbles left in the fluid if they were

not already removed upon taking the initial sample. Before injecting the sample into the Titrator, the syringe was shaken vigorously in order to get a well-mixed sample that was homogenous. After the syringe weight had stabilized and been written down, then the sample was injected into the Titrator for analysis and the syringe was weighed again after the injection. Approximately half of the syringe was injected into the Titrator flask, or around 1 to 1 ½ milliliters (mL), so that the sample could be tested twice for reading verification. Once the titration process had finished, the value given by the Titrator was noted and the next sample was tested using the same procedure as before. The samples were tested randomly to avoid bias errors from the instrument potentially drifting when taking readings. If the value from the Titrator seemed unusual, then the system had to be taken apart and cleaned, then calibrated again to verify its readings. This would occasionally happen if a drop of the fluid sample was spilled in the sampling port, and then ran down slowly in the Titrator flask where it would gradually affect the moisture level reading. The electrode on the Karl Fischer Titrator could also have contaminants stuck to it, such as phospholipids, from testing soybean oil samples. When this happened, the Titrator was again taken apart and cleaned, then it had to be calibrated again to determine if it was reading correctly.

4.3.4 Repeatability Test

Being able to obtain nearly the same moisture percent values when repeating an experiment in the drying system at a specified condition was an important requirement for validating the relationships obtained from the results. Trying to duplicate the same values for moisture percent obtained at the base case condition also tested the repeatability of the drying system. The repeatability test was carried out at 28 inHg of vacuum, 220 °F, 1 gpm

condenser flow rate, 15 psig of throttling pressure, with a fuel flow rate of 0.456 gpm. Approximately the same moisture percent of the original fuel tested was used for the duplicate test in order to try and obtain the same results from the initial base case. In both cases the initial fluid moisture percent was 0.3. The results of this test are presented in the Results and Discussion section of this thesis.

4.3.5 Vacuum Gauge Calibration

In order to compare the experimental data with the EES program, the vacuum pressure gauge on the flash tanks needed to be checked in order to confirm its accuracy. If the vacuum gauge was reading incorrectly, either slightly above or below the actual vacuum that was being pulled on the flash tank, then the assessment of the drying system using the EES program would not be valid due to skewed readings.

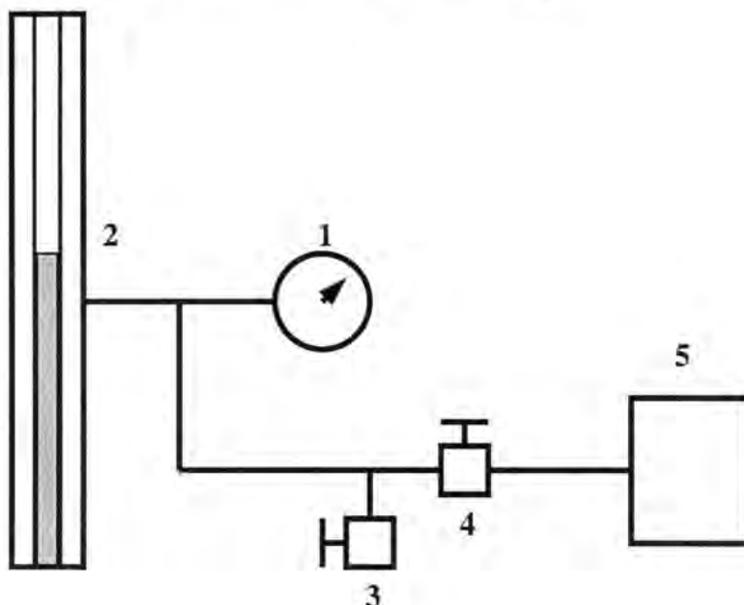


Figure 4.6 Schematic for Vacuum Gauge Testing.

To determine if the vacuum gauge was reading correctly meant that another gauge that was known to be accurate had to be used for comparison, so a correction could be made if the vacuum gauge was reading incorrectly. An accurate Dwyer mercury-filled manometer was used for comparison and correction factor determination. A schematic of the system used to test the vacuum gauge for accuracy is shown in Figure 4.6.

Both the vacuum gauge (1) and the manometer (2) were connected to different ends of a pipe tee. Then, the third opening of the tee was connected to another pipe tee. Two gate valves, (3) & (4) were attached to each end of the tee so that both valves could be used to produce different levels of vacuum by bleeding off vacuum. All connections had Teflon tape used on them and were checked for tightness.

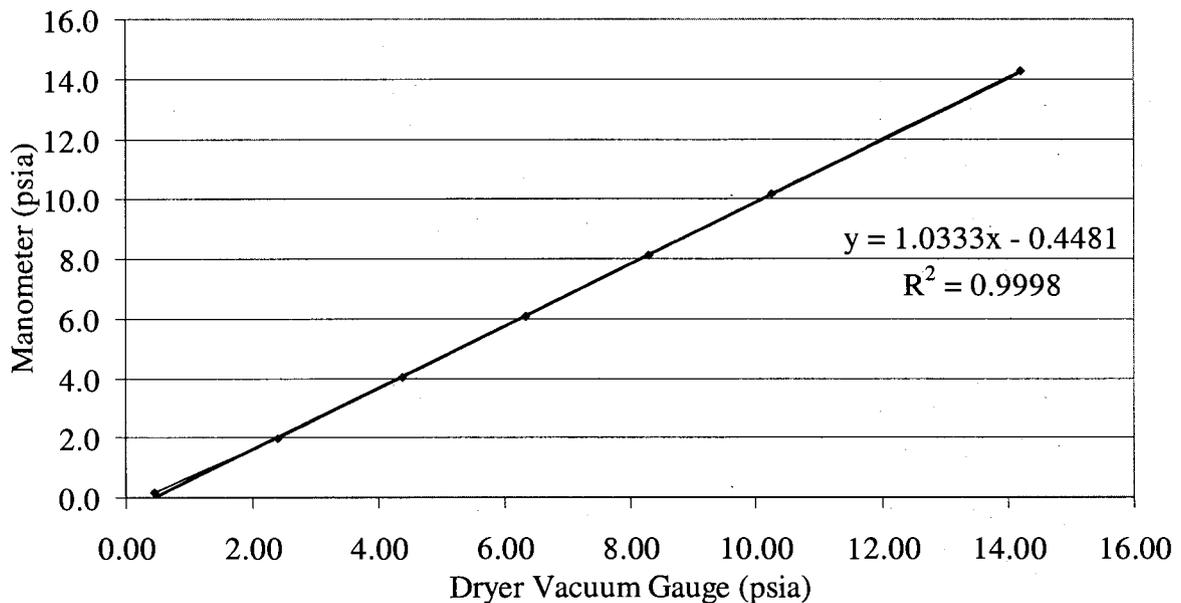


Figure 4.7 Correction Factor Graph for Vacuum Gauge.

To do this, the pipeline was connected to an air hose with compressed air in order to check for leaks using a soap and water solution. After the pipeline was confirmed to be leak free, it was now ready to be used for testing. A vacuum pump (5) was used to pull a vacuum on the gauge and manometer while using the combination of the two gate valves to create the desired vacuum by allowing air to bleed in to relieve some of the vacuum.

A series of points were recorded and plotted as seen in Figure 4.7. It was important to get values that were as high a vacuum as the normal operating point of the drying system to make sure the difference between the vacuum gauge and the manometer was accurate for the drying system operation testing range.

Table 4.5 shows the values recorded from the test and the values to be used for correction. The different vacuum gauge pressures were entered into Equation 15 in order to obtain the actual corrected values of the tests performed on the vacuum drying system.

Table 4.5 Correction Reference Table for Vacuum Gauge.

Actual Reading (Gauge) (Not Corrected)		Actual Reading (Absolute) (Corrected)		Actual Reading (Gauge) (Corrected)
Vacuum Gauge (inHg)	Manometer (inHg) (ABS)	Vacuum Gauge (psia)	Manometer (psia)	Manometer (inHg)
0	29.1	14.20	14.3	-0.1
8	20.7	10.27	10.2	8.2
12	16.5	8.31	8.1	12.4
16	12.4	6.34	6.1	16.6
20	8.2	4.38	4.0	20.7
24	4.0	2.41	2.0	24.9
28	0.3	0.45	0.1	28.6

$$y = 1.0333x - 0.4481 \quad (15)$$

where:

y = the corrected manometer pressure, psia

x = the vacuum gauge pressure reading, psia

Absolute and gauge pressure are both displayed in order to allow the author of this thesis to navigate between absolute and gauge pressure when changing variables in the EES program for system evaluation. The vacuum pressure was found knowing that it equals the local absolute atmospheric pressure minus the absolute pressure, where the local absolute pressure was taken as 14.2 psia.

5. RESULTS AND DISCUSSION

This chapter discusses the results of the experiments on the vacuum drying system, while determining the relationships between moisture removal from the oil and biodiesel and the four variables that were investigated. The experimental results will be compared with the theoretical model developed using the computer program EES.

5.1 Moisture Distribution

Various known amounts of water were added to biodiesel in the glycerol separation tank and to the soybean oil in the staging tank in order to achieve different initial moisture levels for the transient and continuous flow rate tests. The flow rates for both the soybean oil and biodiesel drying systems were investigated using the base case condition. The moisture distribution inside the glycerol separation tank was determined first with no mixing of the separation tank, then with mixing via recirculation with an air-diaphragm pump. Figure 5.1 represents the process equipment used for the recirculation of fluid in the glycerol separation tank. The equipment used for testing the moisture distribution in both the glycerol separation and staging tanks can be seen in Table 5.1.

Table 5.1 Equipment List for Moisture Distribution Testing.

Component	Description
Glycerol Separation Tank	Stainless Steel Cone Bottom, 130 gallons
Glycerol Separation Tank Pump	Huskey 1040 Air Diaphragm
Spray Nozzles	4 Nozzles with 8 holes per nozzle at 0.064" diameter
Staging Tank	Stainless Steel Flat Bottom, 70 gallons
Staging Tank Mixing Motor	Indco Inc., 115V, 1/2 hp, 1725 rpm

Note: Equipment items specific to the Karl Fischer Titrator unit are list in the section describing the Karl Fischer Titrator.

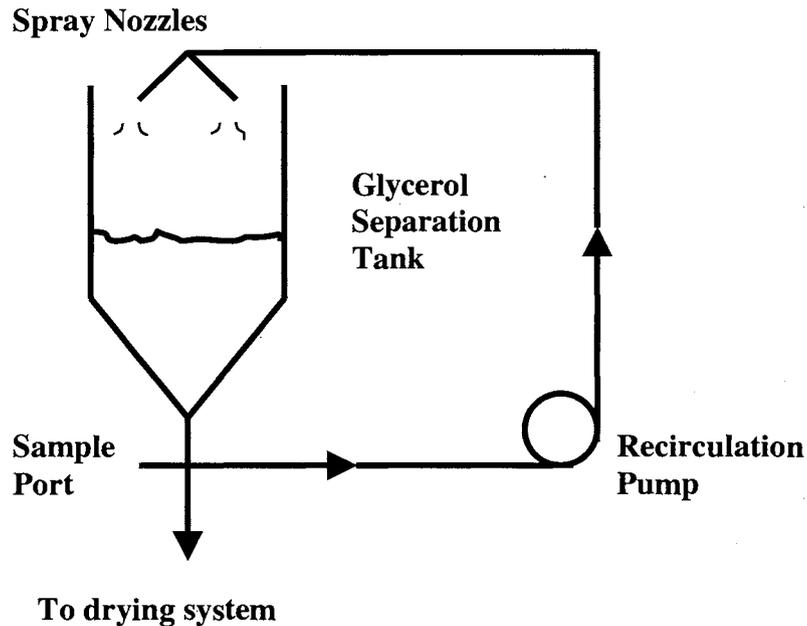


Figure 5.1 Glycerol Separation Tank Recirculation Schematic.

In operation, the recirculation pump would pull a small quantity of fuel from the bottom of the tank and pump it to the top of the tank through four equally spaced spray nozzles. The diaphragm pump would recirculate the fluid at a pressure of 40 pounds per square inch (psi), while causing a swirling of the outgoing fluid in the tank and an approximately uniform spray and distribution of the fluid in the top of the tank. The fluid was recirculated to see if mixing with the pump versus no mixing resulted in different moisture distributions inside the tank. The numbers on the x-axis in Figure 5.2 represent the sample number with respect to where it was sampled from inside the glycerol separation tank. Sample 1 was sampled from the bottom of the tank, while sample number 2 was approximately 1/8 of the tank height above number 1 in the tank position and so on until

reaching the top of the tank and sample number 8. The sampling was performed by first pulling a small amount of the fluid from the bottom of the tank and then draining off 5 gallons into a 5 gallon bucket in preparation for the next sample. Then, another sample of fluid was taken after the 5 gallons of fluid were drained from the bottom of the tank. This was repeated until the tank was emptied.

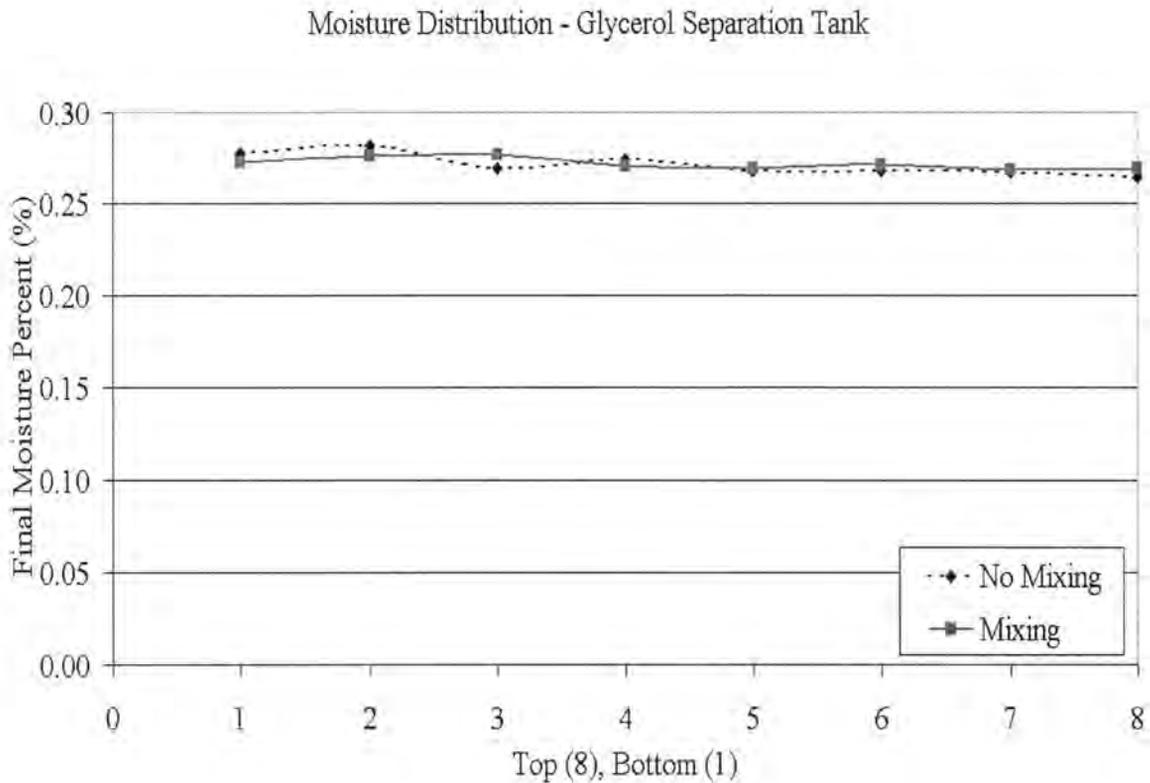


Figure 5.2 Moisture Distribution Test in Glycerol Separation Tank.

Figure 5.2 shows that there was a negligible difference in the moisture distribution in the separation tank when comparing mixing versus not mixing the fuel when pulling fluid from the tank into the drying system. As a result of this, tests performed on the biodiesel drying system were performed with no mixing. The reason for this was because of the

connections on the bottom of the glycerol separation tank. The bottom of the tank had a tee, where one side went to the recirculation pump and the other side went to the biodiesel drying system. The recirculation pump pulls fluid from the bottom of the tank and pumps it to the top in pulses, due to the pump being an air-diaphragm type. This would affect the fluid flow into the drying system since both pumps were pulling from the same connection and the recirculation pump caused pulsing in the line, affecting fluid flow rates.

Moisture distribution inside the staging tank for the soybean oil was assumed to be uniform since a mixing motor was used throughout the testing. Various known amounts of water were added to the soybean oil in the staging tank in order to achieve different initial moisture percents for continuous flow rates. The flow rates were investigated using single variable deviations from a base case condition.

The staging tank also had fixed baffles inside that aided in the mixing of the moisture and oil. The fixed baffles on the inside of the staging tank kept the fluid from swirling around as a whole when the motor was mixing the fluid. Another important item, which aided the mixing inside the staging tank, was that there were two props on the mixing shaft. One prop was located at the bottom of the shaft while the other one was located one foot from the top of the shaft. This aided in the mixing of the fluid from top to bottom along with radial mixing provided by the rotation of the mixing shaft. Since it had been shown that both tanks contained evenly distributed moisture inside the fluid, testing on both drying systems could begin.

5.2 Transient

A series of transient tests were performed on the drying system in order to determine how long it would take the system to warm-up before continuous operation could begin. It was determined that around 16 minutes were needed to warm-up the system when operating at ideal conditions, which were near the highest temperature, vacuum, and throttling pressure possible. Figure 5.3 shows the warm-up time required for various temperatures at 28 inHg of vacuum (or 28.6 inHg corrected vacuum gauge reading), 15 psig of throttling pressure, and 1 gpm for condenser flow rate. The test fluid at all four temperatures had around 0.3 percent initial moisture level, and the output flow rate for each test was the same at 0.44 gpm. As shown in Figure 5.3, higher temperatures for the warm-up test resulted in lower moisture levels in the fluids. The reason for this was that the higher temperatures resulted in more vaporization taking place inside the flash tank when compared to lower temperatures.

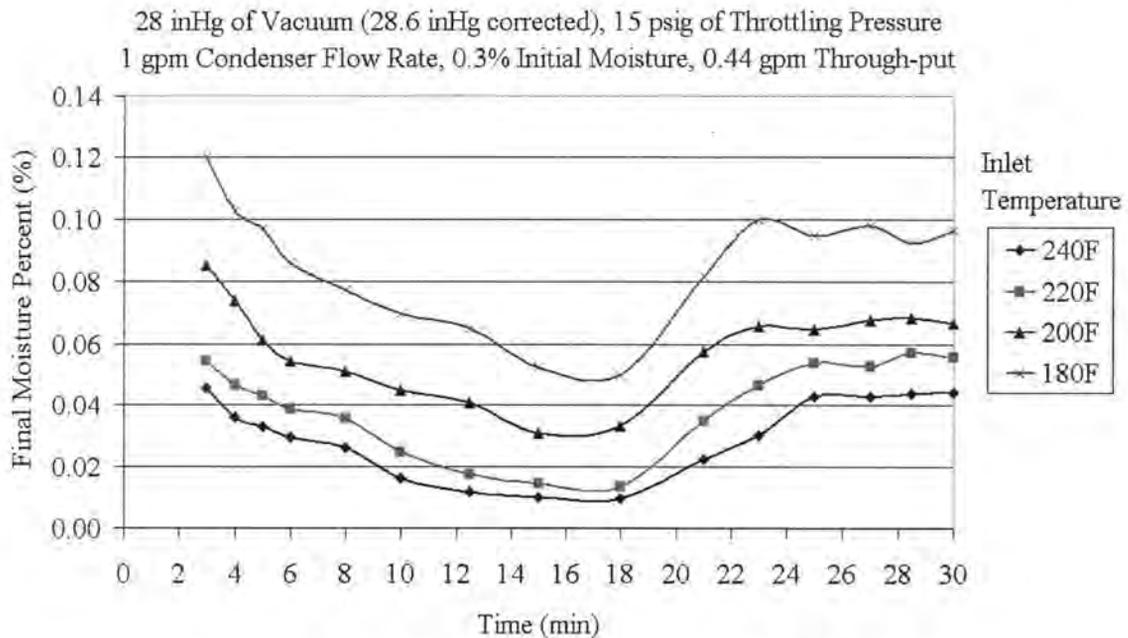


Figure 5.3 Warm-up Moisture Test – 28 inHg.

Higher temperatures in the falling thin film, Figure 3.3, meant more vapor removal due to evaporation. As a result, more vaporization of the moisture took place and lower levels of moisture were seen in the outgoing fluid.

The warm-up time for the other flash tank pressures corresponding to different inlet temperatures can be seen in Appendix B at the end of this thesis. Each of these graphs displays the same trend of decreased moisture levels until the fluid was allowed to flow through the drying system continuously for about 16 minutes.

Each temperature case in Figure 5.3 was not taken to the same moisture level. For example, the 240 °F case was taken to around 0.012% moisture, 200 °F was taken to around 0.03% moisture, and so on. It was thought that some of the tests would not reach the same moisture levels as the previous ones due to the limitations of the drying system and the thermodynamic properties themselves. So, for a better comparison, each case was taken to around the same time of recirculation, about 16 minutes, before allowing the continuous flow to begin.

Figure 5.3, along with the other warm-up tests in Appendix B, all show the same increase in moisture levels and wavy plots after reaching their respective low moisture readings. The reason for the wavy plots after reaching a low moisture level was because the flow rate out of the flash tank was not maintained consistently, but varied some in order to maintain the fluid level inside the flash tank. Plus, the system had just been converted over to a new control and fluid routing system, which required some time getting used to in terms of setting control points. Each test was carried out with samples taken at specific periods of time in order to obtain a plot of the warm-up time at specified conditions. The tests were carried out until the moisture percent was less than the specification value of 500 parts per

million (ppm) or close to 400 ppm for the base case. Other corresponding tests at different conditions were carried out for approximately the same amount of time it took the base case to reach the desired moisture level of less than 500 ppm. The curve shown in Figure 5.3, for system warm-up, help the operator of the drying system determine what is needed for proper warm-up time before continuous flow through the system can be started.

5.3 Continuous Flow

The drying system at the biodiesel pilot plant was designed to run in continuous mode for water removal. This meant determining the maximum flow rate for the drying system at a certain initial moisture level in order to achieve the desired level of less than 500 ppm of water in the biodiesel. Figure 5.4 shows the different moisture levels and flow rates taken at the base case condition of 28 inHg of vacuum (or 28.6 inHg corrected vacuum gauge reading), 220 °F for heater temperature, 15 psig of throttling pressure, and a flow rate of 1 gpm for the condenser.

As seen in Figure 5.4, increasing the flow rate through the drying system while maintaining the operating conditions and inlet moisture level resulted in higher levels of moisture in the fluid exiting the drying system. Part of the reason for this was because the higher flow rates meant a shorter residence time on the inside surface wall of the flash tank. The main reason higher flow rates caused increased moisture levels in the exiting oil (or biodiesel) was probably because of the increased vapor production due to the higher flow rates and the decreased vapor pressure difference between the vapor region and the liquid surface. This reduced pressure difference was caused by the increased vapor being present in the flash tank due to a larger flow rate or higher initial moisture levels.

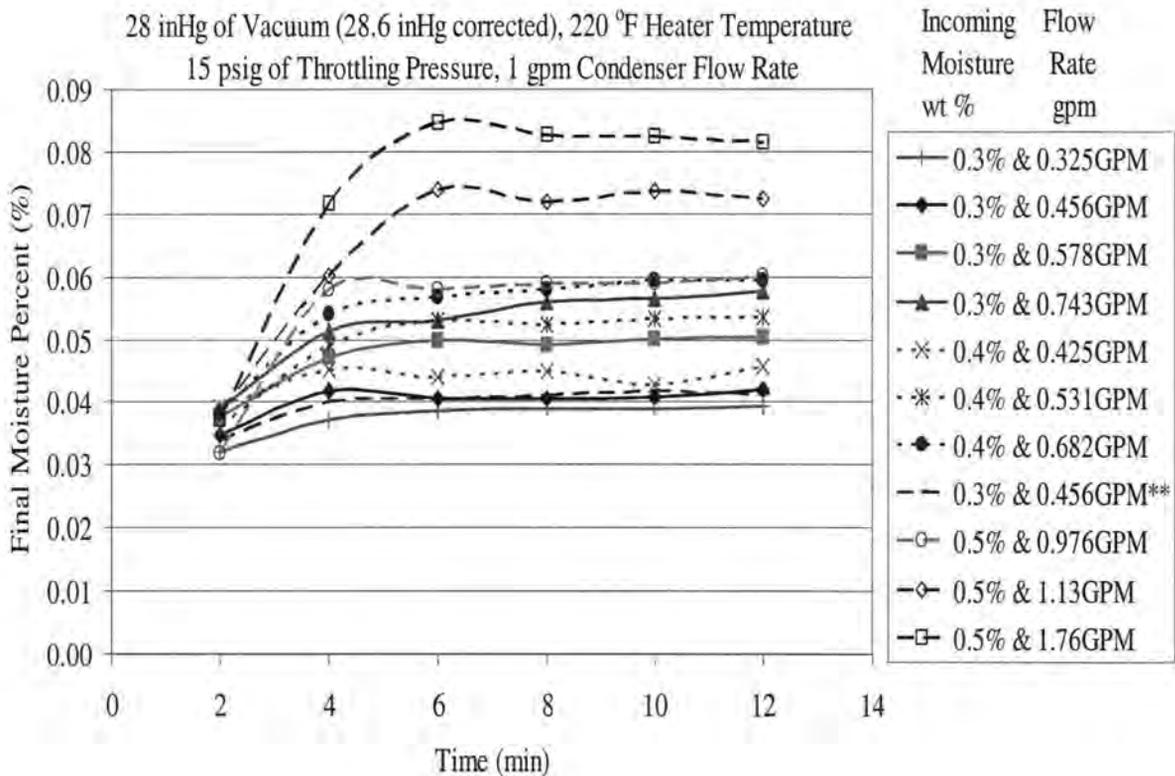


Figure 5.4 Biodiesel Continuous Flow.

Another important trend that is present in Figure 5.4 is that as the initial moisture percent increased, the flow rate through the system must be decreased in order to achieve the desired 500 ppm specification for moisture in the biodiesel. This was also expected, since higher levels of moisture meant a greater production in vapor.

Figure 5.4 also helps the operator of the drying system determine what would be the best flow rate for the drying system during continuous drying of biodiesel, knowing the initial moisture percent. One thing to note in Figure 5.4, the “**” by one of the flow rates represents a repeatability experiment, which will be discussed later in this thesis.

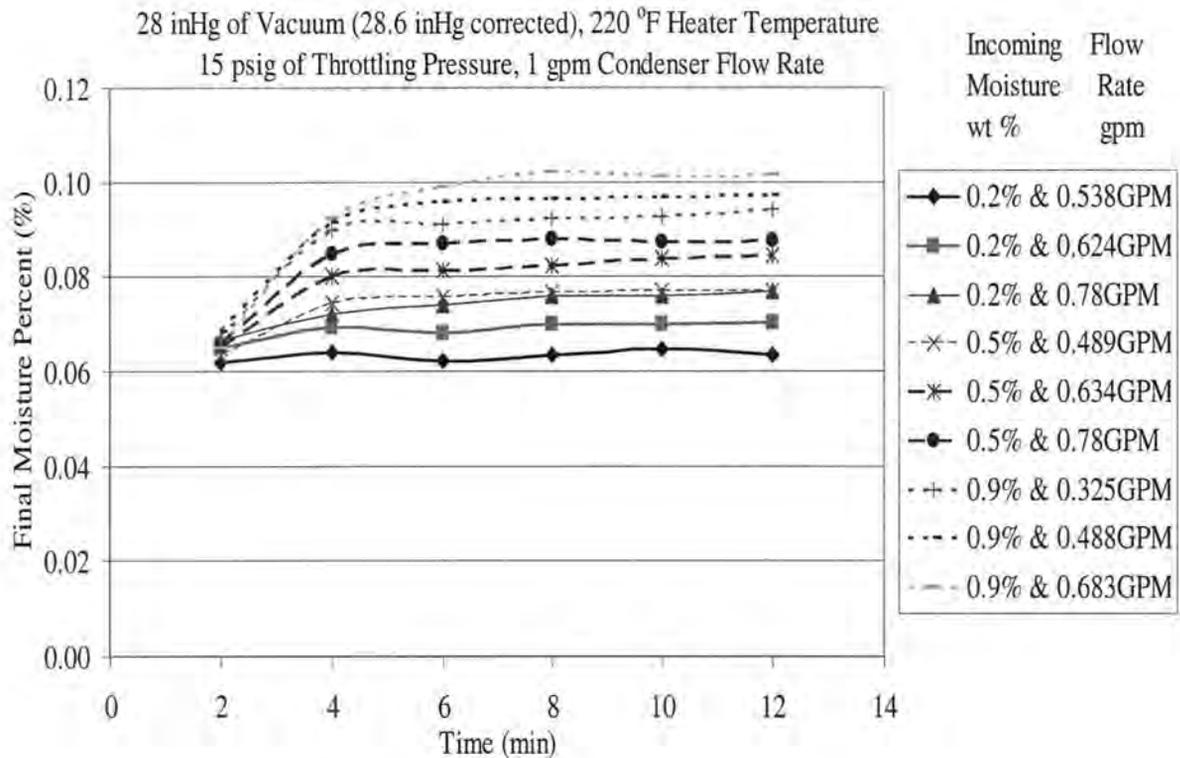


Figure 5.5 Soybean Oil Continuous Flow Test.

Figure 5.5 shows the final moisture levels for different flow rates of soybean oil through the drying system. The soybean oil has the same trend as the continuous flow tests for biodiesel. Again, this was the trend of higher moisture levels for higher flow rates and higher initial moisture levels. The higher level of moisture in the exiting soybean oil for increased flow rates and initial moisture levels was also caused by the increased flow rates and initial moisture levels into the drying system.

The various curves above represent the different moisture levels and flow rates used for the continuous steady state testing. The legends in Figures 5.4 and 5.5 contain two numbers for each curve. The first number was for the incoming moisture level by weight

percent and the second number was for the flow rate of the outgoing fluid from the flash tank. As an example, 0.2% & 0.538GPM means an initial moisture level of 0.2 percent, and an outlet fluid flow rate of 0.538 gpm.

It was thought that the reason for the higher final levels of moisture in the soybean oil versus the biodiesel was due to the different properties of the two fluids. Soybean oil is more viscous than biodiesel, which meant that there was more resistance to mass transfer in the thicker film that would form inside the flash tank. The higher resistances to mass transfer in the soybean oil meant water could not migrate as fast to the surface as it can in biodiesel. So, not as much moisture can be removed from the soybean as it can from the biodiesel when all things are equal, such as the operating conditions, flow rate, and initial moisture levels. To compensate for the higher resistance to mass transfer in the soybean oil means the operator of the drying system needs to decrease the fluid flow rate in order to achieve more removal of moisture from the soybean oil.

There was not a specification for soybean oil in terms of required moisture levels. The moisture level in soybean oil, and other oils for that matter, should be as low as possible when using them for biodiesel production. An important note for the continuous and transient curves was that the continuous flow curves start after the 16-minute warm-up period. The continuous flow curves shown in Figures 5.4 and 5.5 represent the second half of the warm-up curves shown in Figure 5.3, where fluid flow rate through the system was investigated. Two graphs were generated for each phenomenon, even though they are linked together, in order to study each phenomenon separately.

5.4 Comparison of Theoretical Calculations and Measurements

As discussed in the model development section, EES was used to solve the algebraic equations developed for the model, and to compare the vacuum drying system to the experimental data. It will be shown in the following sections that as the conditions deviated from what would be the best possible conditions to run at, 240 °F, vacuum of 28 inHg (or 28.6 inHg corrected vacuum gauge reading), a throttling pressure of 25 psig, and a condenser flow rate of 1 gallon per minute, so did the amount of moisture that could be removed from the fluid. The base case condition was 220 °F, 28 inHg of vacuum (or 28.6 inHg corrected vacuum gauge reading), 15 psig, and 1 gpm for flow rate. The reason these values were chosen as opposed to the best possible case above was because it was believed that the same trends shown in the base case condition would be seen in the best conditions possible. It was also easier to maintain the temperature of 220 °F since the temperature of 240 °F was the maximum temperature of the system. This assumption of the same trends shown at different temperatures was correct according to the EES computer program model and experimental data, and this will be discussed in the proceeding sections.

As the conditions for the drying system deviated from the base conditions, such as a lower vacuum pressure or a lower heater temperature, then the comparison between the EES model and the experimental data was not as good. This may have been because there are processes going on inside the flash tank during the drying processes that are not taken into account in the EES computer program model. These included velocity changes associated with the throttling pressure, the thin film development, and its affect on heat and mass transfer. It was thought that the main reason for the deviation between the model and the

experimental data was the assumption of the ideal solution theory applied to the model, which will be discussed later in this thesis.

The local cooling affect at the interface due to evaporation may slow down the vaporization of the moisture in the fluid, and as will be discussed in the heater section, cause temperature gradients that were not included in the model. There was also a gradient associated with the concentration of the water in the thin film. The model assumed that the concentration was uniform, and that as moisture was removed from the thin film, water diffused evenly and quickly to the interface to replace the vaporized moisture. In reality, there was a resistance to the migration of moisture to the interface as the vaporization process proceeds. This was also demonstrated in the EES computer program by increasing the initial moisture level and noticing that it could attain the same final moisture level, but never attain very low levels of moisture.

Increased throttling pressure should not have affected the moisture level of the exiting oil (or biodiesel) from the drying system, as the model predicted, but it did. It was believed the reason for this was due to the increased velocities associated with higher throttling pressures, which meant increased drying rates. This will be discussed in more detail later on in this thesis.

As mentioned when describing the test with the EES computer program and different initial moisture levels resulting in similar final moisture levels, fluid flow rate in the system was never accounted for in the EES computer program. From the experimental data, it was seen that higher initial moisture levels required slower flow rates. This shows some of the limitations of the EES computer program when comparing it to the experimental data and the actual phenomena. It is possible that if the model could incorporate the processes going on

inside the flash tank, such as velocity changes associated with throttling, thin film development, and the effect of heat and mass transfer, that a little better agreement between the model and experimental data could have been attained. It is still believed that the ideal solution theory was the main reason for deviation between the model and experimental data. This is not known for sure and can only be checked with future model development.

5.5 Vacuum Pressure

The driving force for vaporization was the difference in the vapor pressure at the liquid surface and that inside the flash tank. Pulling a vacuum on the tank can reduce the vapor pressure inside the flash tank. This reduced pressure increases the driving force for the vaporization process. Increased vacuum also translates into a higher volume of moisture that can be removed from the oil and biodiesel. A vacuum drying system, as opposed to an atmospheric system, was needed in order to achieve the desired moisture levels when working with dilute solutions. Reducing the pressure, or pulling a vacuum on a process, assists in achieving the vapor pressure difference inside the flash tank, which drives the moisture removal from the oil and biodiesel and hence the vaporization goes on much quicker [21]. The reduced pressure also helps the vaporization process since it will proceed throughout the mass of the substance instead of just at the free surface.

Figure 5.6 shows how the vacuum affects the exiting liquid moisture levels, while holding the rest of the conditions constant at a heater temperature at 220 °F, throttling pressure at 15 psig, and condenser flow rate at 1 gallon per minute. The initial moisture percent for each test was around 0.3 percent, and the through-put for the system was 0.578 gpm for each test. The data points in the curves above were obtained after the warm-up

period and during the continuous flow part of the drying process. As the vacuum pressure was reduced from 28 inHg to a lesser value, more of the moisture inside the fluid tends to stay with the fluid.

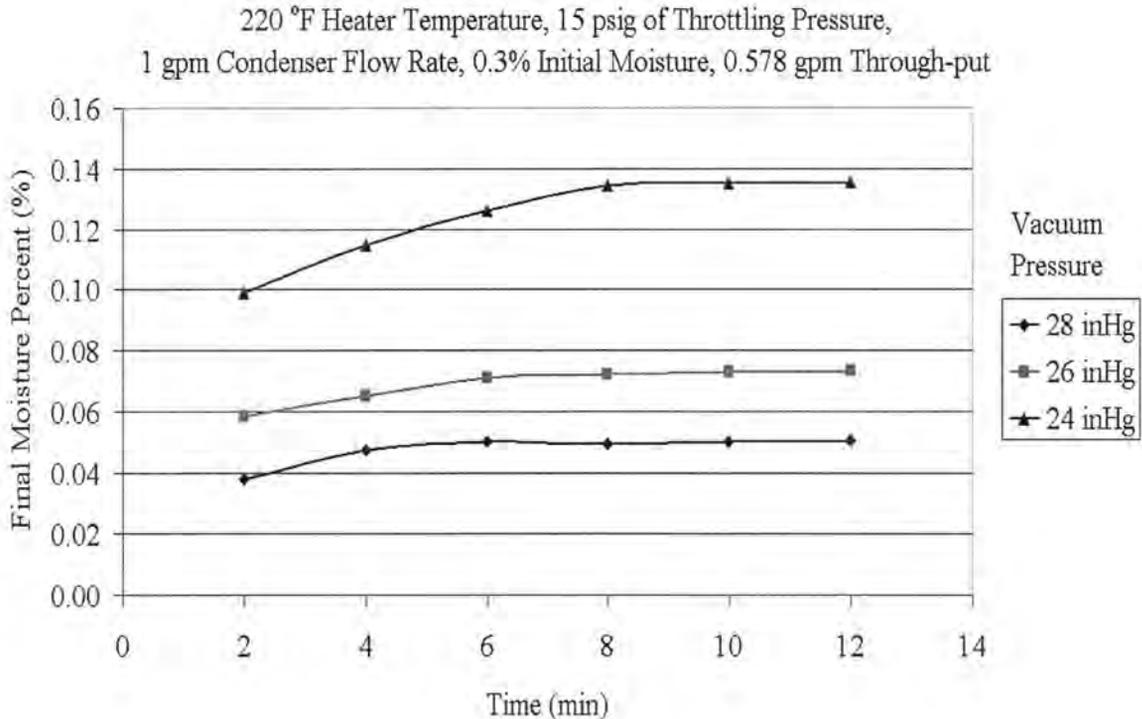


Figure 5.6 Test for Vacuum Pressure Effect on the Drying System.

Table 5.2 compares the values predicted by the EES program versus the values that were obtained in the drying system experiments. From the table it was clear that the 28.6 inHg (corrected vacuum) case predicted by the model was close to what the experimental value was found to be. However, as the vacuum pressure becomes less, the model deviated from the experimental values by a large amount.

Table 5.2 Vacuum Pressure Comparison – Experimental vs. Model.

Experimental Data			EES Program		
Absolute	Corrected		Absolute	Corrected	
Vacuum Tank	Vacuum Gauge	Residual	Vacuum Tank	Vacuum Gauge	Residual
Pressure (psia)	Reading (inHg)	Water (%)	Pressure (psia)	Reading (inHg)	Water (%)
0.155	28.6	0.0504	0.155	28.6	0.0596
1.055	26.75	0.0734	1.055	26.75	0.3100**
1.97	24.9	0.1355	1.97	24.9	0.3100**

Note: “**” means EES program iteration ceased

Part of the reason for this was mentioned above, and that was because of the reduced driving force. As the vacuum was reduced, the water did not want to come out of the fluid by vaporization. It was also assumed that there was a uniform temperature and water concentration in the thin film inside the flash tank. The main reason for the deviation was the assumption of the ideal solution theory. Both the model and the experiment are assumed to be in equilibrium, and yet the model is predicting higher moisture levels, which indicates that there is probably a positive deviation from the ideal solution theory.

An important note can be seen from the residual water values “**” in the EES Program column marked “Residual Water (%)”. After a vacuum level of 27.08 inHg, the program no longer performs the iterations and stops, hence every vacuum level after this value will have the same residual moisture percent. The model assumes the pressure in the vacuum tank is equal to the vapor pressure at the surface of the liquid, and at this point the model assumes no more vaporization takes place. In reality, if the condenser temperature is low enough, vapor still will be removed from the liquid and condensed. The residual water percent for 26.75 and 24.9 inHg in Table 5.2 are the same for the EES program, which is not likely. It is caused by the tank pressure being greater than or equal to the vapor pressure at

the liquid surface. This is another discrepancy in the program because after some value the residual water should not be the same as the conditions deviate more from the optimal conditions, but keeping increasing until reaching the initial moisture level. This point would not happen at 27.08 inHg of vacuum as the model predicts, but in reality would be closer to a point of no vacuum.

The equating of pressures in the model meant that the pressure in the vapor region of the flash tank was the same as it was at the surface of the thin film. At the higher vacuum level, in the EES computer program, the pressure at the surface was initially higher than the pressure in the vapor region. So, much of the moisture was vaporized until the two pressures were in equilibrium, meaning no more moisture could be removed from the surface. This is correct, in that no more moisture can be removed once the two pressures are in equilibrium, but the pressure in the vapor region was not the same as it was at the surface. This is because the vacuum pump is always trying to pull down the vacuum inside the flash tank to the lowest level that it can. Eventually the vacuum pump will not be able to pull down any farther and the two pressures will be in equilibrium, meaning no more moisture can be removed from the oil (or biodiesel). However, the pressures are not the same initially or during the process as the model assumes, which causes part of the deviation in values as the pressure decreases. This larger deviation at lower levels of vacuum is partially the result of the pressures in the EES computer program being the same for the film surface and vapor region in the flash tank. The model also did not account for the actual variation in the temperature and water concentration as the thin film traveled down the inside of the flash tank. It was thought that not accounting for these gradients was part of the reason the experimental data and model started to differ in values as the operating conditions changed.

As the operating conditions worsened in terms of moisture removal efficiency, the effects not taken into account in the model become more significant, which means the model was less likely to predict the actual moisture levels in the outgoing fluid.

The model also did not account for the resistance in the mass transfer of the water in the fluids. As the water starts to vaporize from the surface of the film, water has to migrate to the surface in order to replace the water that has now been vaporized. Since the levels of moisture are low in the fluid, the driving force was low when compared to higher levels of moisture. The drying system was designed to handle small values of moisture of less than one percent. This was one of the reasons why a vacuum pump was used in the drying process. It helps with the vaporization process at lower moisture levels. It was thought that if the model accounted for these differences and did not deviate from the Ideal Solution Theory that the values predicted by the model would closely resemble those from the experiment as the operating conditions were reduced from optimal conditions. The fact that the experimental data show higher amounts of moisture removal than what is predicted by the model indicates that the positive deviation from the ideal solution theory is probably the major cause of the differences.

5.6 Heater Temperature

Figure 5.7 shows how the heater temperature of the vacuum drying system affects the fluid moisture level. As the temperature of the fluid entering the flash tank was decreased, moisture removal from the fluid was reduced because of the lower difference in partial pressure of vapor at the liquid surface and the flash tank pressure. Figure 5.7 shows the tendency of decreased moisture removal from the fluids as the temperature was reduced

for the drying system at the base case condition of 28 inHg of vacuum (or 28.6 inHg corrected vacuum gauge reading), 15 psig of throttling pressure, and 1 gpm of water flow through the condenser. The initial moisture percent for each test was around 0.3 percent, and the through-put for the system was 0.325 gpm for each test.

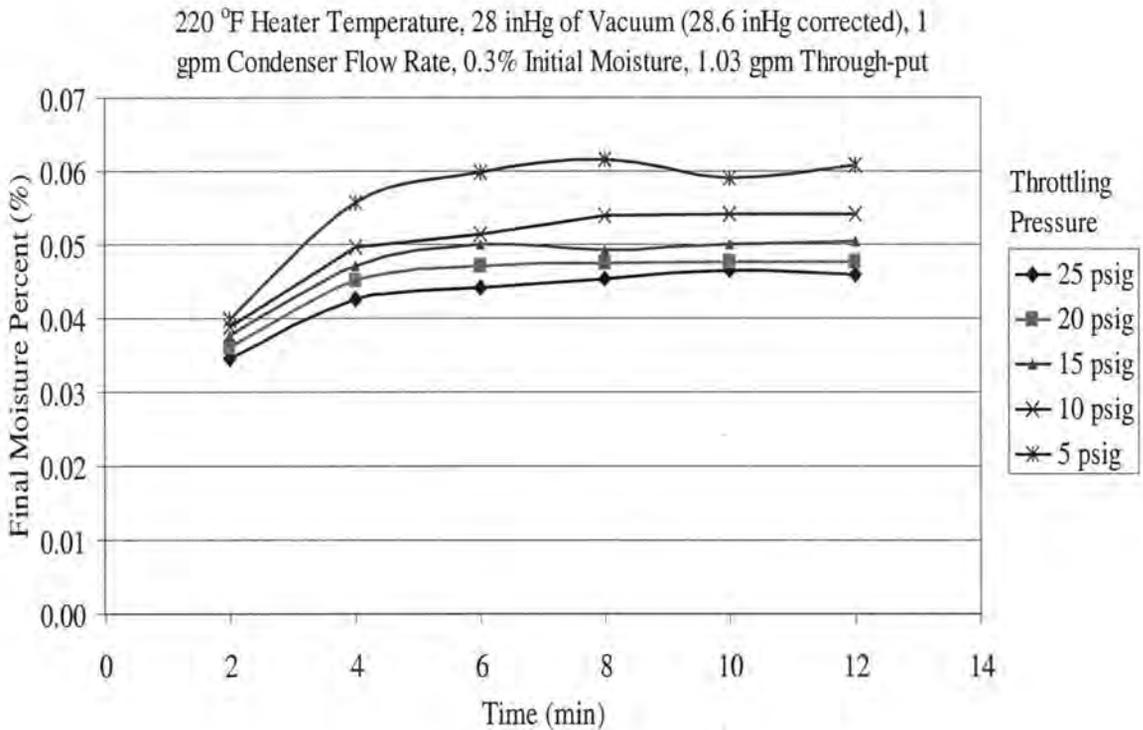


Figure 5.7 Test for Temperature Effect on the Drying System.

The cause of this decrease in moisture removal was probably due to the lower vapor pressure difference between the fluid surface and the vapor region inside the flash tank. A lower heater temperature meant a lower oil (or biodiesel) temperature going into the flash tank, which means the initial vapor pressure at the film surface was lower because of the lower oil (or biodiesel) temperatures. Since the vapor pressure was now lower, not as much moisture could be driven from the oil (or biodiesel) due to a smaller difference in pressure

from the film surface and vapor region. The reduced driving force results in less moisture removal from the “wet” fluid [26].

Table 5.3 Temperature Comparison – Experimental vs. Model.

	Experimental	EES Program
Temperature	Residual Water	Residual Water
(F)	(%)	(%)
240	0.0358	0.0409
220	0.0414	0.0596
200	0.0559	0.0889
180	0.0708	0.1358

Table 5.3 shows a comparison between the experimental data and the EES computer program when varying the temperature. The conditions that the drying system was run at for Table 5.3 were 28 inHg (or 28.6 inHg corrected vacuum gauge reading), 15 psig throttling pressure, and 1 gpm for condenser flow rate. Table 5.3 shows how the experimental data and EES computer program model are in near agreement for the two higher temperatures, while starting to show differences in moisture level for the lower two temperatures. It was believed that part of the reason for this was lower pressure differences between the film surface and the vapor region at the lower heater temperatures. As discussed previously, the EES computer program assumes the vapor pressure at the film surface and in the vapor region are the same. In reality, they are not the same, so as the heater temperature for the EES computer program was reduced, the problem associated with a smaller or nearly equal pressure difference meant the EES computer program would start to deviate in predicted values for moisture removal. This resulted in more moisture being removed at the higher

temperatures when compared to the lower temperatures. Therefore, the main reason for the difference between the model and the experimental data was due to the deviation from the ideal solution theory as mentioned in the vacuum pressure section previously. Accounting for the effect of the vapor pressure difference between the film and vapor region in the model along with the ideal solution theory deviation would have improved the predicted values for the EES computer program as the heater temperature was reduced.

Another part of the experiment that needs to be considered was the overall throughput of the system. Higher flow rates through the flash tank resulted in higher moisture levels in the exiting fluids. This was because of the larger amount of vapor produced as a result of the higher flow rates. This trend of higher moisture levels with increased fluid outlet flow rate was seen in Figure 5.4 for the biodiesel and Figure 5.5 for the soybean oil.

5.7 Throttling Pressure

Heating a fluid to its boiling temperature, and then reducing the pressure will cause the fluid to rapidly vaporize. The boiling temperature of a fluid is dependent on pressure. As boiling begins, bubbles start to form on the surface of the liquid leading to the vaporization of the fluid. The vaporization of the fluid occurs throughout the bulk of the liquid until the latent heat of vaporization cools the liquid to a lower temperature [14]. Boiling before the throttling valve was undesirable because there was the potential to damage the piping and valve, and because there was no pressure difference inside piping or valve as there was in the flash tank. Without this pressure difference, no moisture could be removed from the oil (or biodiesel) while in the piping or valve. There was also no vacuum for pulling vaporized moisture away from any region where water could have been removed from the oil (or

biodiesel). In both drying systems a throttling valve was located just before the flash tank in order to prevent the boiling of the fluid before it reaches the flash tank by maintaining the higher pressure upstream of the valve.

A pressure drop in the flow before the flash tank due to the throttling valve can also lead to higher fluid velocities. High input velocities will lead to higher drying rates in the flash zone [27]. The restriction in the drying system is a gate valve, which allows the throttling pressure to be varied for testing purposes. As the throttling pressure was lowered, the potential for boiling to take place upstream of the valve becomes greater.

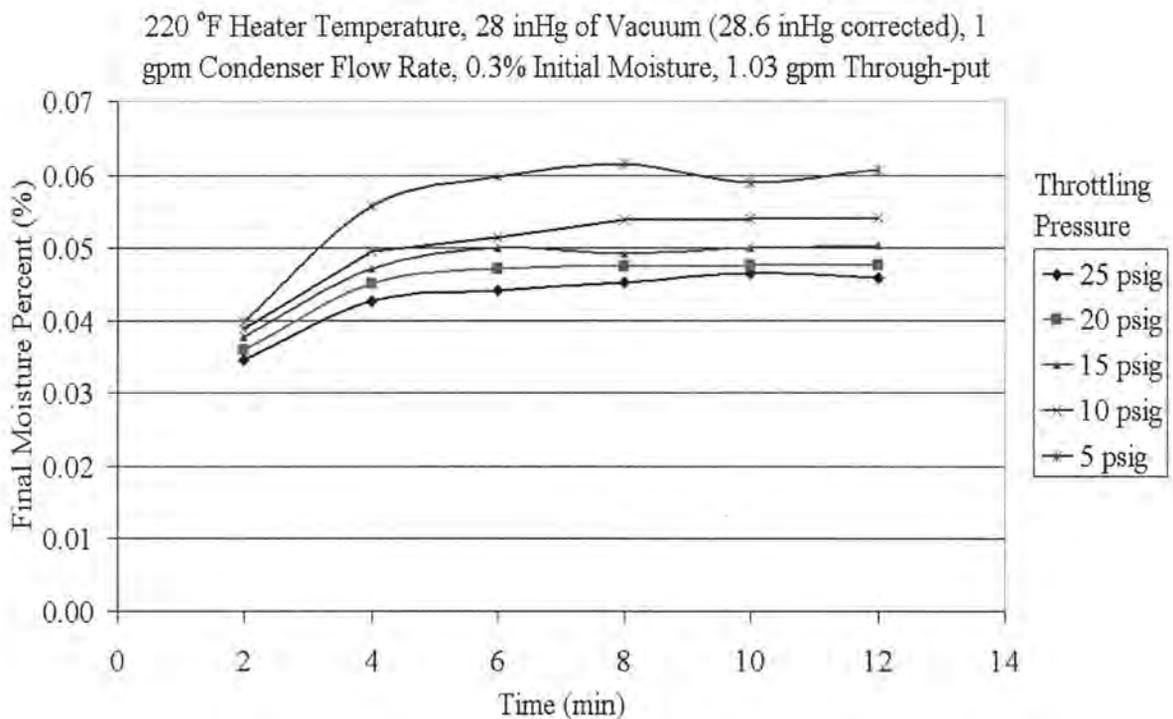


Figure 5.8 Throttling Pressure Test.

Increasing the throttling pressure before the flash tank had a slight effect on the moisture values obtained even when the temperature was held constant. Figure 5.8 shows the trend observed when taking data samples from the drying system at various throttling pressures for the base case condition of 28 inHg of vacuum (or 28.6 inHg corrected vacuum gauge reading), 220 °F for temperature heating, 15 psig throttling pressure, and 1 gpm for the condenser flow rate. The initial moisture percent was around 0.3 percent, and the throughput for the system was 1.03 gpm. There was a slight increase in the steady state moisture percent as the throttling pressure was decreased. This was unexpected since the purpose of the throttling valve was to prevent the boiling of the fluid by maintaining the higher pressure before the flash tank.

A higher throttling pressure may have helped reduce the moisture levels of the exiting fluid because the increased velocity into the flash tank may result in a thinner film on the inside surface of the flash tank. As the film becomes thinner there would be less resistance for moisture migration to the vapor-liquid interface. This results in more complete moisture removal.

The EES computer program predicts no change in the moisture reading upon changing the throttling pressure. Changing the throttling pressure should have no effect on the moisture reading except for a change in the velocity of the fluid into the flash tanks. This velocity effect was not taken into account in the EES computer program and it was assumed that this was the reason for the gradual increase in the moisture level of the experimental data as the throttling pressure was decreased.

5.8 Condenser Flow Rate

Figure 5.9 shows the inside of a liquid ring vacuum pump. Liquid ring vacuum pumps have an off-center driving wheel with stationary fixed blading in a cylindrical casing [28]. As the gas enters the inlet, it gets compressed and pushed out the outlet as the off-center wheel rotates.

Liquid inside the case is thrown to the outside walls by the centrifugal forces from rotation and forms the liquid ring. Between the liquid ring and the off-center wheel is a volume of space that increases and decreases as the off-center wheel rotates. This increasing and decreasing of space creates the vacuum inside the pump.

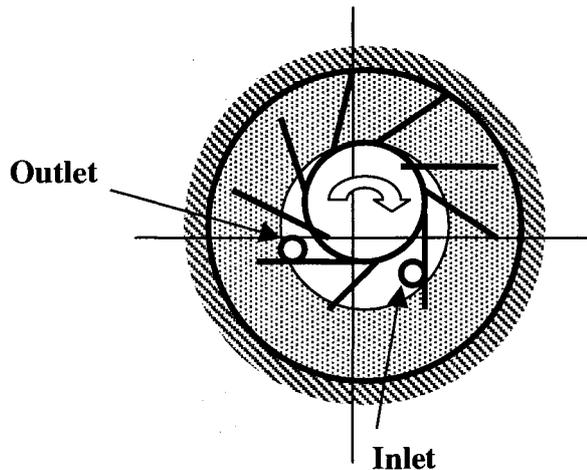


Figure 5.9 Liquid Ring Vacuum Pump – Inside.

The vacuum level will decrease as the temperature of the fluid used to create the vacuum or seal in the vacuum pump increases. If the temperature of the sealing fluid (water in our case) increases, the molecules gain more molecular kinetic energy and can escape

from the surface of the water. The higher temperatures result in more molecules escaping, and a corresponding increase in vapor pressure. This higher vapor pressure results in a lower inlet volumetric flow rate, which means less of the vapor can be removed from the flash tank and a lower vacuum level. A heat exchanger for the condensing portion of the drying system was used to lower the temperature of the gas entering the vacuum pump in order to improve the negative pressure or vacuum that could be drawn on the system.

An additional purpose of the heat exchanger was to condense the water vapor from the flash tanks, which decreases the volume of material that needed to be removed by the vacuum pump. The decrease in the volume was the result of the vapor being condensed to a liquid. An energy and mass balance was performed on the system to determine the approximate amount of water needed to operate the condenser. The equations used for the energy and mass balance are shown in Equations 16 and 17.

$$\dot{m}_{H_2O,3} [h_{g@T_3} - h_{f@T_b}] = \dot{m}_{Cool} C_{p,Cool} [T_b - T_a] \quad (16)$$

$$\dot{m}_{H_2O,1} = \dot{m}_{H_2O,2} + \dot{m}_{H_2O,3} \quad (17)$$

where:

- \dot{m}_{Cool} = the mass flow rate of cooling water
- $\dot{m}_{H_2O,1}$ = the mass flow rate of water from state 1
- $\dot{m}_{H_2O,2}$ = the mass flow rate of water from state 2
- $\dot{m}_{H_2O,3}$ = the mass flow rate of water from state 3
- $C_{p,Cool}$ = the specific heat of cooling water
- T_a = the incoming temperature of the cooling water

T_b = the outgoing temperature of the cooling water

$hg_{@T_3}$ = the saturation enthalpy of the water at T_3

$hf_{@T_b}$ = the saturation enthalpy of the cooling water at T_b

Figure 5.10 shows a schematic of the control volume used to perform a mass and energy balance on the drying system condenser. The program written in EES and the graph plotted from the program (Figure 5.11) shows how the condenser flow rate results in minimal temperature rise in the fluid exiting the heat exchanger. The condenser flow rate ($\text{Flow}_{\text{Cool}} = \dot{m}_{\text{Cool}}$) for the drying system had very little effect on the moisture removed from either the oil or the fuel.

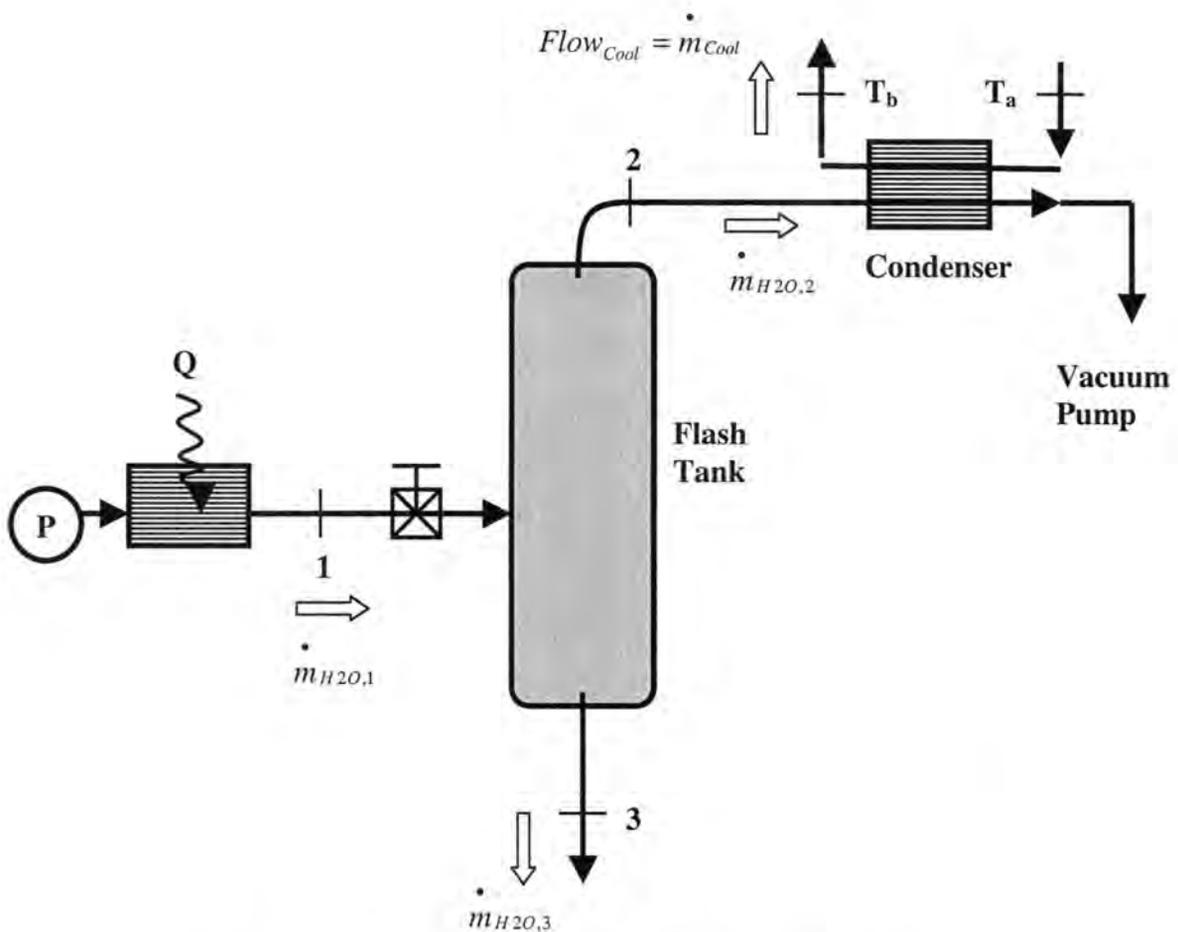


Figure 5.10 Flow Schematic of Vacuum Pump Condenser.

This results in the condenser flow rate having very little effect on the moisture removed from the fluid in the drying system unless the flow rate was close to zero. The table of data used to create the plot in Figure 5.11 can be seen in Appendix B at the end of this thesis.

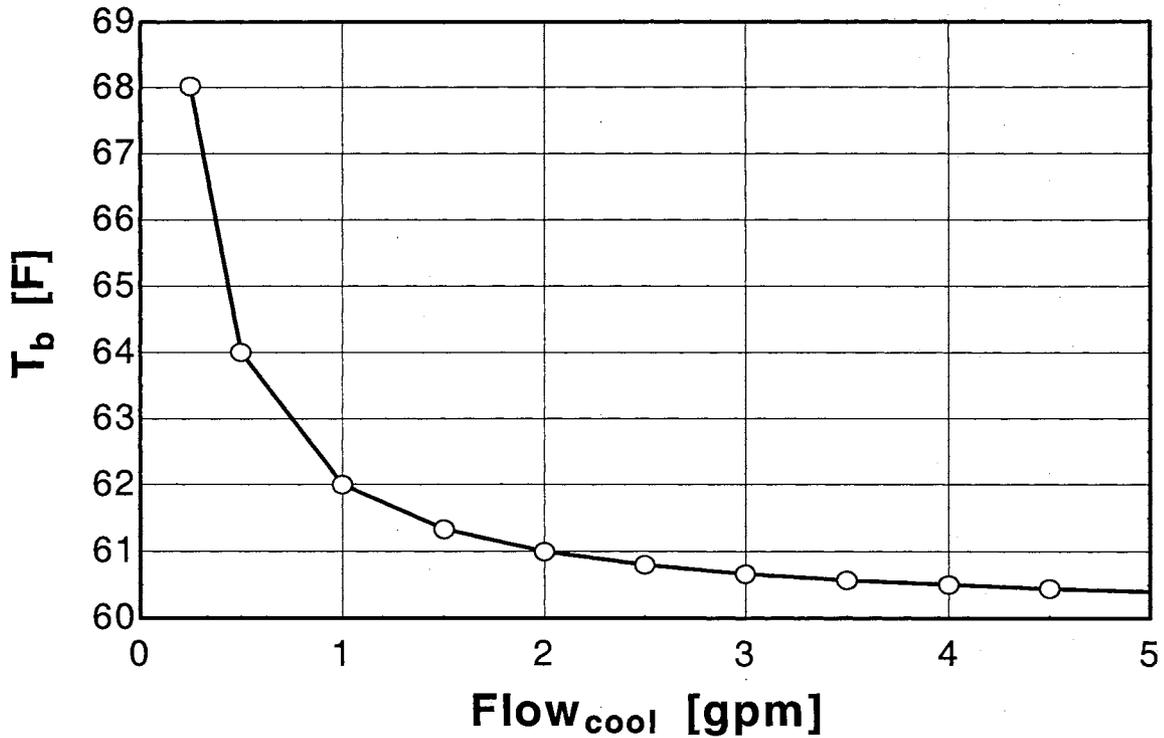


Figure 5.11 Condenser Outgoing Water Temperature versus Water Flow Rate.

Figure 5.12 was created from the experimental data at the base case condition of 28 inHg of vacuum (or 28.6 inHg corrected vacuum gauge reading), 220 °F, and 15 psig throttling. The initial moisture percent of the biodiesel was around 0.3 percent and the through-put for the system was 0.425 gpm. It confirms the indication from the EES

computer program graph, Figure 5.11, that the condenser flow rate does not influence the moisture removal from the oil or fuel. One important note was that Figure 5.12 shows how no flow through the condenser heat exchanger results in a slow and gradual increase in the moisture percent in the exiting oil or fuel. This was the result of the sealing fluid in the vacuum pump slowing increasing in temperature due to the hot water vapor not being condensed in the heat exchanger.

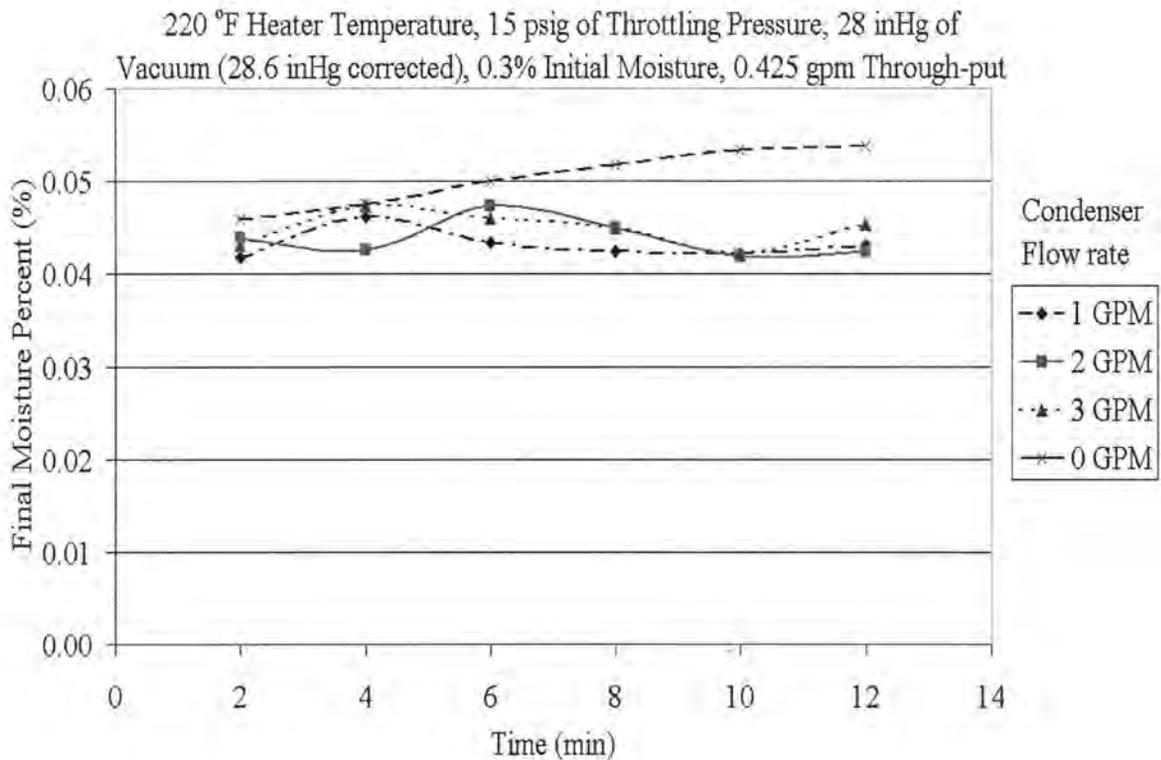


Figure 5.12 Condenser Flow Rate Test.

This increases the volume of gas that the vacuum pump needs to remove, resulting in a slow decrease in the level of vacuum in the flash tanks. All of this leads to the conclusion

that the effect of the condenser flow rate was small in comparison to other variables considered in this study, but it still has a role in the effectiveness of the drying system.

5.9 Repeatability

In order to validate the relationships developed for the drying system at specified conditions, the repeatability of experimental data needed to be investigated. Not being able to duplicate the same moisture percent reading at the same conditions of a previous test would mean that not only are the relationships generated questionable, but so is the control system. If the control system was not capable of properly controlling the conditions, such as maintaining the proper level inside the flash tank using a VFD on the pump, then the results of the experiment are not valid.

Figure 5.13 shows the results of the repeatability test, which proves that the values obtained for the moisture readings can be duplicated at set conditions. Test 1 was first done when investigating various conditions on the drying system. Test 2 was performed two days later in order to prove that the system was giving repeatable and reliable values. Both tests were carried out at the base case conditions, 220 °F heater temperature, 28 inHg of vacuum (28.6 inHg corrected vacuum gauge reading), 15 psig of throttling pressure, and 1 gallon per minute for condenser flow rate. The initial moisture percent was around 0.3 percent, and the fluid through-put of the system was 0.456 gpm. The slight variations in the two tests were within reason, and the system can be considered reliable in terms of reproducibility.

28 inHg of Vacuum (28.6 inHg corrected), 220 °F Heater
Temperature, 15 psig of Throttling Pressure, 1 gpm Condenser
Flow Rate, 0.3 % Initial Moisture, 0.456 gpm Through-put

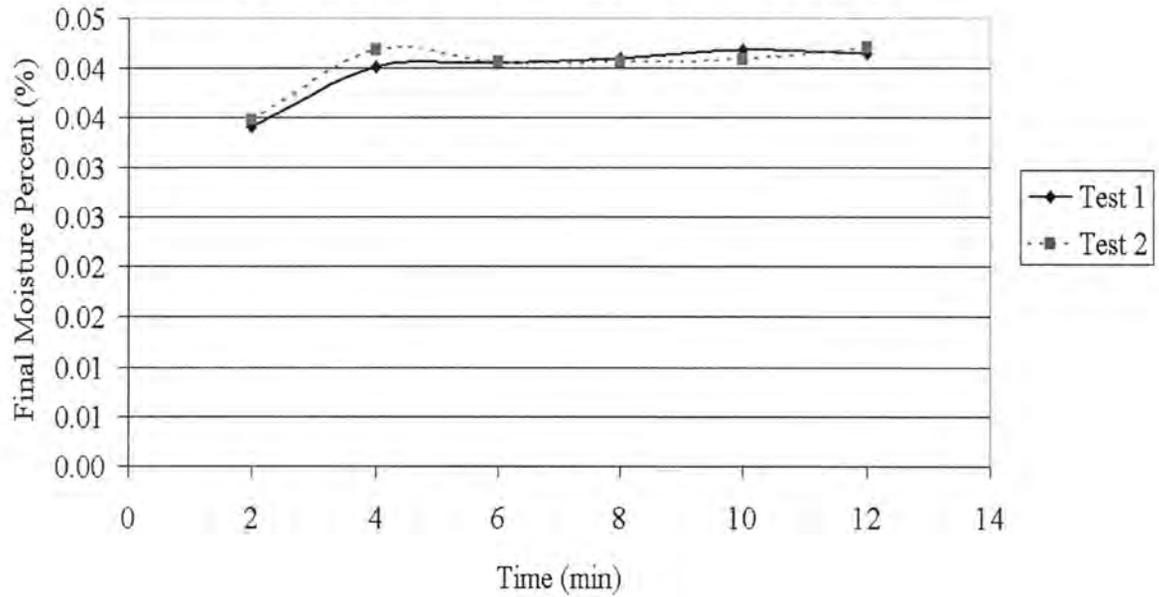


Figure 5.13 Repeatability Test.

6. CONCLUSIONS

The purpose of this study was to determine the effect of four operating variables on the drying process for oil and fuel at a biodiesel pilot plant. The reason for this was so one could attain the desired moisture levels in oil and biodiesel for production. A model was developed so it could be determined how vacuum pressure, heater temperature, throttling pressure, and condenser flow rate affect the performance of a vacuum drying system.

All of this was based on important assumptions, the first and most important was the ideal solution assumption. As first mentioned, very few fluids in a mixture exhibit the characteristics of an ideal solution. The main difference between the model and the experimental data appeared to be due to a positive deviation from the ideal solution theory. If this deviation could have been accounted for in the model, then it was believed that the model and experimental data would have been in very close agreement. Other things also needed to be considered in order to attain a complete model for the process going on inside the flash tank. These forces and other thermodynamic processes all are affected by the four variables under investigation, where some variables have a larger effect than others.

The vacuum pressure and heater temperature were the two most influential variables on the drying process. These two variables, in conjunction with the thin film assumptions and ideal solution theory, need to be modeled completely in order to obtain better agreement between the model and the experimental data. The assumptions for the thin film; uniform distribution of moisture, thickness, and temperature profile need to be modified in order to obtain a more complete model. The film thickness will increase as it travels down the wall,

hence affecting the resistance to mass transfer in the film, and as a consequence, change the amount of moisture that can be removed from the fluid.

The level of vacuum in the flash tank had a major influence on the moisture removal. A large difference in the pressure in the vapor region versus the higher vapor pressure at the surface of the thin film meant that there was a driving force for vaporization to take place. As the vacuum was reduced so was the driving force, as was shown in the experimental data and the model. The intermolecular forces between the water and the fluid became harder to overcome as the level of vacuum was decreased, and as a result, less moisture could be removed from the fluids.

The heater temperature had the most effect on the vapor pressure difference between the film surface and the vapor region inside the flash tank. Higher temperatures meant a larger vapor pressure at the film surface, so the greater difference between the film and vapor region in the flash tank meant more moisture was removed from the oil (or biodiesel). The vaporization of the water causes a temperature gradient in the thin film. Larger temperature gradients were due to local cooling at the surface from evaporation, which slowed down the vaporization of the moisture in the fluid. Both the model and the experimental data predicted this, and tended to not to deviate as much from each other as other variables did when operating at less than ideal conditions. If the temperature profile inside the film could have been accounted for along with the deviation from the ideal solution theory, then the model and experimental data might have agreed even more at lower temperatures.

Throttling pressure had a small influence on the amount of moisture that could be removed from the fluids. The model predicted that there should be no influence from throttling pressure, but the experimental data predicted different. It was thought that the

reason for the improved moisture removal at higher throttling pressures was the higher inlet velocities as a result of the higher throttling pressure. Higher throttling pressures meant higher velocities for the fluid entering the flash tank, and potentially a thinner layer on the inside of the tank.

The condenser flow rate seemed to have the least effect of the four variables, excluding the no flow condition. Only a small amount of water was needed to condense the vapor coming from the flash tank before reaching the vacuum pump. If the fluid sealant temperature of the vacuum pump increases by a large amount, then this results in less vacuum that the pump can pull on the flash tank. Higher sealant temperatures, because of low water flow through the condenser, meant higher vapor pressures inside the vacuum pump. The higher vapor pressure meant a lower inlet volumetric flow due to the molecules gaining molecular kinetic energy, and escaping from the surface of the water at the higher sealant temperatures.

In summary, if the deviation from the ideal solution theory along with the effect of gradients, resistance to mass transfer, and inlet velocities had been taken into account when developing the model, it is believed that the model would better predict the moisture removal seen from the experimental data. The vacuum drying system did what it was designed to do for biodiesel production at the pilot plant. This was to remove moisture from oil for biodiesel production, and attain less than 500 ppm of moisture in the outgoing biodiesel.

7. REFERENCES

1. Mujumdar, Arun S. Handbook of Industrial Drying, Second Edition. Marcel Dekker, Inc., New York, New York, 1995.
2. ASTM D 6751- 02 Standard Specification for Biodiesel Fuel (B100) Blend Stock for Distillate Fuels. American Society for Testing and materials, Philadelphia, PA, 2002.
3. ASTM D1796 – 02 Test Method for Water and Sediment in Fuel Oils by the Centrifuge Method. American Society for Testing and Materials, Philadelphia, PA, 2002.
4. Canakci, M. and Van Gerpen, J. Biodiesel Production from Oils and Fats with High Free Fatty Acids. Transactions of the ASAE 44(6), 2001, 1429-1436.
5. Canakci, M. and Van Gerpen, J. A Pilot Plant to Produce Biodiesel from High Free Fatty Acid Feedstocks. ASAE paper 01-6049, 2001.
6. Ma, Fangrui and Hanna, Milford A. Biodiesel production: a review. Bioresources Technology 70, 1999, 1-15.
7. Canakci, M. and Van Gerpen, J. Biodiesel Production via Acid Catalysis. Transactions of the ASAE 42(5), 1999, 1203-1210.
8. Cummins, C. Lyle Jr. Diesel's Engine Volume One From Conception to 1918. Carnot Press, Wilsonville, Oregon, 1993.
9. Owen, Keith and Coley, Trevor Automotive Fuels Handbook. Society of Automotive Engineers, Inc, Warrendale, PA, 1990.

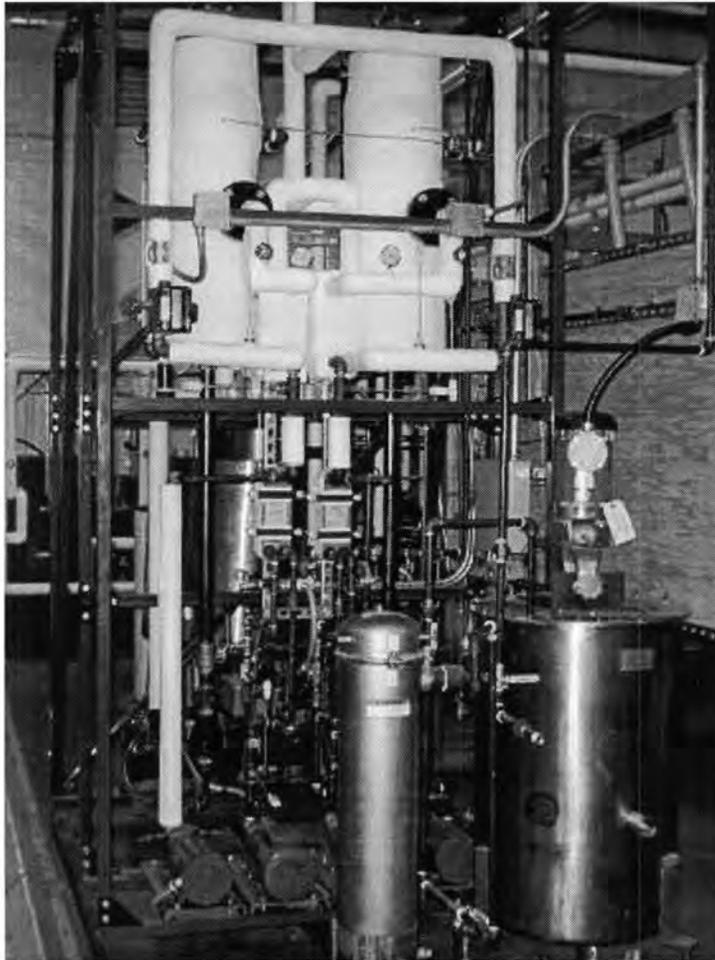
10. JND Thermal Process, Retford, England, Rotary Dryer.
http://www.jnd.co.uk/JNDThermalProcess/rotary_c.html
(Date accessed: 5/20/2003).
11. Petrie Group Limited, Oldham, England, Conveyor Dryer.
<http://www.petrie-group.co.uk/conveyor.htm> (Date accessed: 5/20/2003).
12. Vacuum Dryer. <http://www.conditcompany.com> (Date accessed: 5/25/2003).
13. Rozanov, L.N. Vacuum Technique, edited by Hablanian, M. H.. Taylor & Francis, London, England, 2002.
14. Nisenfeld, A. Eli Industrial Evaporators: Principles of Operation and Control. Instrument Society of America, Research Triangle Park, NC, 1985.
15. Swenson Technology, Inc., Monee, IL, Falling Film Evaporator, 2003.
<http://www.swenson-equip.com/fig7.html> (Date accessed: 7/16/2003).
16. Swenson Technology, Inc., Monee, IL, Rising Film Evaporator.
<http://www.swenson-equip.com/fig5.html> (Date accessed: 7/16/2003).
17. Moran, Michael J. and Shapiro, Howard N. Fundamental of Engineering Thermodynamics, Third Edition. John Wiley & Sons, Inc., New York, New York, 1996.
18. Hui, Y.H. Fifth Edition Bailey's Industrial Oil & Fat Products. John Wiley & Sons., New York, New York, 1996.
19. Moore, Walter J. Physical Chemistry, Fourth Edition. Prentice-Hall Inc., Englewood Cliffs, New Jersey 1972.
20. Treybal, Robert E. Mass-Transfer Operations, Second Edition. McGraw-Hill Book Company, New York, New York, 1968.

21. Smith, R.A. Vaporisers: Selection, Design, and Operation. John Wiley & Sons, Inc., New York, New York, 1986.
22. Purdue University, West Lafayette, IN, EES – Engineering Equation Solver.
<http://me.www.ecn.purdue.edu/~me300/Fall2002/EES.pdf>
(Date accessed: 7/7/2003).
23. Partial Recovery Vacuum Pump. <http://www.travainipumps.com>
(Date accessed: 3/20/2003).
24. Basic theory of Karl Fischer Titration.
<http://www.laboratorytalk.com/news/mea/mea101.html> (Date accessed: 4/19/2003).
25. Chang, Raymond. Chemistry: Fourth Edition. McGraw-Hill Book Company, Hightstown, NJ, 1991.
26. Hoffman, Dorothy M., Singh, Bawa and Thomas, John H., III Handbook of Vacuum Science and Technology. Academic Press, Chestnut Hill, MA, 1998.
27. Strumillo, Czeslaw and Kudra, Tadeusz Drying: Principles, Applications and Design. Gordon and Breach Science Publishers, Montreux, Switzerland, 1986.
28. Marlow, Thomas G. Drying Machinery and Practice. Crosby Lockwood and Son, New York, 1910.

APPENDICES

Appendix A

Vacuum Drying Equipment Standard Operating Procedure (SOP)



Forward

Reading of this standard operating procedure manual completely and understanding all information is important before actual operation of the vacuum drying system. The operator should remember the NOTES listed in this operating procedure and familiarize themselves with these for avoidance of potential problems. There are two vacuum drying systems, one for oils and one for the fuel itself. Both systems are identical, so unless noted that something applies specifically to one system, assume each direction and procedure pertains to both systems. Always fill out the Biodiesel Pilot Plant Log Book for a record of drying system operation and problems in order to help the next operator of the system.

This standard operation procedure for the vacuum drying system will walk the operator through the “Initial Start-up” procedure where important switches and valves will have to be turned on, along with going through an initial checklist to prepare the operator for the next section.

Once the “Initial Start-up” procedure has been gone through, the operator is ready to proceed to the “Heating System Warm-up”. This section deals with the controls of the paratherm/propylene glycol heating system and the piping to the vacuum drying system. Once the paratherm/propylene glycol heating system is operating, the heater controls of the vacuum drying system will be discussed in preparation for “Dryer System Warm-up”.

In the “Heating System Warm-up” section, the operator will then be shown how to warm-up the drying system in preparation for continuous operation. This will entail what controls, switches, and valves need to be activated in order to complete the “Dryer System Warm-up” and proceed to continuous drying of oil or fuel.

“Dryer System Steady State Operation” of the drying system will be covered in the next section. The operator will learn the procedures needed to keep the vacuum drying system running at a balanced and steady state. This will cover the potential problems associated with “steady state” operation and what to do to maintain this state.

The last section of the SOP will walk the operator through the “Dryer System Shut Down” procedure and what needs to be done in order to properly shut down the dryer in system. The “Heating System Shut Down” procedure will also be covered along with the potential problems associated with vacuum dryer system operation.

The next part of the SOP is the pictures of components used in the vacuum drying system. Inspecting each of these pieces of equipment beforehand will help with system familiarization, item location, and ease of operation.

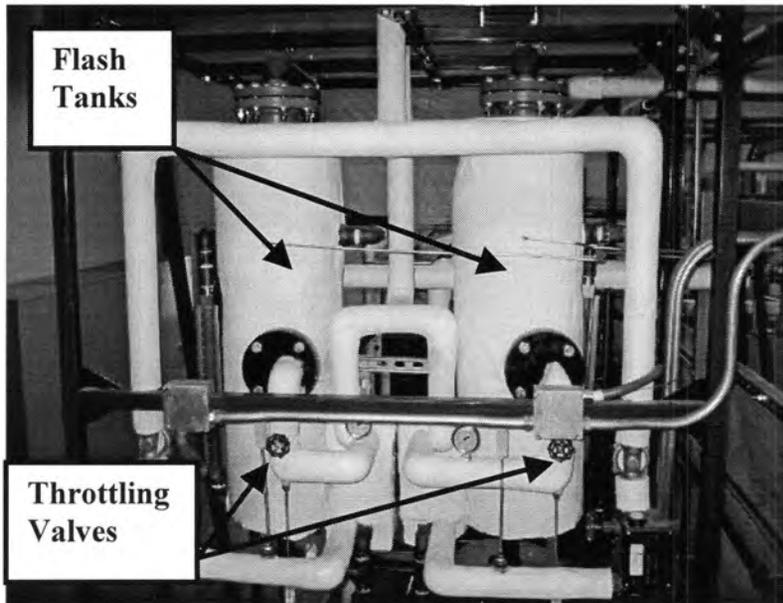


Figure 1 Flash Tanks & Throttling Valves



Figure 2 208/120V Main Breaker Panel (P1A) (for Biodiesel Pilot Plant)

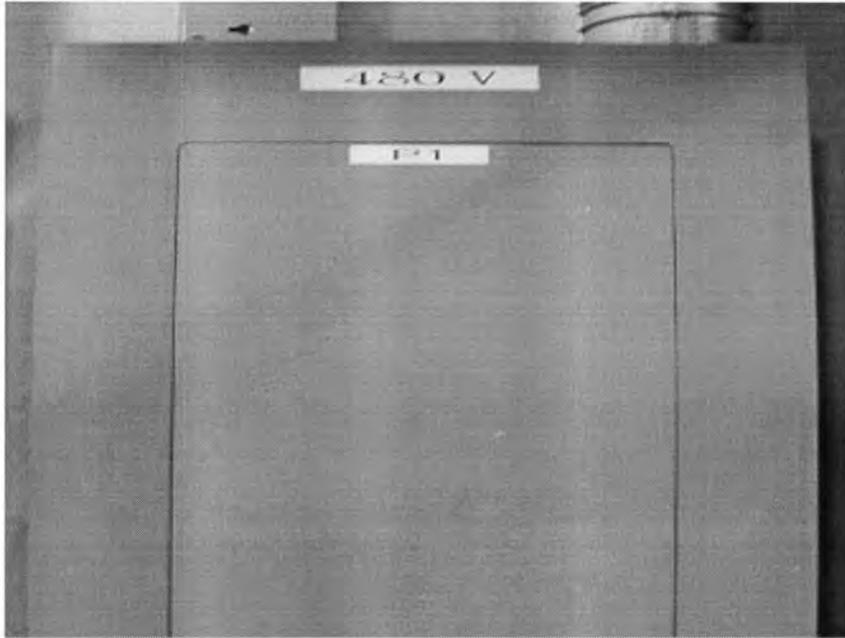


Figure 3 480V Main Breaker Panel (P1) (for Biodiesel Pilot Plant)

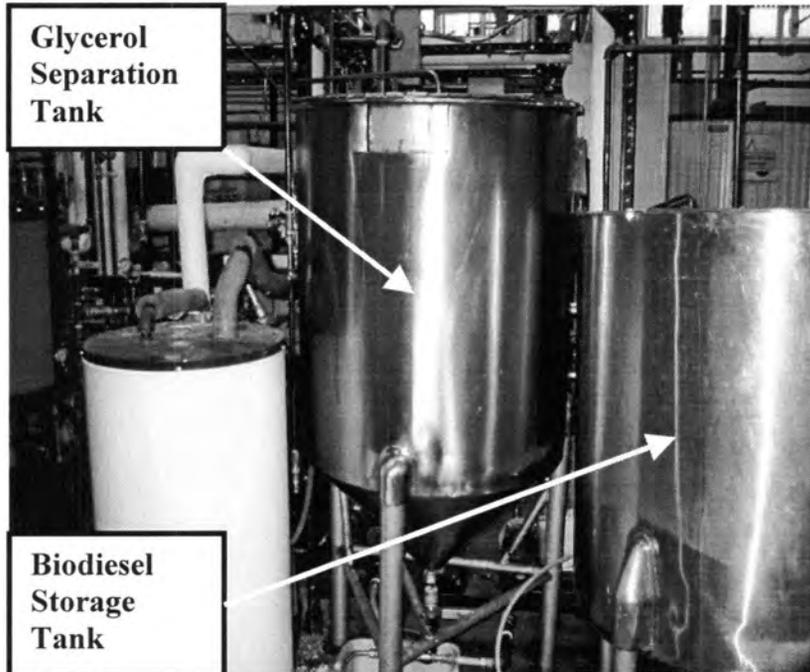


Figure 4 Glycerol Separation & Biodiesel Storage Tank



Figure 5 Staging Tank (for Soybean Oil)

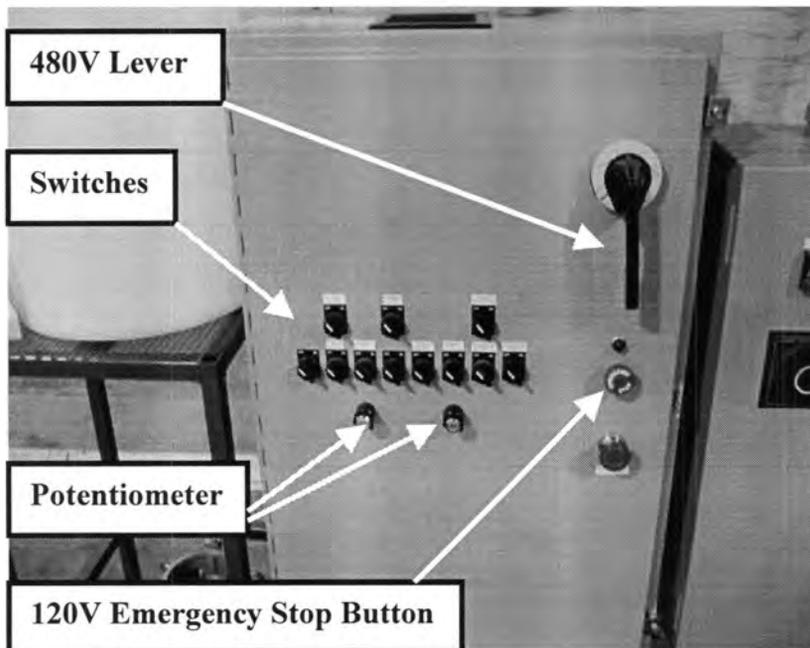


Figure 6 Dryer Control Cabinet (Variable Frequency Drive)



Figure 7 Dryer Control Cabinet (Omega Controllers)

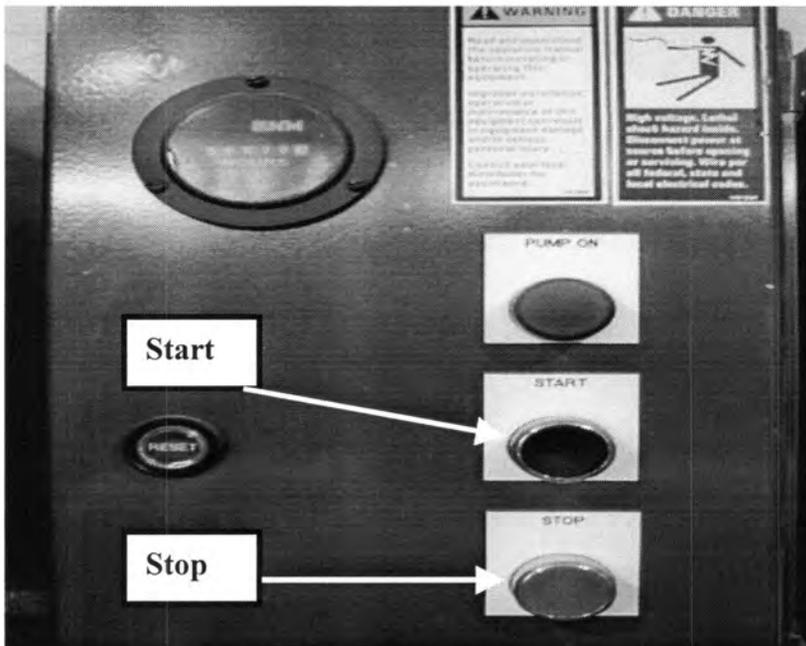


Figure 8 Vacuum Pump Control Cabinet

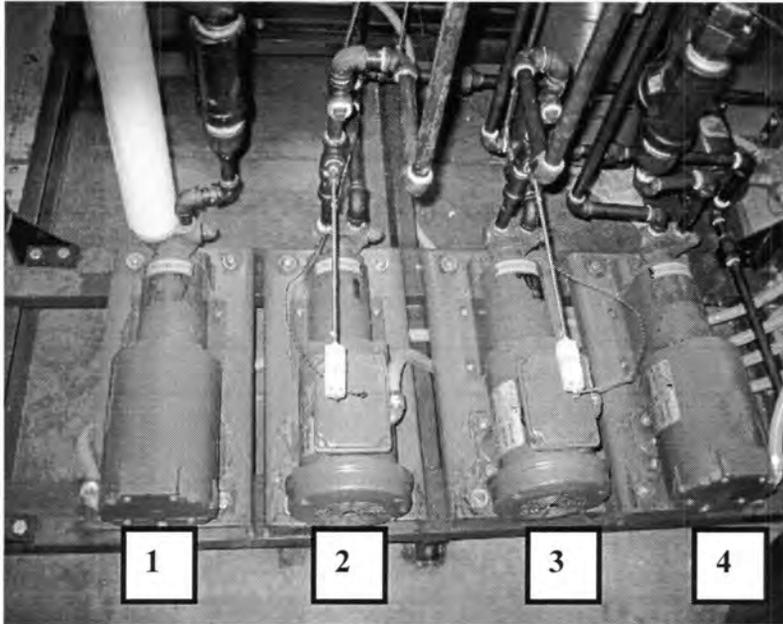


Figure 9 Vacuum Drying System Gear Pumps

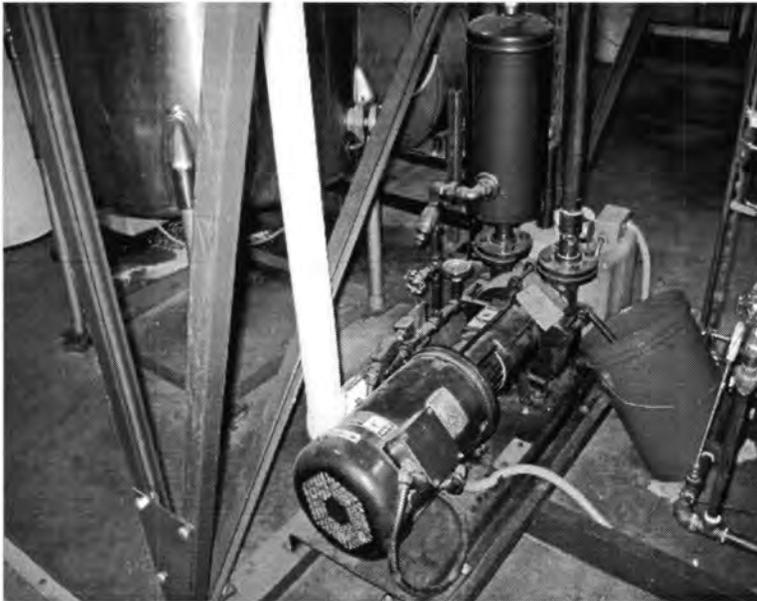


Figure 10 Vacuum Pump

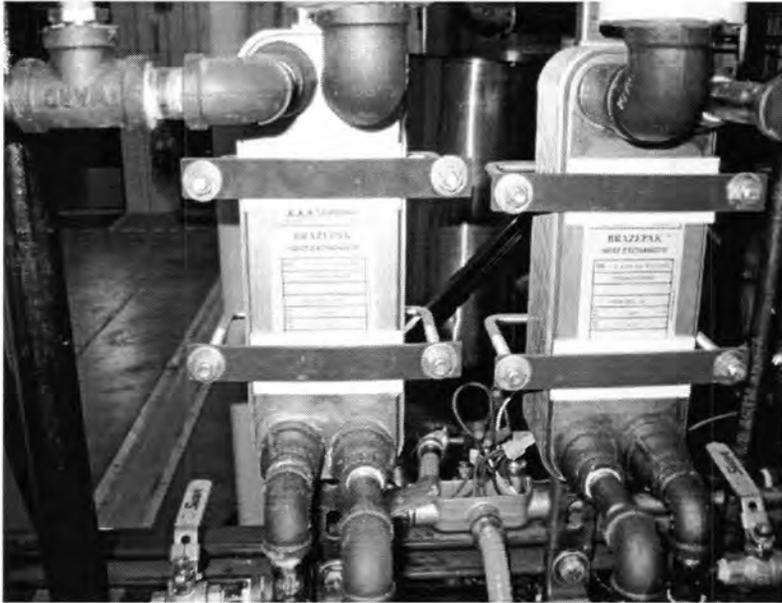


Figure 11 Economizer Heat Exchangers

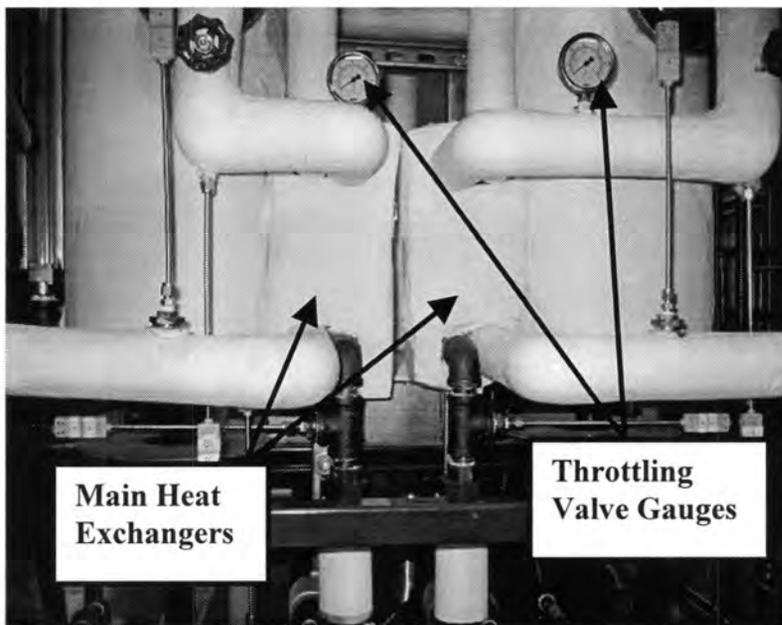


Figure 12 Main Heat Exchangers & Throttling Valve Gauges

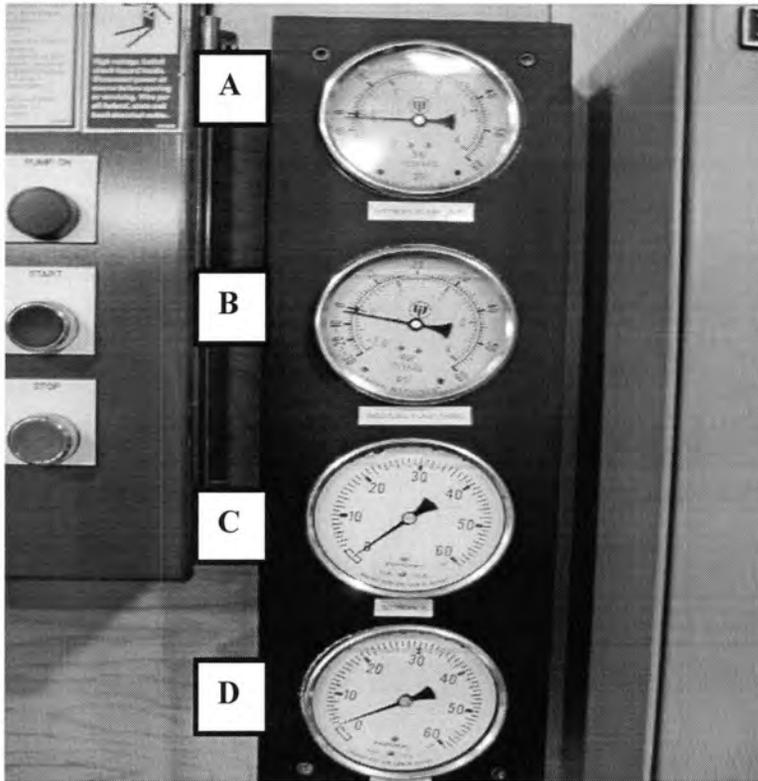


Figure 13 Flash Tank Compound Gauges & Gear Pump Gauges

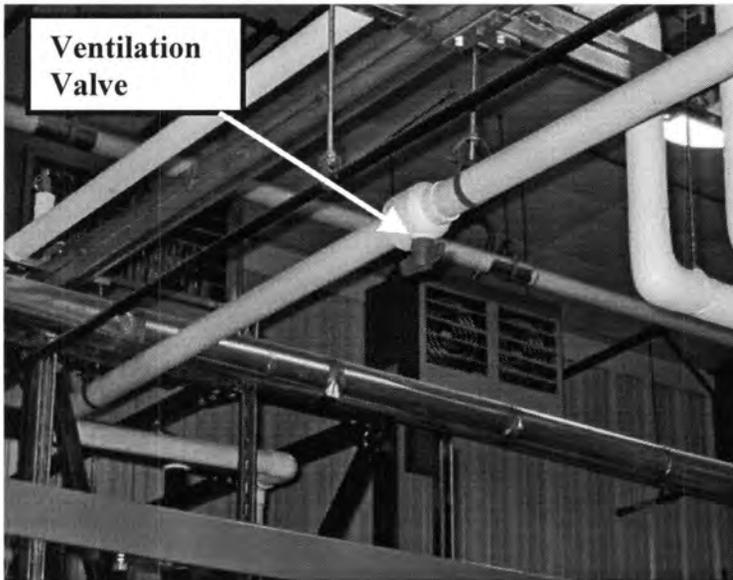


Figure 14 Vacuum Pump Ventilation Valve

Initial Start-up

Procedure

1. Ensure that the main water supply valve to the Biodiesel Pilot Plant is open (parallel with the pipe line). The main water valve is located above and to the left of the 208/120V Main Breaker (Figure 2 & 15) for the Biodiesel Pilot Plant. The valve is located on top of the insulated piping and has a red handle. It should always be open unless repairs are being made on the water lines. See Figure 15 for main water supply valve and location.

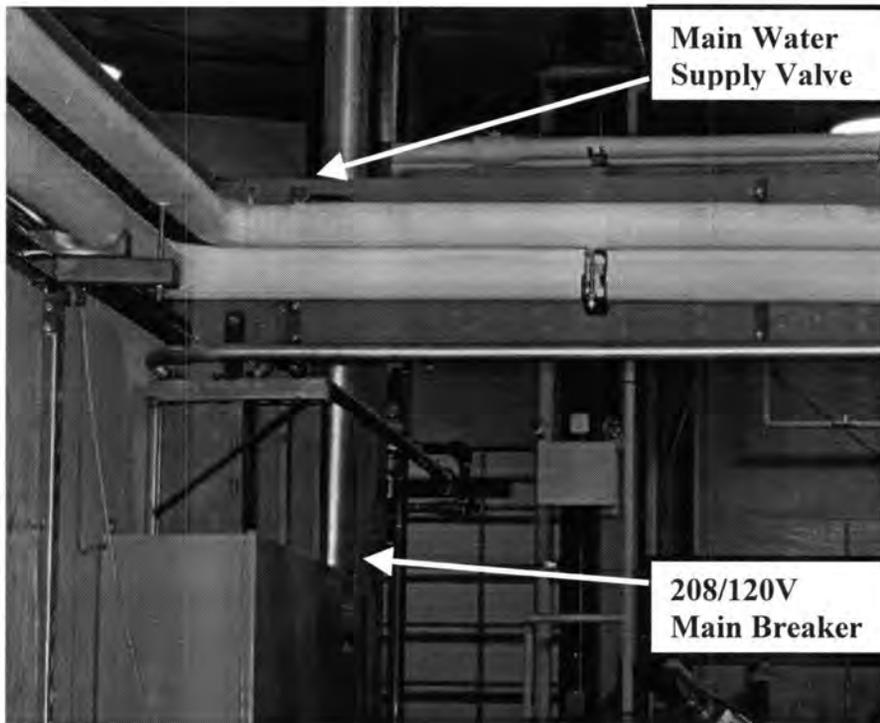


Figure 15 Main Water Supply Valve Location

2. Next the main water supply valve to the vacuum pump must be turned on if it is not already. The main water supply valve for the vacuum pump has a green handle, and is located on the vacuum pump itself, on the side of the vacuum pump next to the biodiesel storage tank. See Figure 16 for the main water supply valve location for the vacuum pump.



Figure 16 Main Water Supply Valve for the Vacuum Pump

NOTE: Failure to supply water to the vacuum pump can severely damage the pump. It is important to make sure there is water flow to the vacuum pump before ever turning it on.

3. Check the vacuum pump drive coupler. This is the black rubber connector that is located between the vacuum pump and the vacuum pump electric motor. A shield covers the coupler, as it should at all times unless performing the check listed below. The shield is painted black on the outside and yellow on the inside. See Figure 17 for the rubber coupler and location on the vacuum pump.

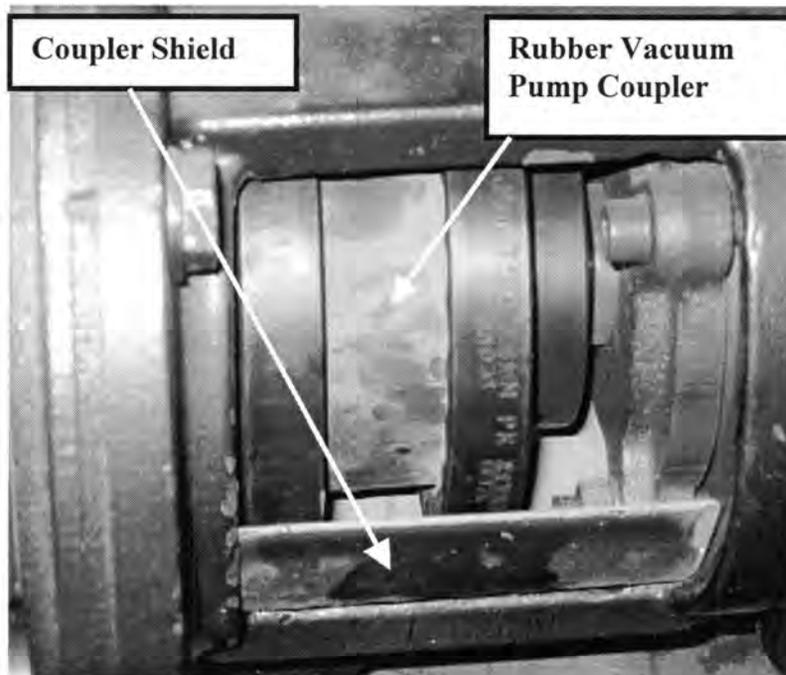


Figure 17 Rubber Vacuum Pump Coupler

Rotate the safety shield until the rubber coupler is exposed and try to rotate the rubber coupler with the wooden end of a hammer. Put the handle of the hammer on one of the metal drives located at the end of the rubber coupler. Push on the metal drive until the coupler spins freely. If the vacuum pump has not been used recently, the pump may have locked up and needs to be freed by simply rotating the rubber couple to break it free. Moisture inside the pump can form rust deposits on the seal of the pump and temporarily prevent it from moving.

NOTE: Be careful not to pinch one's fingers underneath the shield or lodge the wooden hammer handle underneath the shield as the coupler moves. Also, NEVER do this with the power turned on to the vacuum pump. NEVER push or pry on the rubber coupler, only the metal drives at the ends of the coupler. Tearing or damaging the coupler will cause premature failure of the coupler and result in the vacuum pump being disabled.

4. Ensure that the power is on to the Pilot Plant Control Cabinet, See Figure 18.

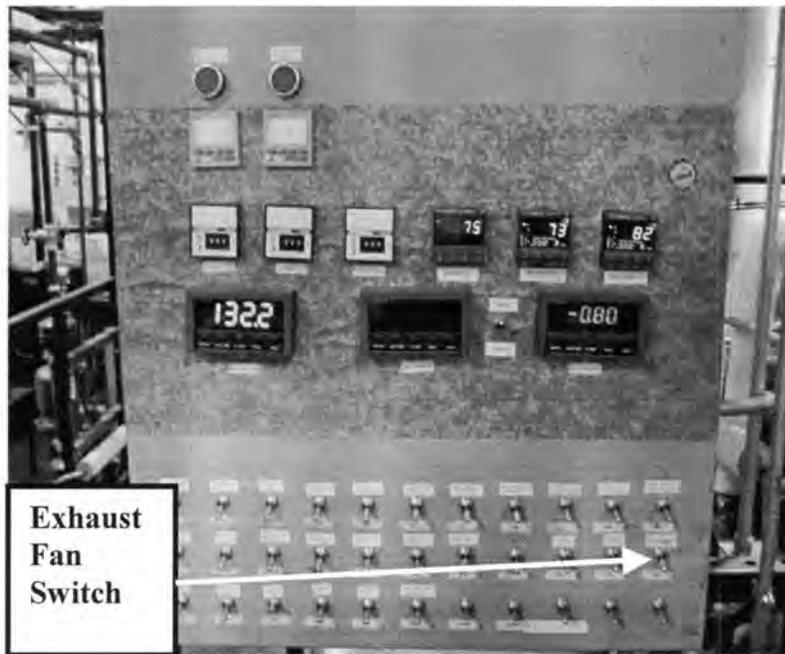


Figure 18 Pilot Plant Control Cabinet & Exhaust Fan Switch Location

If it is not, determine why and if it is all right to turn on power, then turn on power.

5. Turn on the “Exhaust Fan” switch located on the Pilot Plant Control Cabinet (switch is in “On” position when the switch is pointing up as opposed to “Off” and pointing down). See Figure 18 for “Exhaust Fan” switch and location.
6. Make sure all switches on the Dryer Control Cabinet (Variable Frequency Drive), Figure 6, are in the “Off” position. The inside the Dryer Control Cabinet is the variable frequency drives for the gear pumps.
7. Check to see that all appropriate circuit breaker are in the “On” position, see Figures 2 and 3 above for panel locations and Figures required 19, 20, and 21 for breakers.

208/120V Main Breaker Panel (P1A)

#27 Biodiesel Dryer Relays

#28 Biodiesel Dryer Relays

#29 Biodiesel Dryer Controllers

480V Main Breaker Panel (P1)

#22 Vacuum Process Cabinet

#27 Vacuum Pump



Figure 19 208/110 Main Breaker Panel (Inside)

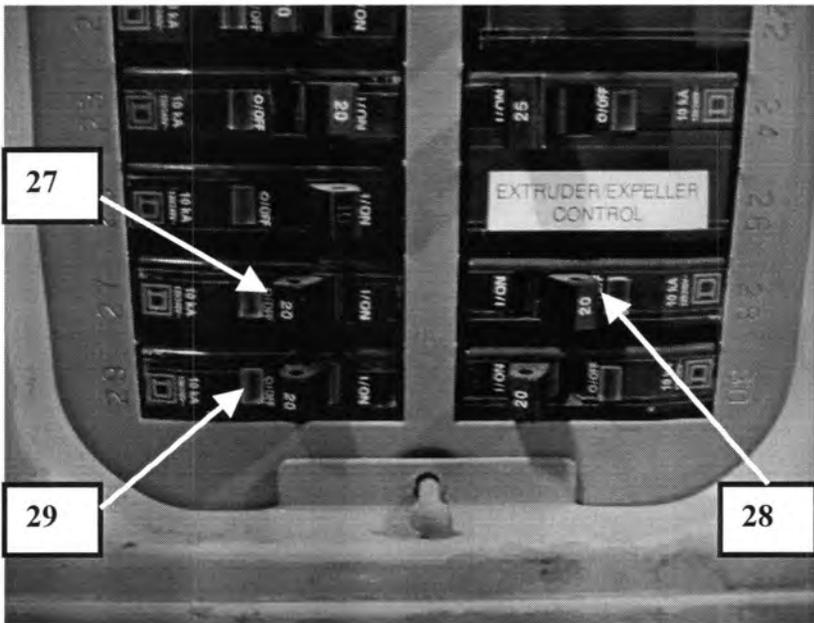


Figure 20 208/120V Breakers for Drying System

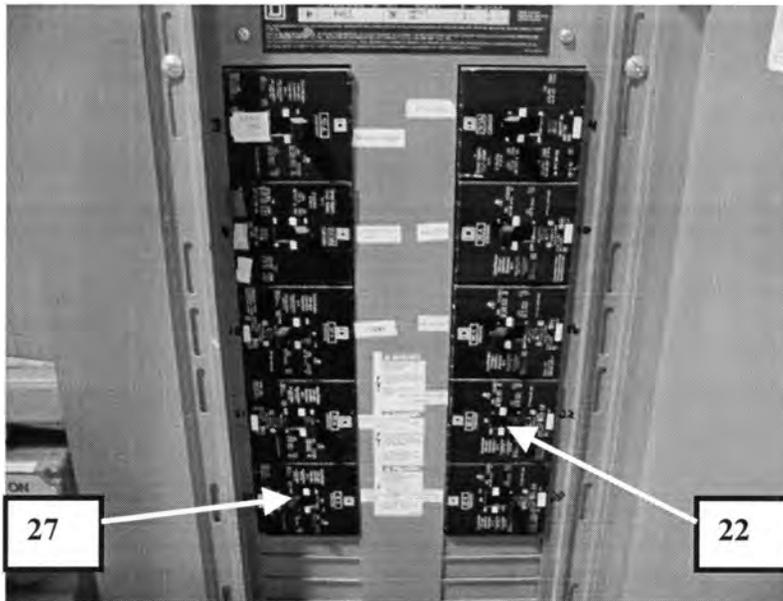


Figure 21 480V Breakers for Drying System

8. Make sure the ventilation valve (see Figure 14) for the vacuum pump ventilation system is open, it should be left open at all times.

Heating System Warm-up

Procedure

1. Rotate the black 480V lever (see Figure 6) on the Dryer Control Cabinet (Variable Frequency Drive) to the “On” position. Turn the “Cabinet Exhaust Fan Switch” to the “On” position, the switch is located on the Dryer Control Cabinet (Variable Frequency Drive) and its location can be seen in Figure 22.

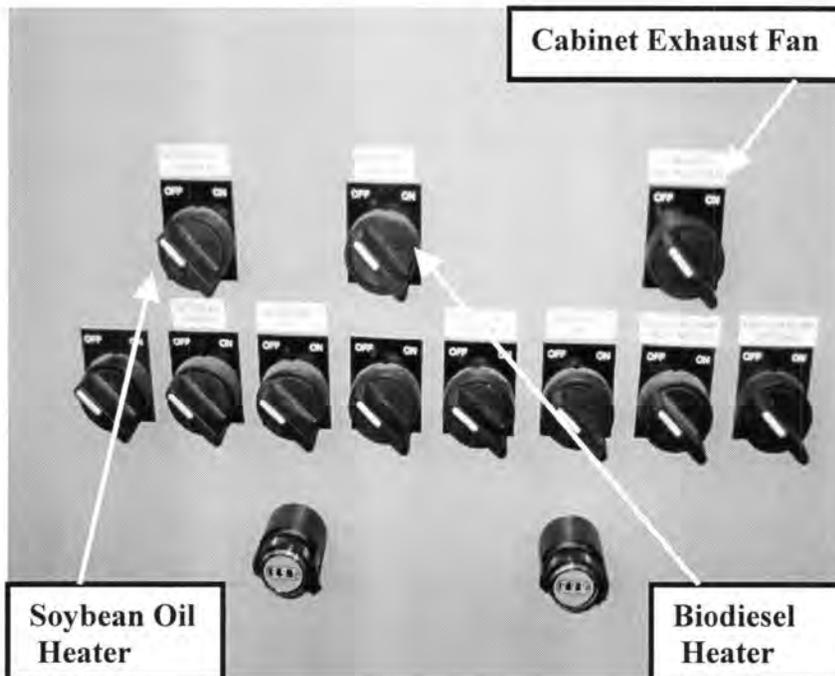


Figure 22 Dryer Control Panel Switches

NOTE: Failing to turn on the “Cabinet Exhaust Fan” could result in the overheating and damaging of the Variable Frequency Drives (VFD) located inside the cabinet.

2. Pull out on the 120V Emergency Stop Button located on the Dryer Control Cabinet (Variable Frequency Drives), see Figure 7. The switch should “click” along with the green light above the switch should now be illuminated.
3. Turn the “Soybean Oil Heater” switch to the “On” position, the switch is located on the Dryer Control Cabinet (Variable Frequency Drives), see Figure 22.
4. Turn the “Biodiesel Heater” switch to the “On” position, the switch is located on the Dryer Control Cabinet (Variable Frequency Drives), see Figure 22.

NOTE: Turning on both switches keeps the pressure down on the paratherm/propylene glycol Heating system. The line pressure for the paratherm/propylene glycol Heating system is typically around 80-90 psig, depending on the temperature the system is running at. The pipe size for the paratherm/propylene glycol Heating system is 2 inches, while the Drying system pipeline is 1 inch. This reduction in size cause the line pressure to reach 100 to over 100 psig, which is higher then what the system is designed to run at. In order to help with this a recirculation loop in the piping was placed just before the piping branches off to the dryer heaters system was put in. This reduces the pressure some what depending on how far the valve is open, but it has a draw back. The draw back is that if the valve is opened to far the fluid takes the path of least resistant and does not want to flow into the drying system piping, but instead through the recirculation loop and back to the pump. It is recommended that both switches be turned on so that one does not have to mess with the recirculation loop valve in order to attain a proper pressure at the pump for the Paratherm/Glycol Heating system. See Figure 23 for recirculation loop valve and location, Area 1.

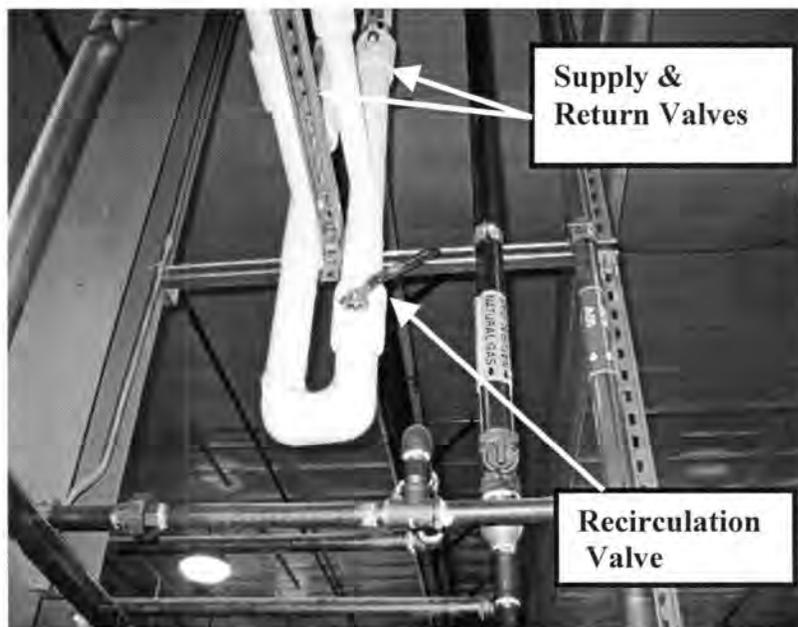


Figure 23 Recirculation Loop Valve -
Paratherm/Propylene Glycol System

The “Soybean Oil Heater” and “Biodiesel Heater” switches should be turn on before the next step, paratherm/propylene glycol Heating system warm-up, in order to prevent the sticking of the paratherm/propylene glycol heating line solenoid valves (see Figure 24), which mean no fluid will flow through the drying system “Main Heat Exchangers” (see Figure 13) and “Heating Fluid Flow Meters”, see Figure 24.

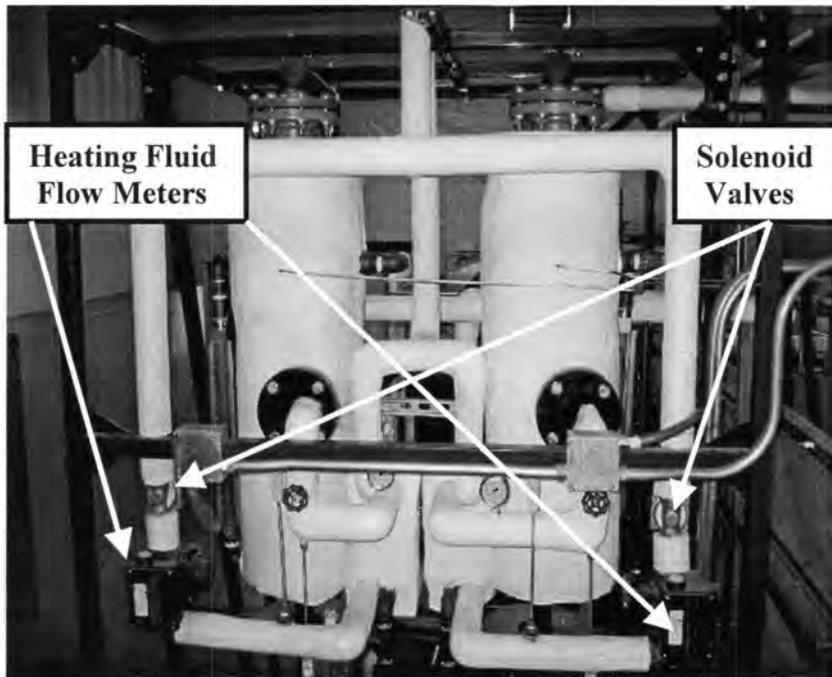


Figure 24 Flow Meter and Solenoid Valve Locations

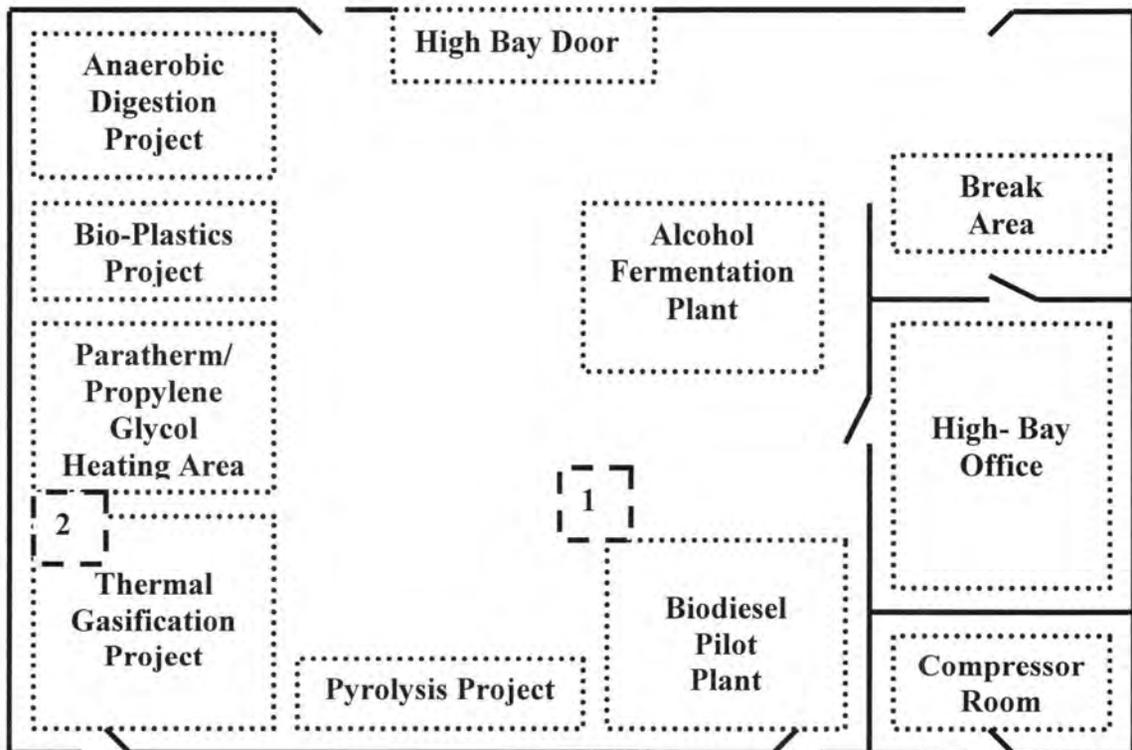


Figure 25 Becon Facility Layout

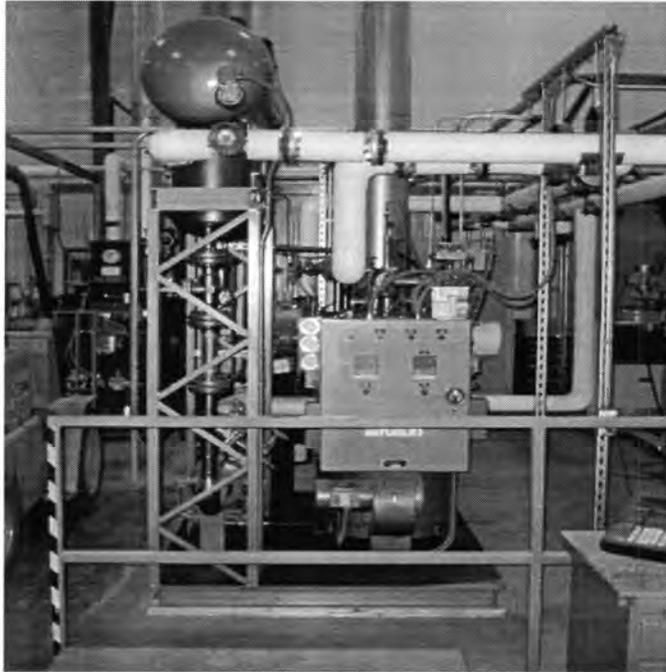


Figure 26 Paratherm/Glycol Heating System

5. Next, the paratherm/propylene glycol heating system, see Figures 25 & 26 for location, needs to be turn on and set to the desired temperature.

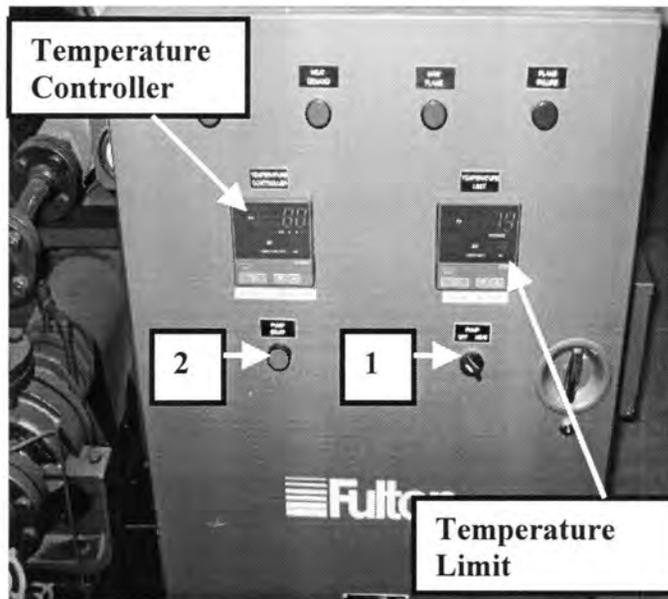


Figure 27 Paratherm/ Propylene Glycol Heating Controls

To set the temperature use “Temperature Controller” controls, NEVER touch “Temperature Limit” controls (see Figure 27). Changing the “Temperature Limit” control set points will result in the flame failure of the paratherm/propylene glycol system and the unit will not work until the proper resetting of the internal controls. Adjust the temperature on the “Temperature Controller” controls by pushing the “up” or “down” arrows located on the controller. After setting the temperature, push the “set/ent” button and hold until the little red light at the very right side of the temperature display disappears.

NOTE: If the paratherm/propylene glycol system is already in operation do not alter it until consulting the person who is using the system for temperature settings. If it is in operation and the temperature the drying system needs to be lower than the temperature all ready set in the Paratherm/Propylene Glycol system then there is no problem, the dryer controls can maintain the needed temperature. If the temperature is lower then what is needed then talk to the other person using the system about changing the temperature settings.

6. Make sure all the “Supply” and “Return” line valves in the piping system from the paratherm/glycol heating system to the drying system are open. They are located in area (1) & (2) in Figures 23 and 25 above. Area 2 is on the backside of the Gasification Project (see Figure 28), and area 1 is the pipeline just above the recirculation loop valve.

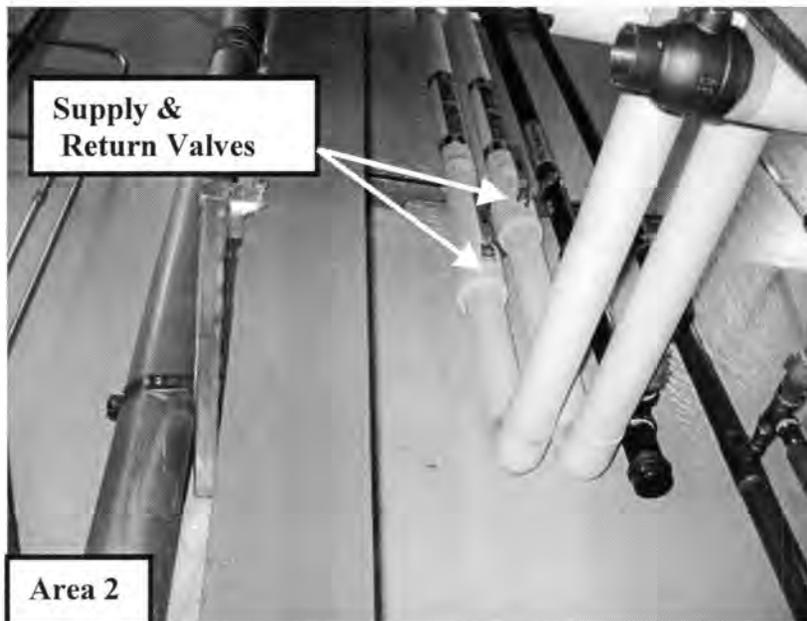


Figure 28 Supply & Return Valves – Backside of Gasification Project

If another project does not want heated propylene glycol supplied to their system, then close the appropriate valves. Unless otherwise needed, always leave the “Supply” and “Return” line valves in their current position, they should never need to be shut unless work is being done on the system

7. Once the temperature is set on the paratherm/propylene glycol system, then turn the switch (1), see Figure 27, located on the right side of the panel to the “Heat” position (very right location, switch should click two times to reach the “Heat” position”). Make sure the switch is not in the “Pump” position otherwise the unit will never heat up. This switch pumps the paratherm system into pump mode where no heat is supplied and heat mode where heat is supplied to the paratherm oil. Use the pump mode for cooling down the system, never shut off hot, let it cool down to around 200 °F
8. Push the green “Pump Start” button (2), see Figure 27, and hold in the button (it should illuminate) for 2-3 seconds until the green “Pressure & Flow Interlock” light (3) comes on along with the green “Heat Demand” light (4), see Figure 29.



Figure 29 Paratherm/Propylene Glycol Heating Controls

Once these two lights come on, release the button. Holding the button in after these lights illuminate for extended periods will result in the failure of the control system for the paratherm/propylene glycol system. The unit should now start to warm up and after a few minutes the green “Main Flame” light (5) should come on. If the red “Flame Failure” light (6) comes on then seek help from the Becon Facility personnel in charge, Norm Olson.

9. Once the paratherm/propylene glycol system is running, immediately walk over to the propylene glycol pump emergency stop switch, see Figure 30, and push the rocker switch so it is in the “On” position.

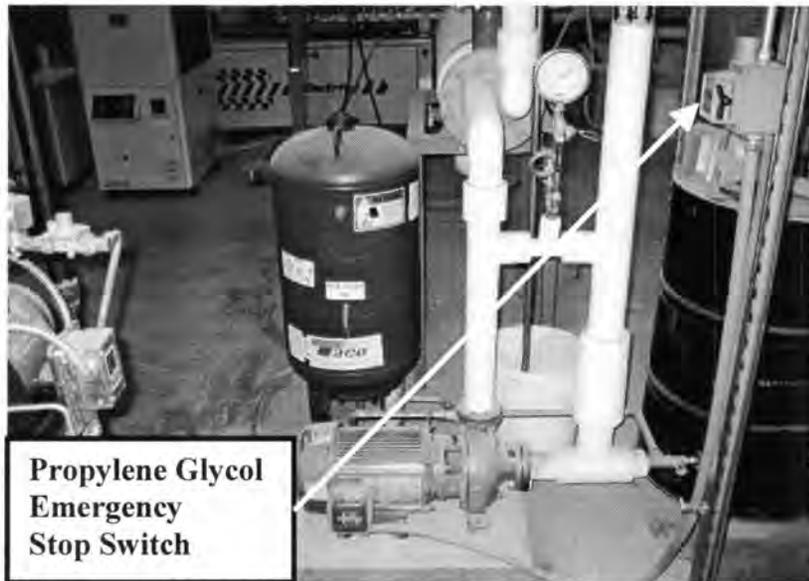


Figure 30 Propylene Glycol Pump and Emergency Stop Switch

Failing to do this will result in extremely high temperatures in the paratherm/propylene glycol heat exchanger, which will potentially cause damage to the heat exchanger and unit if the fluid is not allowed to circulate for extended periods of time.

NOTE: Future plans call for the facility PLC system to control the paratherm/propylene glycol system, which would change the location of the propylene glycol pump switch and potentially other controls.

10. Make sure the propylene glycol is flowing through the flow meters (see Figure 24) of the drying system.

NOTE: The flow rate of the propylene glycol from the paratherm/propylene glycol system is higher than what the dryer system flow meters are rated for. This is why the recirculation loop valve (see Figure 23) is partially open, plus to prevent the high pressures seen in the propylene glycol lines due to the pipe size reduction from the paratherm/propylene glycol heating lines to the dryer system heating lines.

10. Set the Omega CN9000A Controller to the desired temperature for dryer system temperature control. The controllers are located in the “Dryer Control Cabinet

(Omega Controllers), see Figure 31, right next to the “Dryer Control Cabinet (Variable Frequency Drives)”. The “Dryer Control Cabinet (Omega Controllers)” contains all the Omega controllers for the drying system and future modifications.

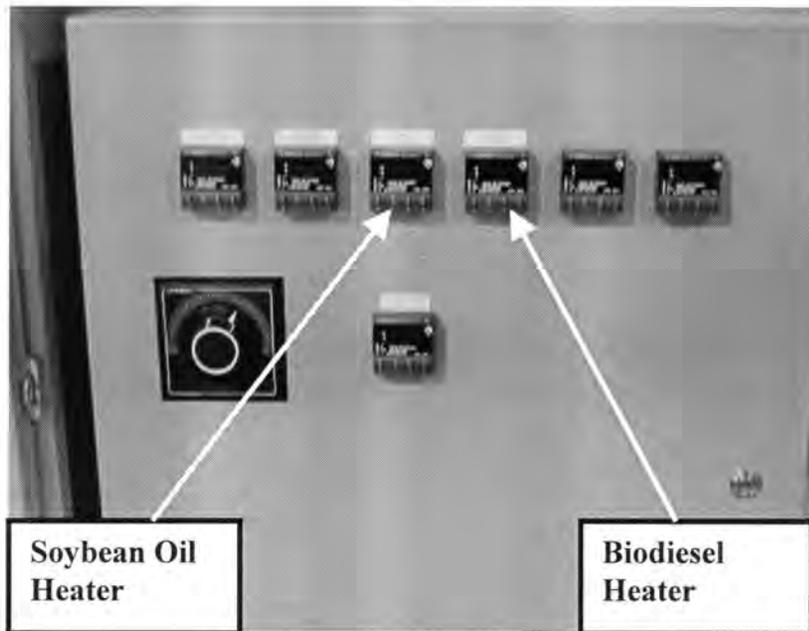


Figure 31 Dryer Control Cabinet (Omega Controllers)

There is an Omega controller for both the soybean oil and biodiesel side heaters. Each respective controller is labeled either “Soybean Oil Heater” or “Biodiesel Heater” for the corresponding position, see Figure 31. To set the Omega controllers, hold in the green “*” button on the bottom left hand side of the controller, while pushing the up and down green button arrows to raise or lower the temperature as desired. When finished set the temperature, release the green “*” button and the controller is now set.

NOTE: Set the temperature to the “Soybean Oil Heater” and “Biodiesel Heater” to 260 °F and leave it. It is recommended that the operator set the desired drying temperature at the paratherm/propylene glycol controls if possible. But if the paratherm/propylene glycol system is in use and set at a different temperature, then the “Soybean Oil Heater” and “Biodiesel Heater” controllers need to be used in order to control the temperature. Then set the temperature to 240 °F on the “Soybean Oil Heater” and “Biodiesel Heater” controllers. The reason it is recommend that the temperature be set on the paratherm/propylene glycol controls as opposed to the dryer system controls is because the paratherm/propylene glycol unit actually heats the heating fluid (propylene glycol) as opposed to the drying system controllers just controlling the fluid and not being able to heat up the propylene glycol.

Dryer System Warm-up

Procedure

1. Completely open ball valve #7 on the piping for the condenser (8), see Figure 32 for the condenser, ball valve and location.

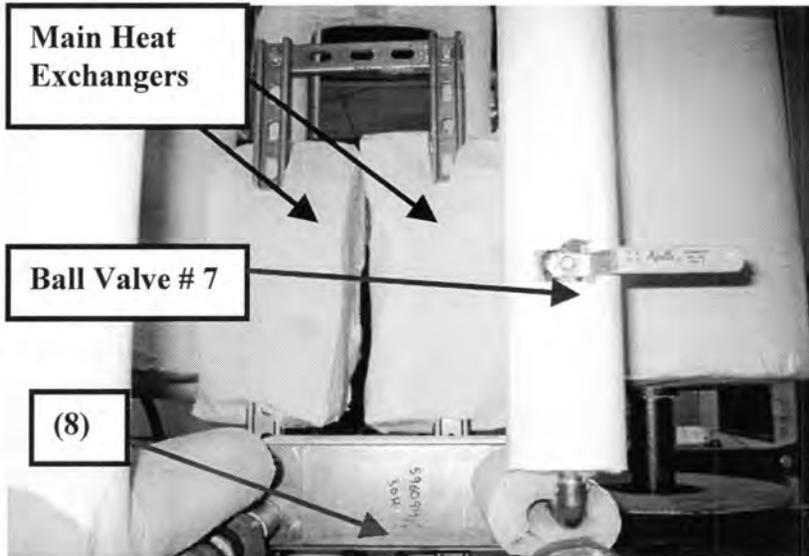


Figure 32 Vacuum Pump Condenser

The flow meter and ball valve are on the backside of the main heat exchangers, located in the center of the drying system structure.

2. Adjust the condenser water flow rate to 1 gallon per minute flow using the knob on the flow meter, see Figure 33.

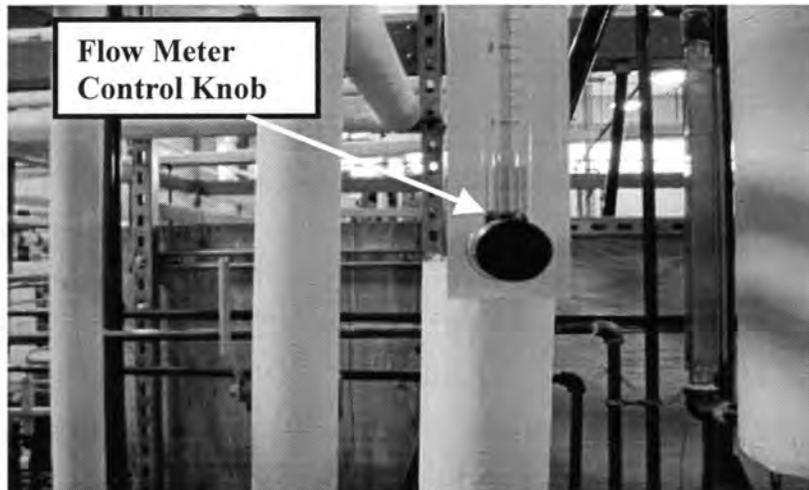


Figure 33 Flow Meter Control Knob

The flow rate will have to be adjusted again once the vacuum pump is turned on because it will take some of the water diverted into the condenser and flow meter. The flow rate is read by looking at the bottom edge of the metal float inside the flow meter.

3. Turn the “Vacuum Sump (Automatic)” switch located on the Dryer Control Cabinet (Variable Frequency Drive) to the “On” position, see Figure 34 for the switch label. The Dryer Control Cabinet (Variable Frequency Drive) can be seen in Figures 6 and 22.



Figure 34 Vacuum Sump Automatic Switch

NOTE: Failing to turn on the “Vacuum Sump (Automatic)” switch will result in water overflowing from the vacuum pump overflow container.

4. Push the “Start” button (See Figures 8 and 35) on the Vacuum Pump Control Cabinet, again double check that the vacuum pump is getting water before turning it on. The vacuum pump control cabinet is located to the right of the Dryer Control Cabinet (Omega Controllers).

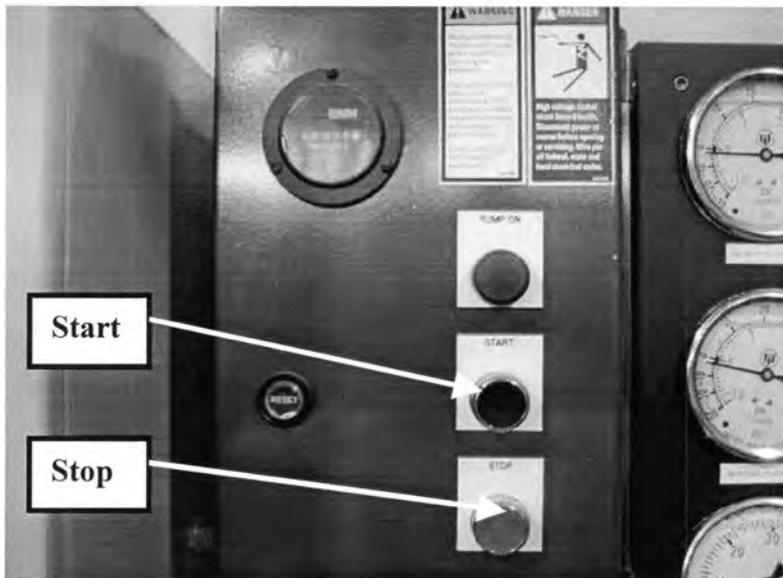


Figure 35 Vacuum Pump Control Cabinet

NOTE: It is important that the operator make sure that the vacuum pump is NOT cavitating; if it is then the bleed valve needs to be opened slightly to obtain the desired vacuum in the flash tanks. See Figure 36 for bleed valves and location. The bleed valves are located on the back side of the dryer system control panel, next to the wood panel.

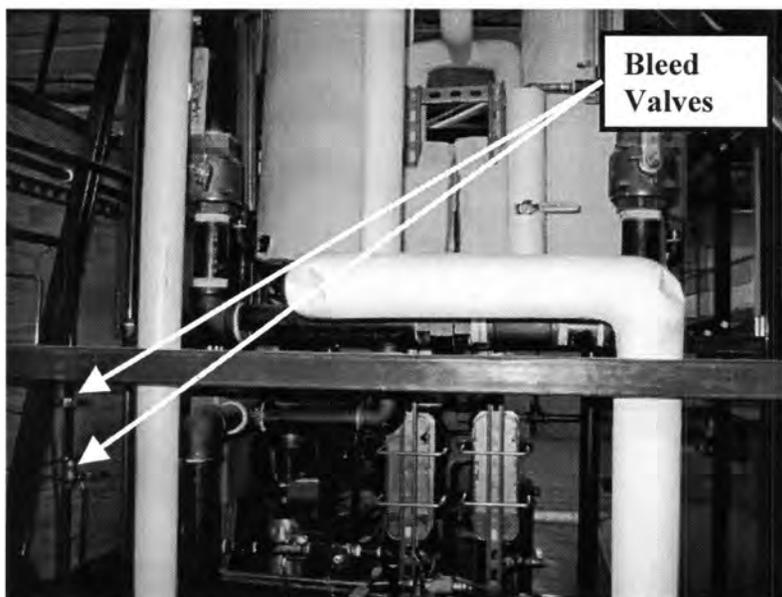


Figure 36 Bleed Valves

5. Open the large one inch ball valve (9) with the yellow handle on the bottom of the glycerin separation tank (see Figures 4 and 37), make sure the red handle sample ball valve (10) is closed on the glycerin separation tank, and also that the other red handle input ball valve (11) is open to the biodiesel drying side of the system.

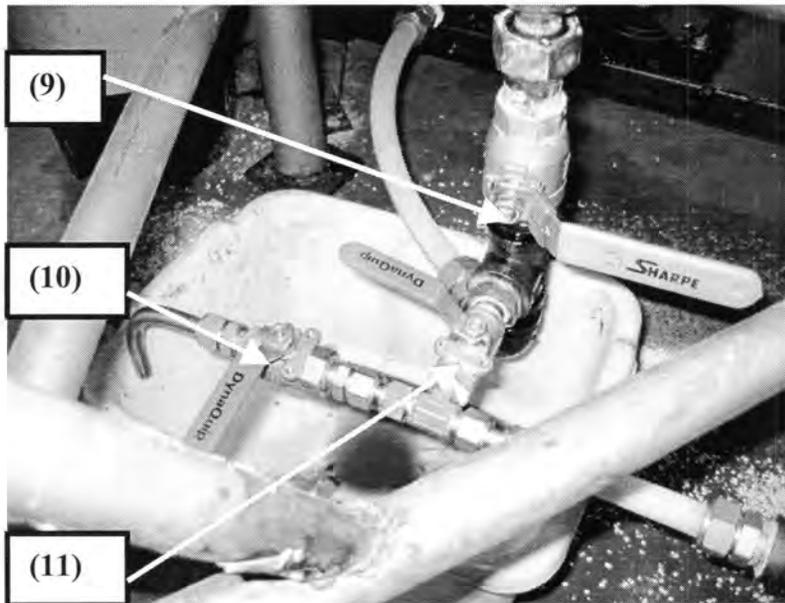


Figure 37 Ball Valves on the Glycerin Separation Tank

For the soybean oil drying system, make sure the yellow handle ball valve (12) on the staging tank is open, see Figure 38.

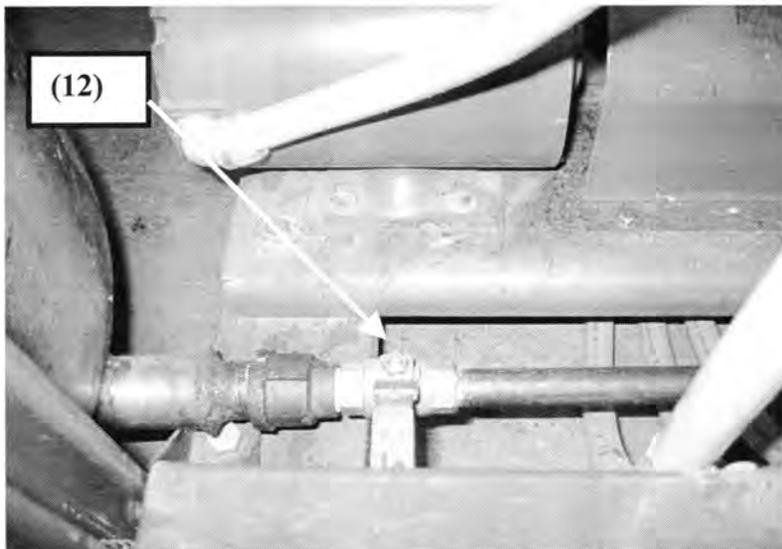


Figure 38 Staging Tank Ball Valve

Both systems do not have to be open at the same time, only the system or systems that are in operation need to be open.

6. Close the gate valve that allows the fluid in either the soybean oil (13) or biodiesel (14) drying systems to flow to their respective storage tanks (depends on which system the operator is using). Open the gate valve on the recirculation loop for either the soybean oil (15) or biodiesel (16) drying system; see Figure 39 for valves and locations. This will allow for the recirculation of the fluid and the warm up of the drying systems.

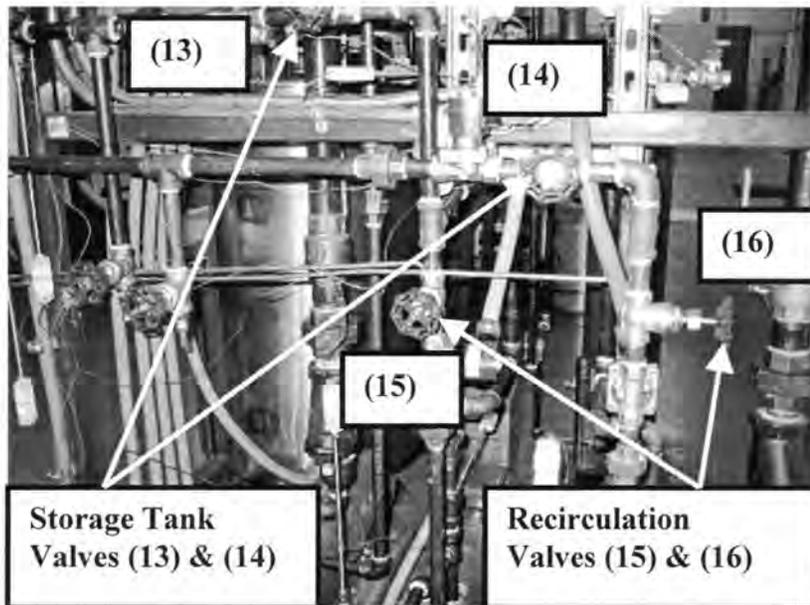


Figure 39 Recirculation/Storage Tank Valve Locations

7. Slowly rotate the Potentiometer (Figure 6) for either the “Soybean Oil” or “Biodiesel” (depending on what system the operator is using) until the gear pump (Figure 9) for the incoming fluid starts to turn, pump 2 for biodiesel and pump 3 for soybean oil. Then set the potentiometer to the desired speed for maintaining the level inside the flash tank, this depends on the ongoing flow rate of the dried fluid exiting the dryer to its respective storage tank. It is recommended that the level inside the flash tank be maintained at the lowest level possible, without causing the gear pump to run dry underneath the flash tank, pump 1 for the biodiesel and pump 4 for the soybean oil in Figure 9. If any of the four gear pumps starts to make a high-pitched noise it is running dry, which will cause the premature failure of the pump. The potentiometers are located on the Dryer Control Cabinet (Variable Frequency Drive), Figure 6.

8. Next turn on the switch for either the “Soybean Oil” (4) or “Biodiesel” (1) recirculation pump to the “On” position.

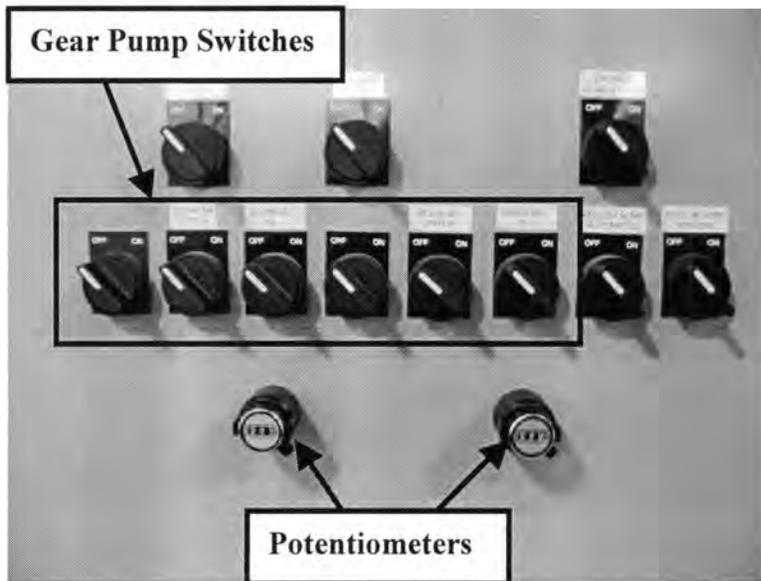


Figure 40 Gear Pump Switches

9. Turn the either the “Soybean Dryer 1” & “Soybean Dryer 2” or “Biodiesel Dryer 1” & “Biodiesel Dryer 2” switches to the “On” position.
10. Allow some 15 minutes for the fluid to fill the system and warm-up. Adjust the throttling valve on either the soybean oil or biodiesel drying system (depending on which system is being used by the operator) to the desired pressure.
11. Check for fluid leaks, and make sure the fluid in the flash tank sight glasses is not above the level of the fluid input into the flash tanks. If it is, adjust the potentiometers on the incoming gear pumps to reduce the fluid level inside the flash tank or to increase the level because the gear pump under the flash tank is running drying. Run the drying systems until the 15 minute warm-up time is reached and the drying system is then ready for steady state operation.

Steady State Operation

Procedure

1. Open the gate valves (see Figure 39, valves (13) and (14)) that directs the fluid to its respective storage tank. The operator has to set the flow rate on the outgoing flow by opening the gate valve the desired amount to obtain the required flow rate for the conditions the drying system is running at for moisture removal. The desired conditions to run the drying system at is 230-240 °F for the heater temperature, 28 inches of mercury for flash tank vacuum, 15-25 psig of throttling pressure, and 1-2 gallons per minute (gpm) for the condenser flow rate. It is also recommended that the operator keep the level in the flash tank as low as possible in order to maintain the largest amount of surface area for development of the thin film. See Figure 41 for sampling valve location.

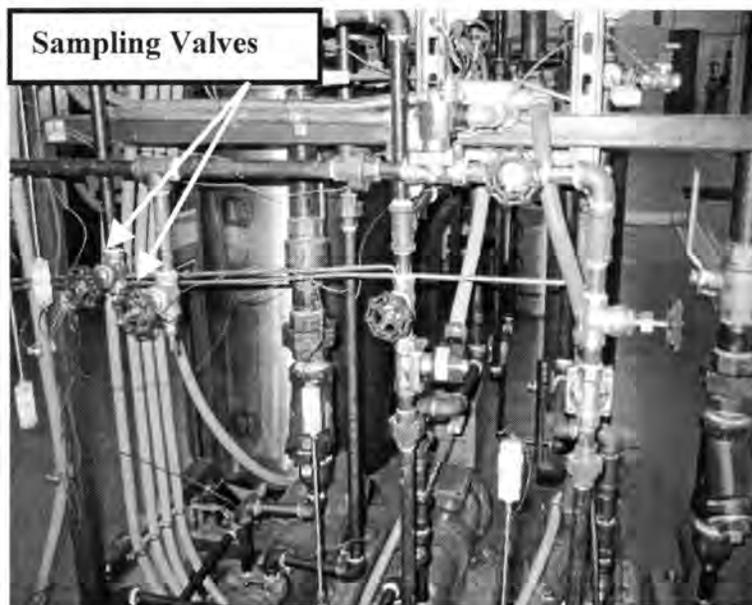


Figure 41 Sampling Valve Locations

The sampling valves can be used to set the flow rate of the dried fluid to the required storage tank. It is recommended that the operator run the system at around 0.5 gpm for maximum efficiency. (PART ABOUT DIFFERENT FLOW RATES FOR HIGHER MOISTURE LEVELS)

2. Close the gate valve for the recirculation loop, see Figure 39, valves (15) and (16). Make sure fluid starts to flow from the discharge pipe into the specified tank that is needed for each respective drying system.

NOTE: Future plans call for the use of a timer to control the solenoid valves for the warm up and steady state operations of the drying system. This will allow the

operator to use the timer to set the time required for warm up before steady state operation instead of using the gate valves for control.

3. Adjust the throttling pressure to 15-25 psig and check all other set points mentioned in step 1; tank level, vacuum pressure, condenser flow rate, and heater temperature. Make sure there are no leaks and the system is running error free.

NOTE: DO NOT let the gear pumps run dry, this will lead to pre-mature failure of the pumps.

4. Three things that the operator should always keep in mind during the steady state running of the drying system; make sure the level in the flash tanks does not get higher than the inlet to the flash tank. This can be monitored visually using the sight glasses (see Figure 42) on the sides of the flash tank. The level can be adjusted using the potentiometers (Figure 40) for the gear pumps.

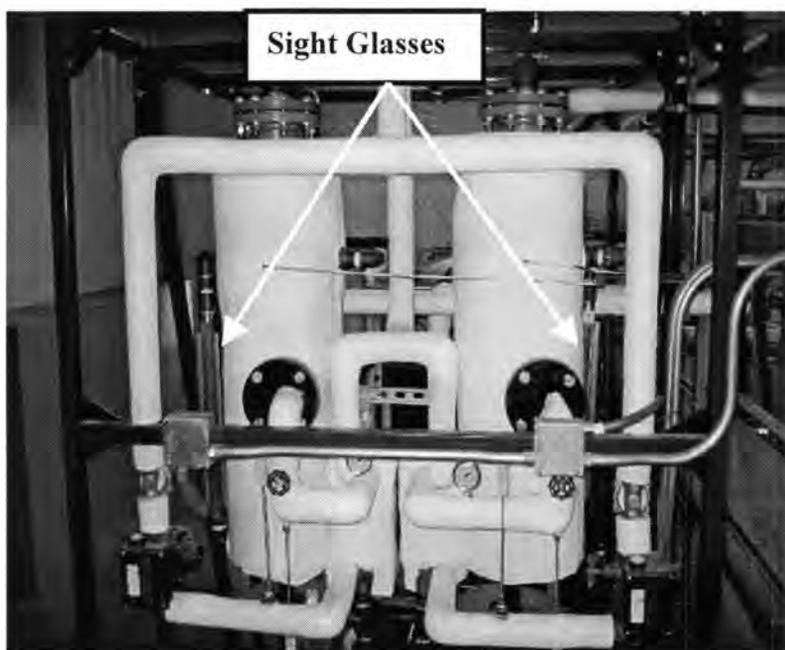


Figure 42 Sight Glasses on Flash Tanks

The operator should also be listening for cavitation of the vacuum pump, as described in step 4 of the “Dryer System Warm-up” section. If the vacuum pump starts to cavitate, the operator should open up the bleed valves (Figure 36). Finally, avoid running the gear pumps dry, this is tied into the level of the flash tank, to low a level and the gear pumps will run out of fluid to pump, hence damaging the pumps from running them dry.

Shut Down

Procedure

1. Turn the potentiometer knobs for the input gear pumps down to a slow rate, along with the recirculation gear pumps.
2. Either let the gear pumps drain out the last bit of fluid from their respective input tanks, or close the input valves on the incoming tanks and watch for the eventual trickle of the fluid into the discharge tanks. Then turn the “Soybean Oil” or “Biodiesel” switch to the “Off” position for the recirculation pumps. Then turn the potentiometers for either the “Soybean Oil” or Biodiesel” incoming fluid gear pumps to the lowest possible setting.

NOTE: Failing to reduce the speed on the gear pumps after either reaching the last bit of fluid in the incoming fluid tanks or closing the tanks valves can lead to potential damage of the gear pumps due to running them dry, especially at a high speed. The pumps can be run dry for a 10-15 seconds, but running them for sustained period dry will damage the pumps.

3. Push the “Stop” button (see Figure 35) on the vacuum pump.
3. Leave the “Vacuum Sump (Automatic)” switch in the “On” position until the vacuum pump overflow tank (see Figure 43) is emptied, then turn the switch to the “Off” position.

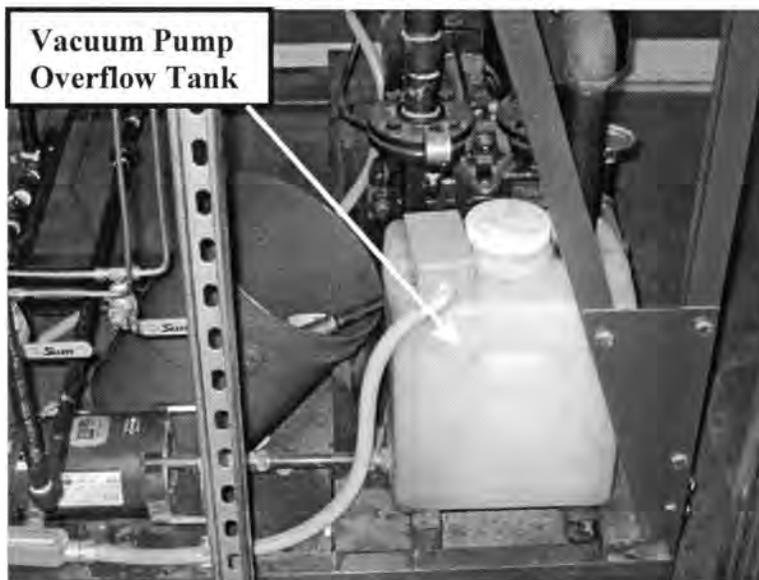


Figure 43 Vacuum Pump Overflow Tank

5. Turn either the “Soybean Dryer 1” & “Soybean Dryer 2” or “Biodiesel Dryer 1” & “Biodiesel Dryer 2” switches to the “Off” position.
6. Rotate the black 480V lever on the Dryer Control Cabinet (VFD’s) to the “Off” position. Turn the “Cabinet Exhaust Fan” switch to the “Off” position
7. Turn the switch located on the right of Paratherm/Propylene Glycol panel to the “Pump” position.
8. Push the rocker switch on the Paratherm/Propylene Glycol heat exchanger pump to the “Off” position.

NOTE: Allow the Paratherm/Propylene Glycol heat exchanger pump to recirculate for a while before turning the Paratherm/Propylene Glycol panel switch to the “Off” position.

9. Turn the switch located on the right of Paratherm/Propylene Glycol panel to the “Off” position.

NOTE: Allow the Paratherm/Propylene Glycol unit to stay in the “Pump” position for a while before turning off. This will allow for some cool down of the fluid.

Appendix B

Raw Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3049	0.3189	0.3119	Initial		0.2998	0.3256	0.3127
1	2	0.0339	0.0342	0.0341	1	2	0.0329	0.0368	0.0349
2	4	0.0404	0.0399	0.0402	2	4	0.0411	0.0426	0.0419
3	6	0.0401	0.0409	0.0405	3	6	0.0403	0.0409	0.0406
4	8	0.0405	0.0416	0.0411	4	8	0.0400	0.0413	0.0407
5	10	0.0414	0.0423	0.0419	5	10	0.0413	0.0405	0.0409
6	12	0.0412	0.0417	0.0415	6	12	0.0416	0.0426	0.0421
Vac. (inHg)	28				Vac. (inHg)	28			
Temp. (F)	220				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	1				Cond. (GPM)	1			
Flow (GPM)	0.456				Flow (GPM)	0.456			

Repeatability Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.2998	0.3256	0.3127	Initial		0.2998	0.3256	0.3127
1	2	0.0319	0.0322	0.0321	1	2	0.0329	0.0368	0.0349
2	4	0.0377	0.0366	0.0371	2	4	0.0411	0.0426	0.0419
3	6	0.0384	0.0388	0.0386	3	6	0.0403	0.0409	0.0406
4	8	0.0389	0.0391	0.0390	4	8	0.0400	0.0413	0.0407
5	10	0.0392	0.0388	0.0390	5	10	0.0413	0.0405	0.0409
6	12	0.0392	0.0395	0.0394	6	12	0.0416	0.0426	0.0421
Vac. (inHg)	28				Vac. (inHg)	28			
Temp. (F)	220				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	1				Cond. (GPM)	1			
Flow (GPM)	0.325				Flow (GPM)	0.456			

Biodiesel Continuous Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.4236	0.4496	0.4366	Initial		0.4236	0.4496	0.4366
1	2	0.0388	0.0396	0.0392	1	2	0.0358	0.0363	0.0361
2	4	0.0452	0.0455	0.0454	2	4	0.0489	0.0493	0.0491
3	6	0.0443	0.0437	0.0440	3	6	0.0521	0.0542	0.0532
4	8	0.0442	0.0456	0.0449	4	8	0.0519	0.0527	0.0523
5	10	0.0424	0.0434	0.0429	5	10	0.0529	0.0536	0.0532
6	12	0.0449	0.0466	0.0458	6	12	0.0538	0.0533	0.0536
Vac. (inHg)	28				Vac. (inHg)	28			
Temp. (F)	220				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	1				Cond. (GPM)	1			
Flow (GPM)	0.425				Flow (GPM)	0.531			

Biodiesel Continuous Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.5989	0.5653	0.5821	Initial		0.5989	0.5653	0.5821
1	2	0.0301	0.0336	0.0319	1	2	0.0387	0.0377	0.0382
2	4	0.0573	0.0585	0.0579	2	4	0.0603	0.0601	0.0602
3	6	0.0581	0.0576	0.0579	3	6	0.0740	0.0736	0.0738
4	8	0.0589	0.0591	0.0590	4	8	0.0715	0.0722	0.0719
5	10	0.0585	0.0593	0.0589	5	10	0.0738	0.0733	0.0736
6	12	0.0606	0.0596	0.0601	6	12	0.0722	0.0725	0.0724
Vac. (inHg)	28				Vac. (inHg)	28			
Temp. (F)	220				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	1				Cond. (GPM)	1			
Flow (GPM)	0.976				Flow (GPM)	1.13			

Biodiesel Continuous Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.2998	0.3256	0.3127	Initial		0.2998	0.3256	0.3127
1	2	0.0381	0.0373	0.0377	1	2	0.0391	0.0389	0.0390
2	4	0.0469	0.0473	0.0471	2	4	0.0519	0.0507	0.0513
3	6	0.0493	0.0506	0.0500	3	6	0.0536	0.0525	0.0531
4	8	0.0489	0.0496	0.0493	4	8	0.0563	0.0559	0.0561
5	10	0.0492	0.0509	0.0501	5	10	0.0581	0.0550	0.0566
6	12	0.0503	0.0504	0.0504	6	12	0.0578	0.0574	0.0576
Vac. (inHg)	28				Vac. (inHg)	28			
Temp. (F)	220				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	1				Cond. (GPM)	1			
Flow (GPM)	0.578				Flow (GPM)	0.743			

Biodiesel Continuous Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.4236	0.4496	0.4366	Initial		0.5989	0.5653	0.5821
1	2	0.0376	0.0389	0.0383	1	2	0.0365	0.0378	0.0372
2	4	0.0546	0.0537	0.0542	2	4	0.0712	0.0723	0.0718
3	6	0.0563	0.0571	0.0567	3	6	0.0843	0.0849	0.0846
4	8	0.0581	0.0579	0.0580	4	8	0.0829	0.0822	0.0826
5	10	0.0591	0.0599	0.0595	5	10	0.0819	0.0827	0.0823
6	12	0.0594	0.0596	0.0595	6	12	0.0811	0.0819	0.0815
Vac. (inHg)	28				Vac. (inHg)	28			
Temp. (F)	220				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	1				Cond. (GPM)	1			
Flow (GPM)	0.682				Flow (GPM)	1.76			

Biodiesel Continuous Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.2998	0.3256	0.3127		Initial	0.2998	0.3256	0.3127
1	2	0.0279	0.0284	0.0282		1	0.0329	0.0336	0.0333
2	4	0.0323	0.0328	0.0326		2	0.0389	0.0394	0.0392
3	6	0.0338	0.0343	0.0341		3	0.0403	0.0409	0.0406
4	8	0.0352	0.0358	0.0355		4	0.0419	0.0413	0.0416
5	10	0.0357	0.0349	0.0353		5	0.0413	0.0406	0.0410
6	12	0.0355	0.0361	0.0358		6	0.0411	0.0417	0.0414
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	240					Temp. (F)	220		
Throttling	0.25	15	psig			Throttling	0.25	15	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	0.325					Flow (GPM)	0.325		

Temperature Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3036	0.3156	0.3096		Initial	0.3036	0.3156	0.3096
1	2	0.0412	0.0415	0.0414		1	0.0573	0.0566	0.0570
2	4	0.0487	0.0499	0.0493		2	0.0619	0.0623	0.0621
3	6	0.0512	0.0520	0.0516		3	0.0642	0.0649	0.0646
4	8	0.0543	0.0556	0.0550		4	0.0689	0.0692	0.0691
5	10	0.0559	0.0549	0.0554		5	0.0699	0.0704	0.0702
6	12	0.0563	0.0555	0.0559		6	0.0706	0.0709	0.0708
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	200					Temp. (F)	180		
Throttling	0.25	15	psig			Throttling	0.25	15	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	0.325					Flow (GPM)	0.325		

Temperature Data

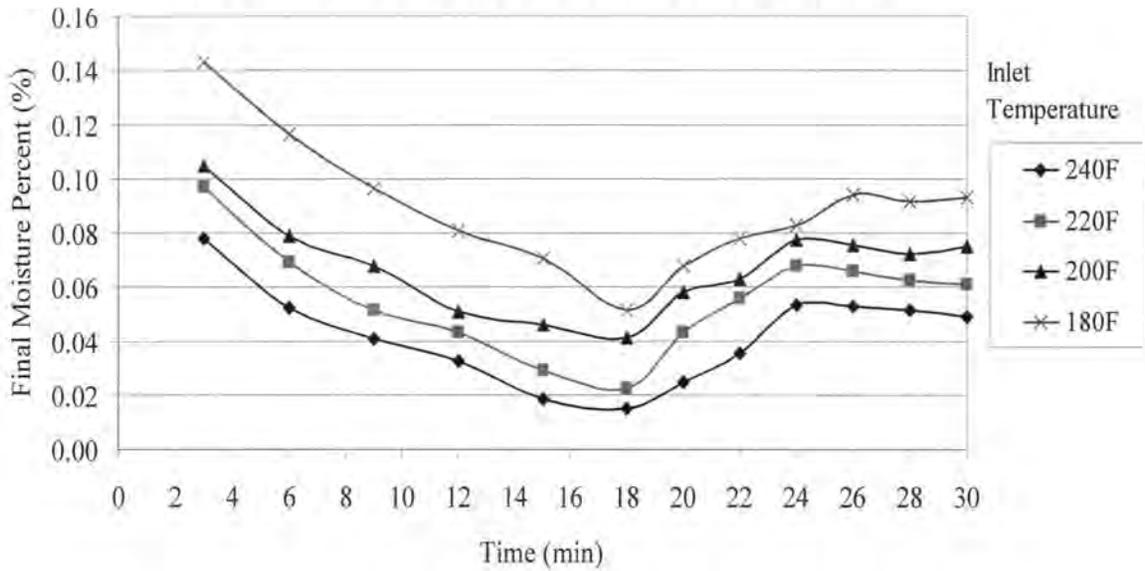
	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3159	0.3248	0.3204		Initial	0.2826	0.2989	0.2908
1	3	0.0452	0.0456	0.0454		1	0.0541	0.0545	0.0543
2	4	0.0356	0.0364	0.0360		2	0.0460	0.0473	0.0467
3	5	0.0326	0.0329	0.0328		3	0.0427	0.0438	0.0433
4	6	0.0293	0.0298	0.0296		4	0.0385	0.0391	0.0388
5	8	0.0256	0.0264	0.0260		5	0.0322	0.0393	0.0358
6	10	0.0156	0.0163	0.0160		6	0.0238	0.0253	0.0246
7	12.5	0.0125	0.0105	0.0115		7	0.0175	0.0173	0.0174
8	15	0.0098	0.0100	0.0099		8	0.0149	0.0141	0.0145
9	18	0.0104	0.0089	0.0097		9	0.0131	0.0135	0.0133
10	21	0.0216	0.0227	0.0222		10	0.0341	0.0356	0.0349
11	23	0.0298	0.0303	0.0301		11	0.0466	0.0468	0.0467
12	25	0.0418	0.0436	0.0427		12	0.0528	0.0548	0.0538
13	27	0.0425	0.0429	0.0427		13	0.0523	0.0528	0.0526
14	28.5	0.0438	0.0439	0.0439		14	0.0568	0.0578	0.0573
15	30	0.0437	0.0448	0.0442		15	0.0556	0.0560	0.0558
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	240					Temp. (F)	220		
Throttling	0.25	15	psig			Throttling	0.25	15	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	0.44					Flow (GPM)	0.44		

28 inHg Vacuum Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3178	0.3187	0.3183		Initial	0.2997	0.3180	0.3089
1	3	0.0846	0.0858	0.0852		1	0.1198	0.1206	0.1202
2	4	0.0739	0.0738	0.0739		2	0.1051	0.1001	0.1026
3	5	0.0608	0.0619	0.0614		3	0.0960	0.0979	0.0970
4	6	0.0554	0.0536	0.0545		4	0.0864	0.0856	0.0860
5	8	0.0504	0.0513	0.0509		5	0.0790	0.0759	0.0775
6	10	0.0457	0.0439	0.0448		6	0.0701	0.0697	0.0699
7	12.5	0.0401	0.0415	0.0408		7	0.0649	0.0653	0.0651
8	15	0.0305	0.0310	0.0308		8	0.0529	0.0519	0.0524
9	18	0.0328	0.0336	0.0332		9	0.0506	0.0495	0.0501
10	21	0.0563	0.0589	0.0576		10	0.0812	0.0823	0.0818
11	23	0.0672	0.0643	0.0658		11	0.0997	0.1003	0.1000
12	25	0.0571	0.0623	0.0647		12	0.0938	0.0959	0.0949
13	27	0.0689	0.0669	0.0679		13	0.0972	0.0989	0.0981
14	28.5	0.0693	0.0674	0.0684		14	0.0929	0.0919	0.0924
15	30	0.0656	0.0679	0.0668		15	0.0956	0.0973	0.0965
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	200					Temp. (F)	180		
Throttling	0.25	15	psig			Throttling	0.25	15	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	0.44					Flow (GPM)	0.44		

28 inHg Vacuum Data

26 inHg of Vacuum (26.75 inHg corrected), 15 psig of Throttling Pressure
 1 gpm Condenser Flow Rate, 0.3% Initial Moisture, 0.44 gpm Through-put



26 inHg Vacuum Graph

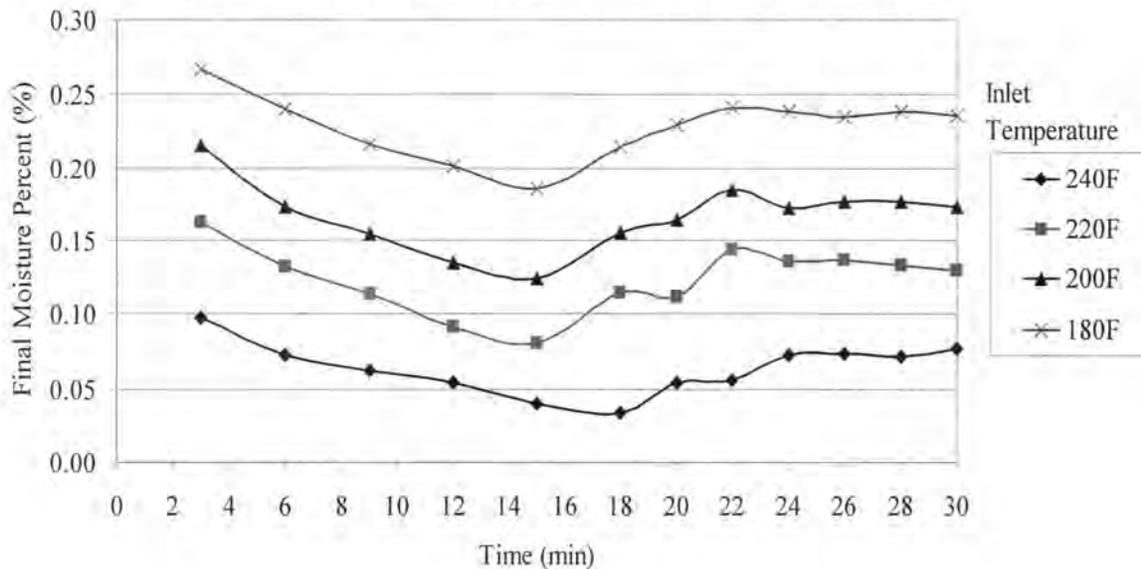
Initial	Time (min.)	First	Second	Average	Initial	Time (min.)	First	Second	Average
		0.2933	0.3008	0.2971			0.3139	0.3102	0.3121
1	3	0.0795	0.0767	0.0781	1	3	0.0963	0.0976	0.0970
2	6	0.0508	0.0538	0.0523	2	6	0.0703	0.0681	0.0692
3	9	0.0404	0.0413	0.0409	3	9	0.0519	0.0506	0.0513
4	12	0.0328	0.0319	0.0324	4	12	0.0429	0.0432	0.0431
5	15	0.0186	0.0187	0.0187	5	15	0.0286	0.0293	0.0290
6	18	0.0158	0.0143	0.0151	6	18	0.0227	0.0223	0.0225
7	20	0.0246	0.0253	0.0250	7	20	0.0431	0.0429	0.0430
8	22	0.0359	0.0348	0.0354	8	22	0.0553	0.0564	0.0559
9	24	0.0538	0.0532	0.0535	9	24	0.0682	0.0676	0.0679
10	26	0.0535	0.0525	0.0530	10	26	0.0667	0.0653	0.0660
11	28	0.0510	0.0515	0.0513	11	28	0.0624	0.0629	0.0627
12	30	0.0493	0.0486	0.0490	12	30	0.0614	0.0609	0.0612
Vac. (inHg)	26				Vac. (inHg)	26			
Temp. (F)	240				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	1				Cond. (GPM)	1			
Flow (GPM)	0.44				Flow (GPM)	0.44			

26 inHg Vacuum Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3157	0.3103	0.3130	Initial		0.3106	0.3086	0.3096
1	3	0.1090	0.1003	0.1047	1	3	0.1421	0.1436	0.1429
2	6	0.0795	0.0789	0.0792	2	6	0.1176	0.1156	0.1166
3	9	0.0680	0.0676	0.0678	3	9	0.0938	0.0989	0.0964
4	12	0.0505	0.0512	0.0509	4	12	0.0801	0.0823	0.0812
5	15	0.0465	0.0454	0.0460	5	15	0.0706	0.0708	0.0707
6	18	0.0407	0.0413	0.0410	6	18	0.0507	0.0523	0.0515
7	20	0.0578	0.0590	0.0584	7	20	0.0676	0.0683	0.0680
8	22	0.0626	0.0633	0.0630	8	22	0.0773	0.0793	0.0783
9	24	0.0783	0.0765	0.0774	9	24	0.0834	0.0821	0.0828
10	26	0.0709	0.0799	0.0754	10	26	0.0929	0.0949	0.0939
11	28	0.0716	0.0726	0.0721	11	28	0.0913	0.0919	0.0916
12	30	0.0747	0.0756	0.0752	12	30	0.0929	0.0936	0.0933
Vac. (inHg)	26				Vac. (inHg)	26			
Temp. (F)	200				Temp. (F)	180			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	1				Cond. (GPM)	1			
Flow (GPM)	0.44				Flow (GPM)	0.44			

26 inHg Vacuum Data

24 inHg of Vacuum (24.9 inHg corrected), 15 psig of Throttling Pressure
 1 gpm Condenser Flow Rate, 0.3% Initial Moisture, 0.44 gpm Through-put



24 inHg Vacuum Graph

	Time (min.)	First	Second	Average		Initial	Time (min.)	First	Second	Average
Initial		0.3062	0.3063	0.3063		Initial		0.2958	0.3065	0.3012
1	3	0.0983	0.0977	0.0980		1	3	0.1608	0.1640	0.1624
2	6	0.0716	0.0731	0.0724		2	6	0.1330	0.1317	0.1324
3	9	0.0624	0.0619	0.0622		3	9	0.1136	0.1139	0.1138
4	12	0.0548	0.0535	0.0542		4	12	0.0919	0.0903	0.0911
5	15	0.0386	0.0404	0.0395		5	15	0.0813	0.0808	0.0811
6	18	0.0338	0.0343	0.0341		6	18	0.1141	0.1156	0.1149
7	20	0.0545	0.0533	0.0539		7	20	0.1123	0.1105	0.1114
8	22	0.0569	0.0568	0.0564		8	22	0.1441	0.1429	0.1435
9	24	0.0729	0.0733	0.0731		9	24	0.1315	0.1397	0.1366
10	26	0.0739	0.0727	0.0733		10	26	0.1357	0.1376	0.1367
11	28	0.0718	0.0724	0.0721		11	28	0.1343	0.1326	0.1335
12	30	0.0793	0.0756	0.0775		12	30	0.1295	0.1302	0.1299
Vac. (inHg)	24					Vac. (inHg)	24			
Temp. (F)	240					Temp. (F)	220			
Throttling	0.25	15	psig			Throttling	0.25	15	psig	
Cond. (GPM)	1					Cond. (GPM)	1			
Flow (GPM)	0.44					Flow (GPM)	0.44			

24 inHg Vacuum Data

	Time (min.)	First	Second	Average		Initial	Time (min.)	First	Second	Average
Initial		0.3056	0.3089	0.3073		Initial		0.2993	0.2845	0.2919
1	3	0.2160	0.2149	0.2155		1	3	0.2664	0.2673	0.2669
2	6	0.1723	0.1736	0.1730		2	6	0.2397	0.2405	0.2401
3	9	0.1549	0.1541	0.1545		3	9	0.2167	0.2173	0.2170
4	12	0.1366	0.1349	0.1353		4	12	0.2013	0.2023	0.2018
5	15	0.1234	0.1256	0.1245		5	15	0.1862	0.1856	0.1859
6	18	0.1549	0.1554	0.1552		6	18	0.2146	0.2143	0.2145
7	20	0.1649	0.1643	0.1646		7	20	0.2298	0.2306	0.2302
8	22	0.1847	0.1837	0.1842		8	22	0.2420	0.2413	0.2417
9	24	0.1723	0.1729	0.1726		9	24	0.2379	0.2388	0.2384
10	26	0.1767	0.1762	0.1765		10	26	0.2359	0.2354	0.2357
11	28	0.1763	0.1771	0.1767		11	28	0.2389	0.2379	0.2384
12	30	0.1721	0.1738	0.1730		12	30	0.2356	0.2363	0.2360
Vac. (inHg)	24					Vac. (inHg)	24			
Temp. (F)	200					Temp. (F)	180			
Throttling	0.25	15	psig			Throttling	0.25	15	psig	
Cond. (GPM)	1					Cond. (GPM)	1			
Flow (GPM)	0.44					Flow (GPM)	0.44			

24 inHg Vacuum Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3175	0.3168	0.3172	Initial		0.3296	0.3159	0.3227
1	2	0.0463	0.0455	0.0459	1	2	0.0412	0.0423	0.0418
2	4	0.0478	0.0472	0.0475	2	4	0.0459	0.0463	0.0461
3	6	0.0502	0.0498	0.0500	3	6	0.0435	0.0433	0.0434
4	8	0.0529	0.0505	0.0517	4	8	0.0419	0.0428	0.0424
5	10	0.0538	0.0530	0.0534	5	10	0.0423	0.0419	0.0421
6	12	0.0535	0.0539	0.0537	6	12	0.0433	0.0429	0.0431
Vac. (inHg)	28				Vac. (inHg)	28			
Temp. (F)	220				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	0				Cond. (GPM)	1			
Flow (GPM)	0.425				Flow (GPM)	0.425			

Condenser Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3296	0.3159	0.3227	Initial		0.3274	0.3378	0.3326
1	2	0.0436	0.0441	0.0439	1	2	0.0433	0.0429	0.0431
2	4	0.0429	0.0422	0.0426	2	4	0.0477	0.0470	0.0474
3	6	0.0479	0.0467	0.0473	3	6	0.0463	0.0456	0.0460
4	8	0.0443	0.0455	0.0449	4	8	0.0451	0.0448	0.0450
5	10	0.0416	0.0421	0.0419	5	10	0.0416	0.0426	0.0421
6	12	0.0422	0.0425	0.0424	6	12	0.0456	0.0451	0.0454
Vac. (inHg)	28				Vac. (inHg)	28			
Temp. (F)	220				Temp. (F)	220			
Throttling	0.25	15	psig		Throttling	0.25	15	psig	
Cond. (GPM)	2				Cond. (GPM)	3			
Flow (GPM)	0.425				Flow (GPM)	0.425			

Condenser Flow Data

No Mixing					Mixing				
		First	Second	Average			First	Second	Average
Bottom	1	0.2777	0.2775	0.2776	Bottom	1	0.2754	0.2703	0.2729
	2	0.2831	0.2800	0.2816		2	0.2891	0.2636	0.2764
	3	0.2634	0.2751	0.2693		3	0.2726	0.2812	0.2769
	4	0.2819	0.2659	0.2739		4	0.2657	0.2752	0.2705
	5	0.2635	0.2724	0.2680		5	0.2589	0.2793	0.2691
	6	0.2611	0.2744	0.2678		6	0.2783	0.2643	0.2713
	7	0.2603	0.2733	0.2668		7	0.2569	0.2806	0.2688
Top	8	0.2678	0.2609	0.2644	Top	8	0.2665	0.2719	0.2692

Glycerol Separation Tank Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3256	0.3198	0.3227		Initial	0.3256	0.3198	0.3227
1	2	0.0348	0.0344	0.0346		1	0.0356	0.0364	0.0360
2	4	0.0429	0.0423	0.0426		2	0.0448	0.0453	0.0451
3	6	0.0439	0.0444	0.0442		3	0.0468	0.0473	0.0471
4	8	0.0448	0.0458	0.0453		4	0.0471	0.0477	0.0474
5	10	0.0468	0.0462	0.0465		5	0.0472	0.0481	0.0477
6	12	0.0455	0.0461	0.0458		6	0.0475	0.0479	0.0477
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	220					Temp. (F)	220		
Throttling	0.25	25	psig			Throttling	0.25	20	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	1.03					Flow (GPM)	1.03		

Throttle Pressure Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.3343	0.3374	0.3359		Initial	0.3343	0.3374	0.3359
1	2	0.0391	0.0385	0.0388		1	0.0394	0.0401	0.0398
2	4	0.0493	0.0498	0.0496		2	0.0562	0.0553	0.0558
3	6	0.0511	0.0518	0.0515		3	0.0594	0.0601	0.0598
4	8	0.0533	0.0545	0.0539		4	0.0619	0.0611	0.0615
5	10	0.0532	0.0549	0.0541		5	0.0587	0.0592	0.0590
6	12	0.0538	0.0544	0.0541		6	0.0603	0.0613	0.0608
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	220					Temp. (F)	220		
Throttling	0.25	10	psig			Throttling	0.25	5	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	1.03					Flow (GPM)	1.03		

Throttle Pressure Data

	Time (min.)	First	Second	Average
Initial		0.2998	0.3256	0.3127
1	2	0.0381	0.0373	0.0377
2	4	0.0469	0.0473	0.0471
3	6	0.0493	0.0506	0.0500
4	8	0.0489	0.0496	0.0493
5	10	0.0492	0.0509	0.0501
6	12	0.0503	0.0504	0.0504
Vac. (inHg)	28			
Temp. (F)	220			
Throttling	0.25	15	psig	
Cond. (GPM)	1			
Flow (GPM)	1.03			

Throttle Pressure Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.2378	0.2356	0.2367		Initial	0.2378	0.2356	0.2367
1	2	0.0611	0.0629	0.0620		1	0.0656	0.0646	0.0651
2	4	0.0638	0.0642	0.0640		2	0.0698	0.0689	0.0694
3	6	0.0626	0.0619	0.0623		3	0.0678	0.0683	0.0681
4	8	0.0636	0.0633	0.0635		4	0.0703	0.0696	0.0700
5	10	0.0642	0.0653	0.0648		5	0.0692	0.0709	0.0701
6	12	0.0628	0.0639	0.0634		6	0.0703	0.0704	0.0704
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	220					Temp. (F)	220		
Throttling	0.25	15	psig			Throttling	0.25	15	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	0.538					Flow (GPM)	0.624		

Soybean Oil Continuous Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.5568	0.5679	0.5624		Initial	0.5568	0.5679	0.5624
1	2	0.0631	0.0639	0.0635		1	0.0654	0.0649	0.0652
2	4	0.0743	0.0749	0.0746		2	0.0798	0.0803	0.0801
3	6	0.0755	0.0759	0.0757		3	0.0816	0.0812	0.0814
4	8	0.0767	0.0763	0.0765		4	0.0823	0.0825	0.0824
5	10	0.0769	0.0772	0.0771		5	0.0836	0.0843	0.0840
6	12	0.0771	0.0767	0.0769		6	0.0841	0.0852	0.0847
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	220					Temp. (F)	220		
Throttling	0.25	15	psig			Throttling	0.25	15	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	0.489					Flow (GPM)	0.634		

Soybean Oil Continuous Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.2378	0.2356	0.2367		Initial	0.9196	0.9273	0.9235
1	2	0.0671	0.0659	0.0665		1	0.0649	0.0653	0.0651
2	4	0.0729	0.0717	0.0723		2	0.0925		0.0925
3	6	0.0739	0.0743	0.0741		3	0.0989		0.0989
4	8	0.0759	0.0762	0.0761		4	0.1022		0.1022
5	10	0.0763	0.0757	0.0760		5	0.1013		0.1013
6	12	0.0768	0.0774	0.0771		6	0.1016		0.1016
Vac. (inHg)	28					Vac. (inHg)	28		
Temp. (F)	220					Temp. (F)	220		
Throttling	0.25	15	psig			Throttling	0.25	15	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	0.78					Flow (GPM)	0.683		

Soybean Oil Continuous Flow Data

	Time (min.)	First	Second	Average
Initial		0.5568	0.5679	0.5624
1	2	0.0653	0.0665	0.0659
2	4	0.0843	0.0852	0.0848
3	6	0.0869	0.0871	0.0870
4	8	0.0879	0.0878	0.0879
5	10	0.0869	0.0875	0.0872
6	12	0.0889	0.0867	0.0878
Vac. (inHg)	28			
Temp. (F)	220			
Throttling	0.25	15	psig	
Cond. (GPM)	1			
Flow (GPM)	0.78			

Soybean Oil Continuous Flow Data

	Time (min.)	First	Second	Average		Time (min.)	First	Second	Average
Initial		0.2998	0.3256	0.3127		Initial	0.2998	0.3256	0.3127
1	2	0.0381	0.0373	0.0377		1	0.0589	0.0578	0.0584
2	4	0.0469	0.0473	0.0471		2	0.0647	0.0656	0.0652
3	6	0.0493	0.0506	0.0500		3	0.0711	0.0709	0.0710
4	8	0.0489	0.0496	0.0493		4	0.0718	0.0723	0.0721
5	10	0.0492	0.0509	0.0501		5	0.0728	0.0729	0.0729
6	12	0.0503	0.0504	0.0504		6	0.0731	0.0736	0.0734
Vac. (inHg)	28					Vac. (inHg)	26		
Temp. (F)	220					Temp. (F)	220		
Throttling	0.25	15	psig			Throttling	0.25	15	psig
Cond. (GPM)	1					Cond. (GPM)	1		
Flow (GPM)	0.578					Flow (GPM)	0.578		

Vacuum Pressure Data

	Time (min.)	First	Second	Average
Initial		0.2998	0.3256	0.3127
1	2	0.0989	0.0991	0.0990
2	4	0.1153	0.1143	0.1148
3	6	0.1267	0.1258	0.1263
4	8	0.1346	0.1339	0.1343
5	10	0.1348	0.1355	0.1352
6	12	0.1359	0.1351	0.1355
Vac. (inHg)	24			
Temp. (F)	220			
Throttling	0.25	15	psig	
Cond. (GPM)	1			
Flow (GPM)	0.578			

Vacuum Pressure Data

Appendix C

Engineering Equation Solver Program

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{Kirk Menges}
{Biodiesel Pilot Plant Dryer}
{Assumptions: T_3 = T_2, P_3 = P_2}

{Mass Balance}
{mdot_so1 = mdot_so2 }
{mdot_so = mdot_so2}
{mdotH2O_1 = mdotH2O_2 + mdotH2O_3}

{Energy Balance}
{0 = mdot_so(h_so1 - h_so2) + mdotH2O_1*h_H2O_1 - mdotH2O_2*h_H2O_2 -
mdotH2O_3*h_H2O_3}

{Substitution}
{y_1 = mdotH2O_1/mdot_so}
{y_2 = mdotH2O_2/mdot_so}
{h_H2O_1 = Hy}
{h_H2O_2 = Hx}
{h_H2O_3 = Hz}

{Cp_SO = Specific Heat of Water, Btu/lb F }
Cp_SO=0.55

{T = Fluid Temperature before Flash Tank, degrees Fahrenheit }
T_1 = 220

{Pressure, psia}
P_1 =29.6
y_1 = 0.0030 {Biodiesel Moisture}
{y_1 = 0.0150 {Soybean Oil Moisture}}
Hx = ENTHALPY(WATER,T = T_3, x = 0.)
Hy = ENTHALPY(WATER,T = T_1, P = P_1)
Hz = ENTHALPY(STEAM,T = T_3, P = P_2)
Cp_SO*(T_1 - T_3) = y_1*(Hx - Hy) + y_2*(Hz - Hx)
P_2 = xH2O_3*Pg
P_atm = 14.2
P_gauge = P_atm - P_2
P2 = P_gauge*CONVERT(psi,inHg)
Pg = PRESSURE(WATER, T = T_3, x = 0.5)
xH2O_3 = (y_1 - y_2)/(y_1 - y_2+(18/300))
{Note: 18 is MW of Water}
{Note: 880 is MW of soybean oil}
{Note: 300 is MW of Biodiesel}
y_3 = y_1 - y_2
Res_H2O = y_3*100.

```