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NORTHERN ARIZONA UNIVERSITY

Separation of Oil from Water

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Abstract

Industrial processes that involve the extraction of crude oil, create emulsions which contain microscopic oil particles dispersed throughout water. These contaminants need to be removed from the water before being reused in other processes.

The problem is that the microscopic, emulsified, oil particles are so tiny that they will not separate from water over time. Increasing the size of the oil droplets will cause them to coalesce into larger oil particles that are easier to recover as they rise and collect on the surface of the water.

The purpose of this task is to design a water treatment system that is able to separate emulsified oil from a brackish (slightly salty) oil-in-water emulsion. H2Oleum's objective for this project is to design a solution that will recover as much oil as possible from the water by creating a high degree of separation between the two liquids.

The report will outline H2Oleum's proposed design solution that is able to recover 0.234 kg/m^2 of emulsified oil from a brackish water stream in under 50 minutes. This design is limited by the initial oil concentration in the water stream, 200 mg/L, and will be more effective with higher oil concentrations and lower oil densities.

Particular systems that H2Oleum considered were chosen based on: cost (capital investment cost), separation efficiency (amount of oil in water, amount of water in oil), and robustness (system's ability to handle flow rate fluctuations when large volumes of oil or water that are fed to the treatment system unexpectedly).

H2Oleum's analysis of the full scale design was reinforced by the actual results from the bench scale competition analysis. Team H2Oleum was able to successfully remove the oil from the water in the oil-in-water emulsion. The impact of this design is that the water will be safer for the environment and the recovered oil can be used to offset costs for reuse or disposal.

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Client

Our client is the Institute for Energy and the Environment hosted at New Mexico State University where the client hosted the 25th annual WERC design competition on March 29th through April 1st 2015. The goal of the competition is to design, develop, and test actual environmental processes for real-world problems that focus on technologies to tackle renewable energy innovation, sustainable building design, and water issues. The tasks are developed with assistance from government agencies, industrial affiliates, and academic partners.

Problem identified by the client

The purpose of this task is to design a water treatment system that is able to separate emulsified oil from a brackish oil-in-water emulsion.

Problem clarified by H2Oleum

Industrial processes that involve the extraction of crude oil create emulsions which contain microscopic oil particles dispersed throughout water. These contaminants need to be removed from the water before being reused in other processes.

The problem with emulsions is that the microscopic, emulsified, oil particles are so tiny that they will not separate from water over time. Increasing the size of the oil droplets will cause them to coalesce into larger oil particles that are easier to recover as they rise and collect on the water's surface.

H2Oleum's Objective

H2Oleum's objective for this project is to provide a design solution that will create a high degree of separation between the two liquids, oil and water, to recover as much oil as possible from the water. The report will outline H2Oleum's proposed solution to the client's request for a cost effective, efficient, and robust water treatment system that is able to recover the emulsified oil from a brackish water stream.

Project Significance

The significance of this project is that the system will be able to treat the industrial waste water so that it is both safer for the environment and cheaper for disposal. In addition to the water benefits, the system will also be able to recover oil so that it is reusable after additional processing.

Design Considerations with Existing Separation Technology

This section discusses existing technologies for oil in water emulsion creation and separation. This research influenced the technology the team chose to create a representation of the industrial waste water emulsion and the overall system design choice for the full scale processes.

Existing Emulsification Techniques

The most common method used to create a laboratory emulsions is to use a sonicator; sonicators apply sound energy to agitate and break up the particles into microscopic spheres that range in size from 5 microns to 15microns. In the case of the team's emulsion, an oil particle in this size range will not rise to the surface of the water which prevents the removal of oil from the water. The cost of a laboratory horn sonicator will range in price from three hundred to over thousands of dollars depending on the size of the particle the sonicator will create.

An alternative method to emulsify a solution is to use mechanical forces where the particles are shaken, sheared, or stirred at rapid speed until they become small enough to be considered emulsions. One benefit to this method of emulsion is that the cost can be significantly cheaper than a low-end sonicator, but they will produce a tighter emulsion that will not separate over time as quickly as an emulsion created by the low-end sonicator.

The third method that the team considered for emulsification was to use an emulsification agent that will help break the interface between both phases in an emulsion. In the oil-in-water case, emulsifying agents will surround individual oil particles to prevent physical contact with other particles. This agent prevents the oil droplets from combining with one another to increase particle size which would lead to greater separation over time.

Existing Physical Separation

Physical separation of oil from water is the most basic form of separation. Physical separation is accomplished by using two different types of plates: parallel plates and corrugated plates. Parallel plates are flat while the corrugated plates have a shape similar to that of egg carton. Plate separators allow the extraction of large oil droplets by introducing more surface area in the form of the plate which allows the particles to combine more often and increase in size. As the oil droplets increases in size, they will rise up to the surface of the water.

The separators follow Stoke's Law to achieve separation by destabilizing the oil particles in the water; particles combine with each other to increase the overall oil particle size. Once enough oil particles collect at the bottom of each plate, they become large enough to overcome the surface tension of the water and will begin to float to the top of the water. The plates also decrease the vertical distance that the oil particles must travel to reach the surface of the continuous phase. [2]

Another method of separation is gas injection methods. This method dissolves compressed gas into emulsions using an air sparger to create small bubbles. The small bubbles create the additional surface area which is needed to disrupt the oil particles causing them to coalesce into each other; the larger oil particles have increased buoyancy forces which allows them to rise to the surface of the water.

Existing Chemical Separation

In chemical separation, a chemical agent acts as a catalyst to decrease the time needed for the oil and water to separate. The chemical agents that are added are known as demulsifiers, emulsion breakers, or wetting agents. These additives are surfactants that break the oil/water interface. Demulsifiers break the oil film which allows oil particles to join together and separate out. [3]

When using chemical separation, dosage is critical. Adding a small amount of the demulsifier may not break the emulsion completely, while adding too much can be damaging to the continuous phase of the solution. If too much demulsifier is added, it could actually stabilize the emulsion by replacing the emulsifier. [4]

Existing Electrocoagulation

Although demulsification using electricity is the newest technology, it is not yet clearly understood. Electrical separation is achieved by applying a direct or alternating current to the solution to improve water coalescence. [5] The current imposes an electrical charge on the emulsified droplets in the emulsion, as a result the droplets move into larger droplets, which separate with gravity. [6]

Full Scale Design

Overall System Design

This section will provide a breakdown of each component that is used in the full scale design.

Figure 1, Figure 2, and Figure 3 illustrate the full scale design in three different views. The flow of the emulsion will begin with the storage tank and travel from left to right in each of the figures.

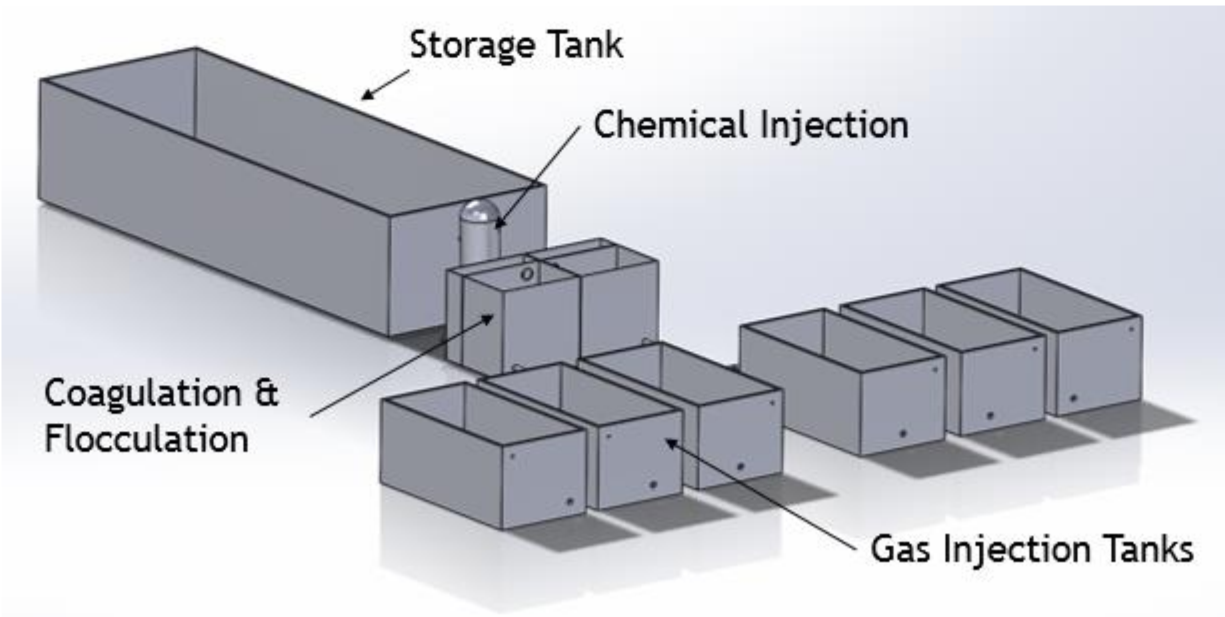

Figure 1: Isometric view of the full scale design

Figure 1 uses callouts to show the name of each component that will be discussed in the following sections. Figure 2 displays the design in two dimensions from the side.

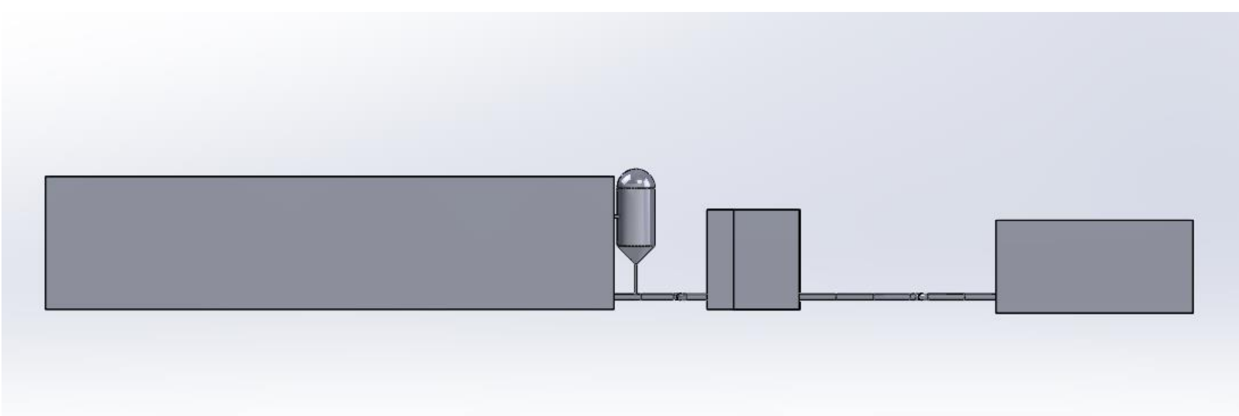

Figure 2: Side view of full scale model, flow will travel from left to right

Figure 3 provides an overhead top view of the full scale design.

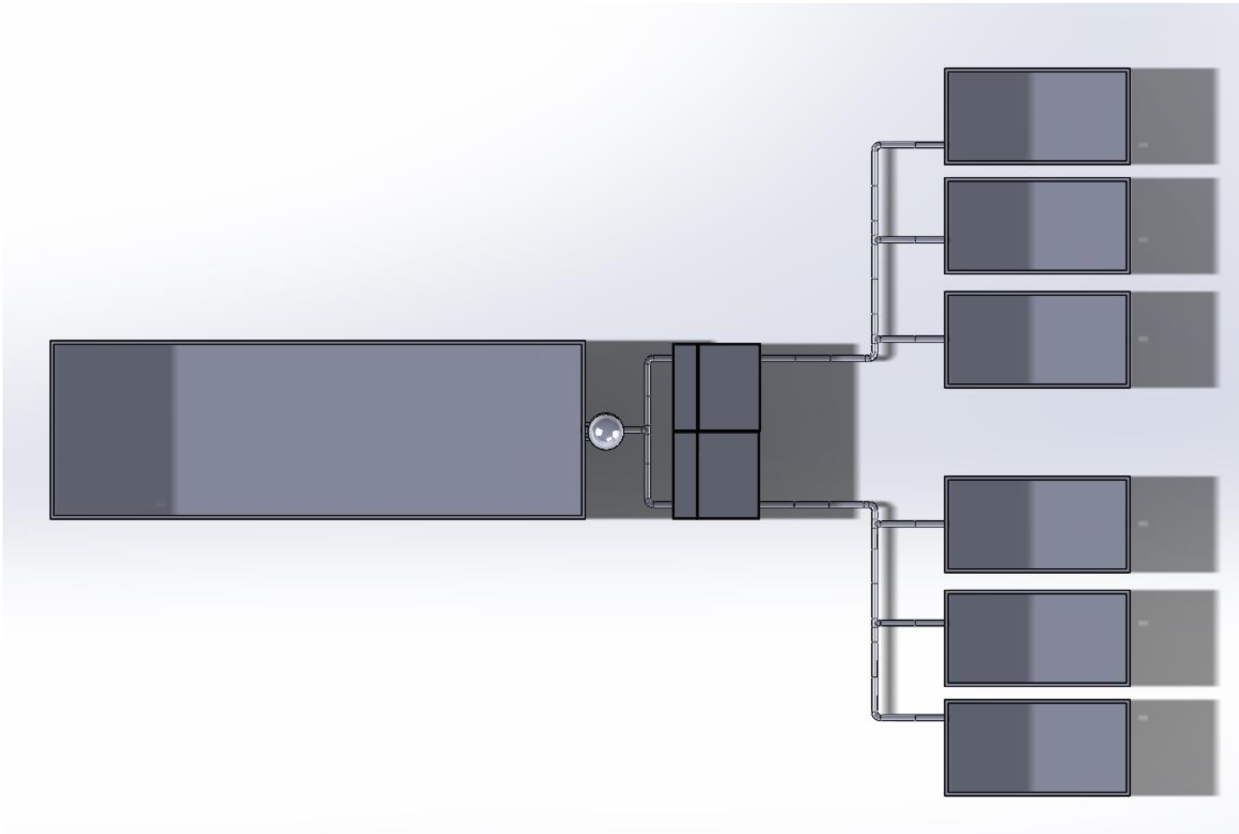

Figure 3: Top view of the full scale design, flow travels from left to right

In Figure 3, the delivery system that will be used to transfer the emulsion through each stage is seen leaving the storage tank, passing to the dual chemical coagulation system in the middle of the figure, followed by the pipes splitting off into the 6 gas injections tanks on the right hand side of the figure (three gas injections tanks will be used for each chemical coagulation tank). All 6 gas injection tanks will be used during overload operations only; the overload operation will be discussed in the gas injection system section of this report.

Storage Tank

In the full scale design, a 16,000 gallon storage tank will receive the emulsion from the upper left corner of the tank where it will accommodate flows of emulsion up to 130GPM for 2 hours.

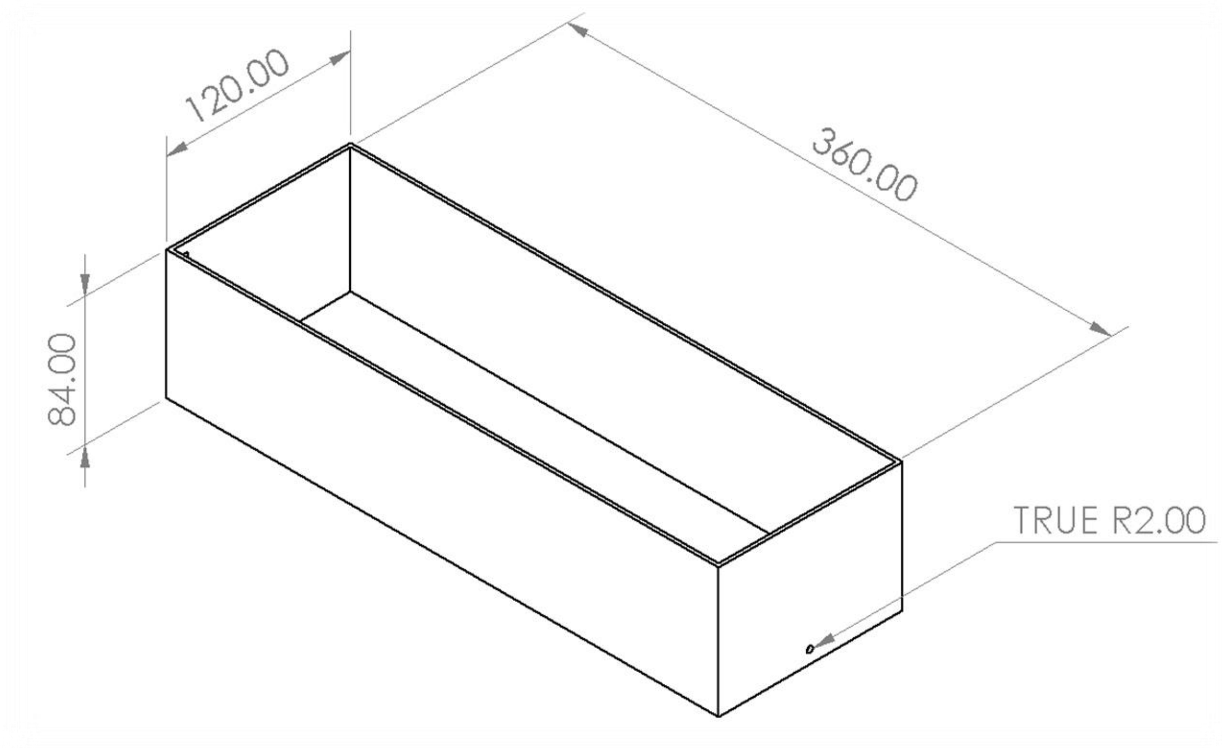

Figure 4: Full scale dimensions of the storage tank

The dimensions of the full scale storage tank are:

$$10\ ft\ (120\ in.)\ width\ \times\ 30\ ft.(360\ in.)\ length\ \times 7\ ft.(84\ in.)\ height$$

The emulsion will be passed to the next stage through the hole at the bottom of the tank which has a radius of 2 inches.

Dry chemical injection

The dry chemical injection system is used to introduce a chemical coagulant into the emulsion. The addition of the chemical destabilizes the emulsified feed solution by causing the oil particles to coalesce and form flocculent masses as a cloud at the surface of the water. The chemical coagulant will be introduced in-line with the feed solution for optimal contact time. The chemical coagulant that will be Ferric sulfate with a dosage of 30 mg/L. Ferric sulfate was chosen as the coagulant due to the specification set by WERC: the feed solution will have a pH of 7.3; based on this pH level, Ferric sulfate will have a high separation efficiency [9]. The chemical flocculation system will have the dry chemical injection system inline before the actual coagulation and flocculation tanks.

Chemical flocculation system (CFS)

The CFS is divided into two sections for rapid mixing and slow mixing. First rapid mixing will occur at over 200 RPM in the first section of the tank with a retention time of 2 minutes to allow for an even dispersal of the dry chemical throughout the emulsion. Rapid mixing also allows the oil particles and other mineral contaminants to destabilize faster as they mix with the chemical coagulant.

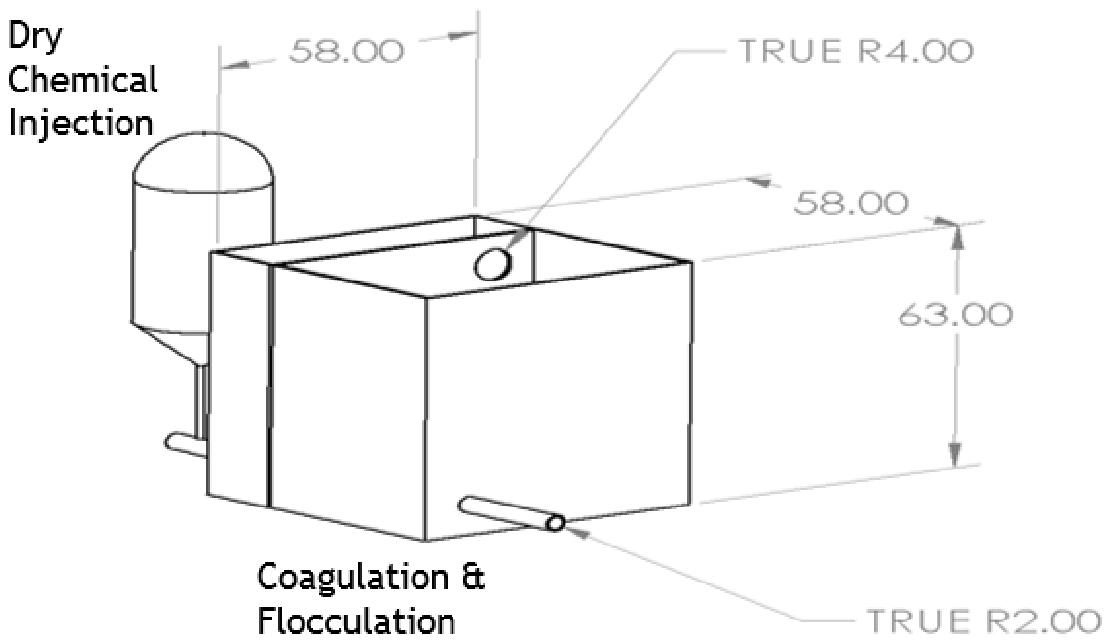

Figure 5: Chemical injection tank dimensions

After the chemical has been dispersed throughout the emulsion, the next step is to pass the emulsion into the second section of the CFS system through the 8 inch hole in the upper right hand corner of the barrier.

The second section of the CFS system involves a transition to slow mixing under 20 RPM for a 5 minute retention time. After completing the retention time, the oil particles will have increased in size and can be classified as part of the dispersed phase range. Valves will open that allow the solution to pass into the tanks for the gas injection system.

The feed emulsion will be broken up into batches and will be diverted into a chemical coagulation tank that will flow into 3 separate gas injection tanks.

Gas injection tanks

From each chemical coagulation tank, the emulsion will pass into 3 separate gas injection tanks. Under overload operations, when the storage tank receives flow over 100 GPM, both chemical coagulation tanks and all six gas injection tanks will be used.

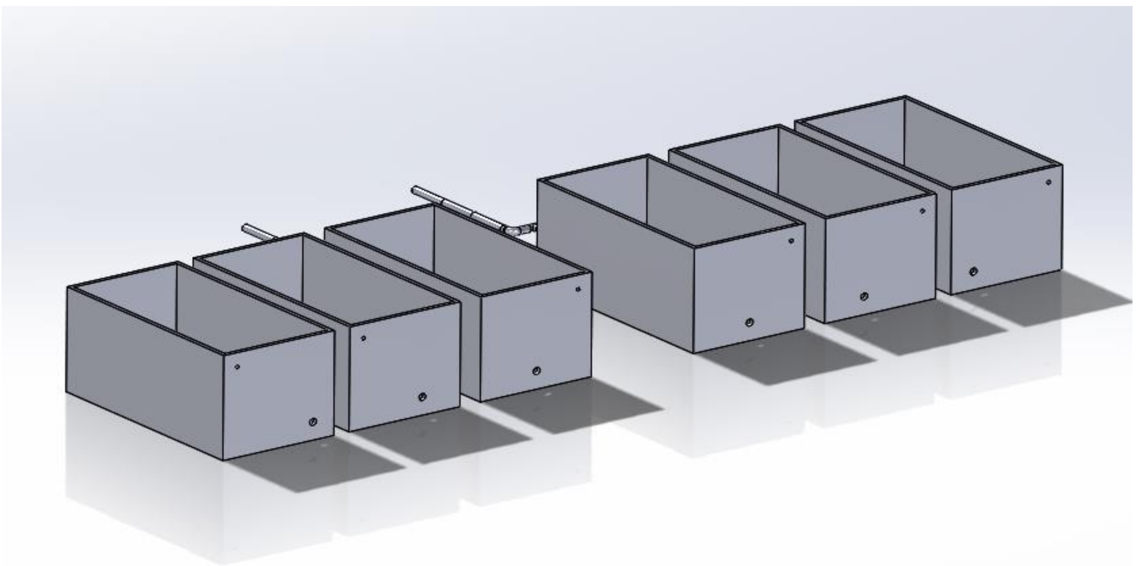

Figure 6: Gas injections tanks with oil exit valve on top, water exit on bottom

Under normal operation, the 1st gas injection tank will be ready for more emulsion by the time the 3rd gas injection tank is halfway full.

The dimensions and components for each gas injection tank will be displayed in Figure 7.

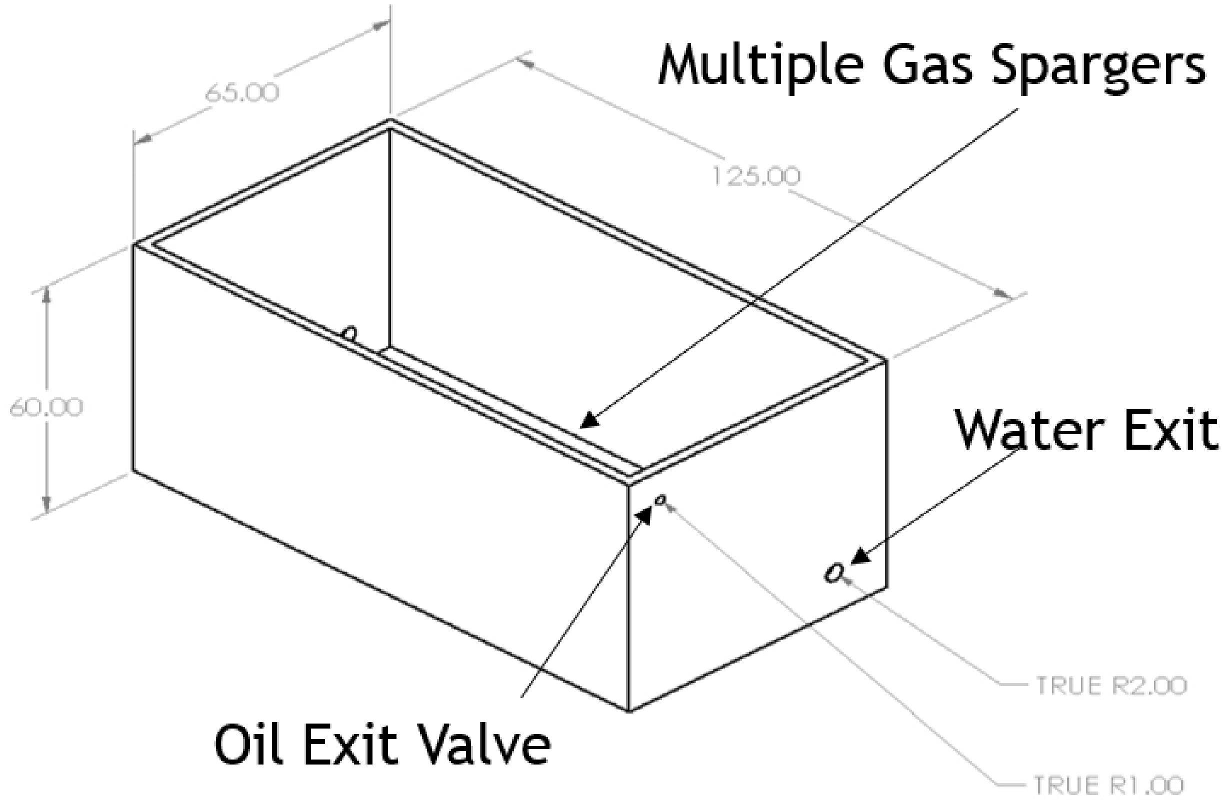

Figure 7: Single gas injection tank with dimensions

Each gas injection tank will use multiple gas spargers to dissolve nitrogen compressed gas into the oil emulsion; the porous gas spargers will allow the dissolved gas to release tiny gas bubbles (2 micron diameter) which create more surface area throughout the emulsion.

More surface area translates to further destabilization in the dispersed oil particles which causes them to coalesce into other oil particles. As the oil particles combine, they will increase in size which will effectively increase their rise rate allowing the oil to accumulate on the surface of the water.

A thick oil layer is achieved by draining the water from each tank but leaving the previous oil layer intact. After multiple batches, the oil layer on the surface of the water will accumulate until the oil layer is thick enough to collect; a valve placed at the top of the gas injection tanks will allow the on-site operator to collect the oil that is above the water interface.

More batches, along with an increase in oil concentration or density will require more chemical coagulant, but would produce a thicker oil layer.

Flow delivery system

Any treated water that is oil-free will be removed from gas-injection system from the bottom of the tank with a pipe. Each component is isolated and components after the storage tank have a redundancy of 100% so that 2 systems could operate in case of flows operating higher than the specified 100 GPM. Flow will be delivered through 4 inch schedule 40 PVC piping with full port flange butterfly valves that are able to handle flows from 20 GPM – 400 GPM.

Post processing

Depending upon the usage of the water and oil, each liquid will need to undergo additional processing to remove any chemical flocculent, in the form of foam, from the oil. The dosage of the Ferric sulfate is low enough that the water's pH will be still be above 5.5 and the color of the water will have a slight yellow tint. After additional treatment, this water can be also be reused as drinking water.

Bench Scale Representation

This section will describe how each component of the bench scale design was used to represent the full scale system. A summary of the competition results will be provided, followed by a break down for each component in the system.

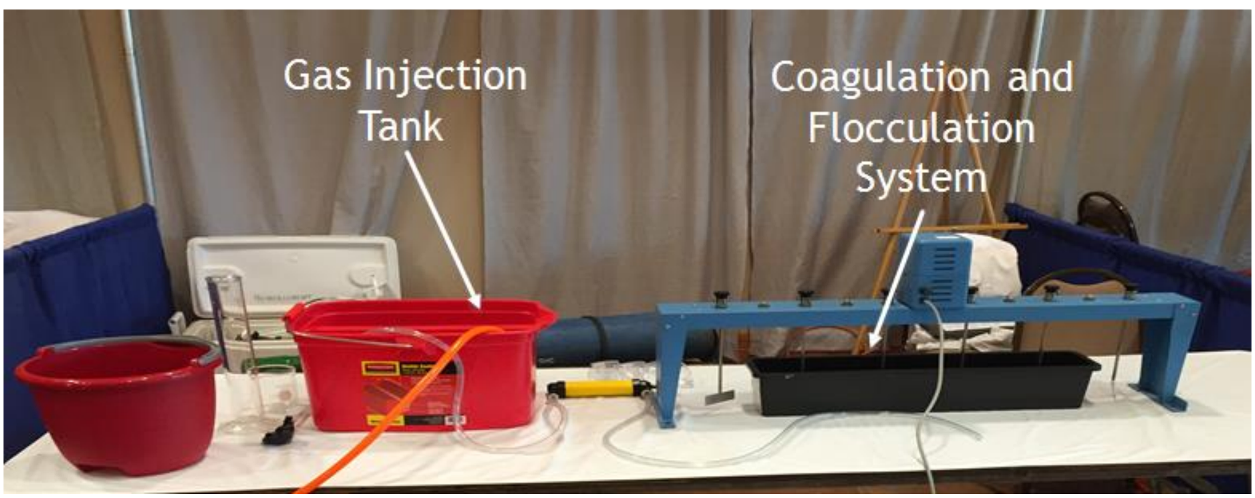

Figure 8:Bench scale with two process oil separation

Figure 8 is a photo of the bench scale representation that was used at the WERC competition. H2Oleum first dispersed the dry chemical into the emulsion by using the flocculating spinners. The emulsion was then passed into the gas injection system by using a hand pump. The gas sparger was then used to dissolve the nitrogen compressed gas into the emulsion. After 45 minutes, the emulsion was passed into the white collection tank where the glass pipet was used to collect oil and water samples.

Figure 9 portrays the team operating the bench scale during the competition.

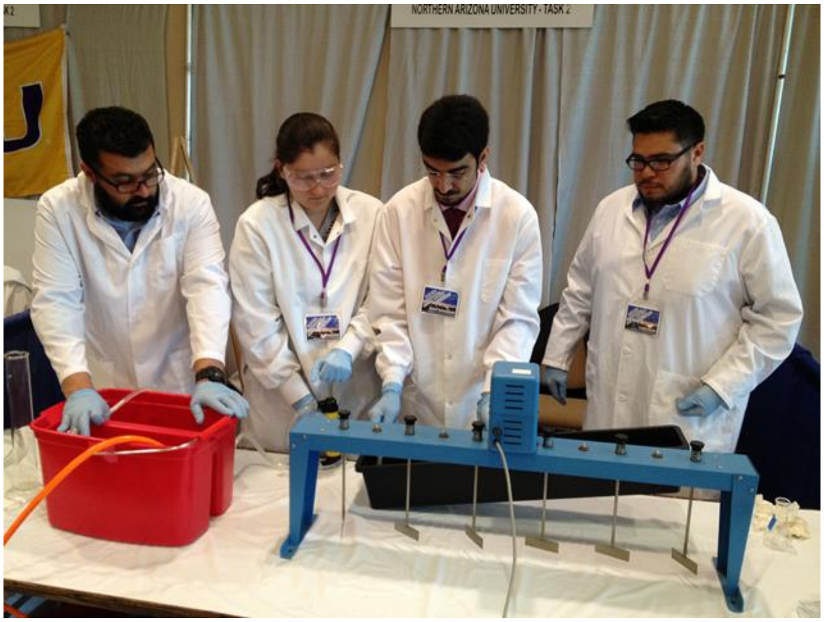

Figure 9: Bench scale operation at the competition

The oil and water sample testing was conducted on-site by the New Mexico State University chemical testing team. H2Oleum was able to successfully remove 100% of the oil from the water sample (see Analysis section). However, the oil sample was minimal due to the incurred oil losses during transfer using the hand pumps throughout the system. As a result, H2Oleum did not win 1^{st} or 2^{nd} place out of the 7 teams that were competing for the same task. Had the team been able to run more than 10 gallons of emulsion through the bench scale system, a larger oil layer would have accumulated, which would have led to easier oil recovery.

Emulsion creation

The team looked into purchasing a horn sonicator, which was hypothesized to be the most effective method of emulsification for the amount of emulsion that was needed. The price of the horn sonicator, along with the tool's very specific purpose for this project, prevented the team from being able to justify the cost of the purchase to the department; this forced the team to consider cheaper alternatives to creating the emulsion.

The team purchased the Vitamix 7500 blender for creating the oil-in-water emulsion (see Appendix, Figure 18). In addition to comparing the costs, availability, power, and consistency in reviews for different blender styles, the team experienced a live demonstration for the Vitamix 7500 blender. The live demonstration was the ultimate deciding factor for the team after witnessing the blender boil 4 quarts of water in under 10 minutes; later the team found that this was attributed to the Vitamix 7500's blade speed of over 22,000 RPM or 270 MPH. [8]

After using the Vitamix 7500 to create the oil-in-water emulsion, there was minimal oil aggregation visible on the surface of the emulsion. With the oil-in-water emulsion completed, the next step in the design process would be to treat the emulsion with a dry chemical injection system as part of the dry chemical coagulation and flocculation system.

Dry Chemical Coagulation and Flocculation

The bench scale model used a dosage of 30 mg/L of ferric sulfate as the chemical coagulant for the system based on the high oil separation efficiency at the water pH level of 7.3. [9] After the chemical was added to the oil in water emulsion, the next step of the process was to use rapid mixing above 200 RPM to disperse the dry chemical for 4 minutes followed by slow mixing under 20 RPM for at least 7 minutes to break the interface between oil particles and water.

Figure 10: Flocculating spinners used for rapid and slow mixing in the bench scale process

Gas injection system

After slow mixing the gas injection system used a gas diffuser to dissolve nitrogen compressed gas into the system at a particle size of 2 micrometers with pressure under 3 PSI. The low pressure of the dissolved gas produces smaller bubbles in the emulsion which create more surface area without causing the emulsion to become a liquid with suspended colloidal particles. The oil particles coalesce into each other and rise to the surface of the water.

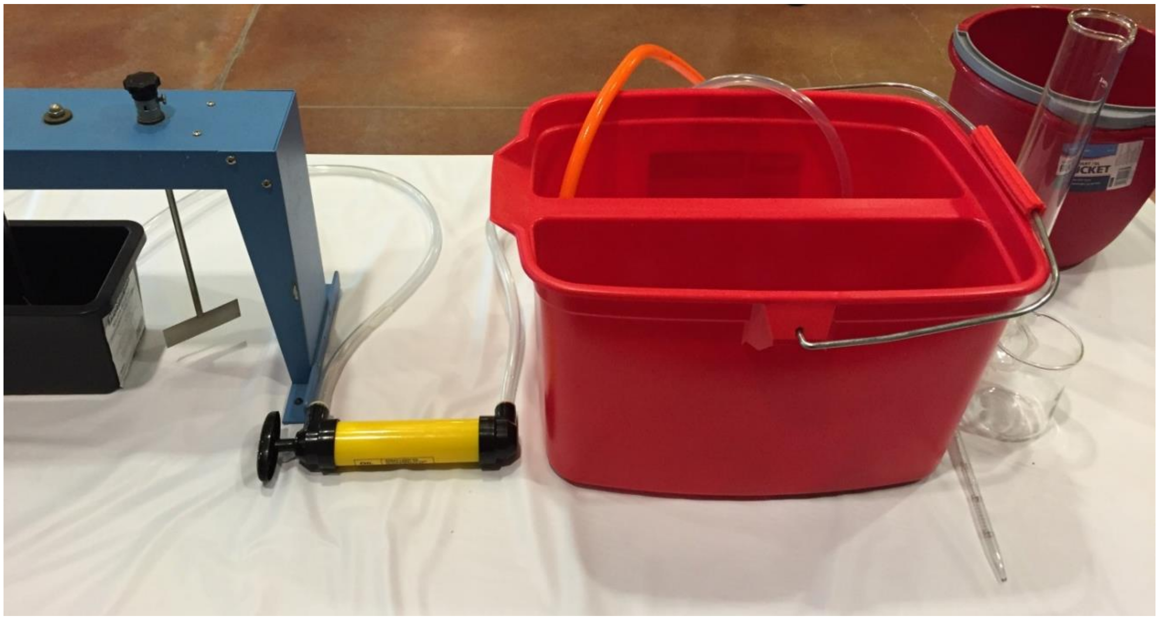

Figure 11: Gas injection tank

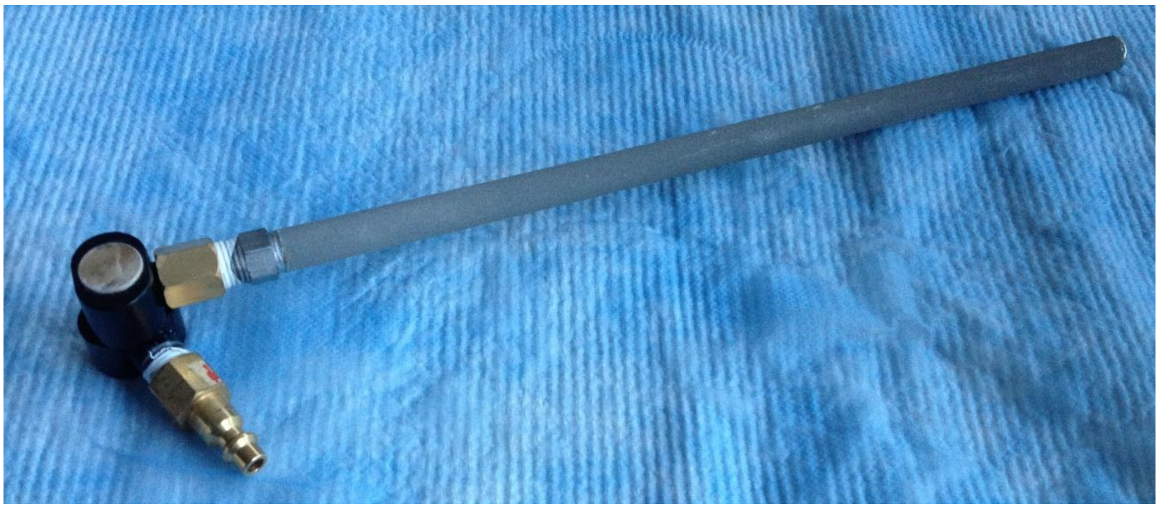

Figure 12: Porous gas sparger, 2 micron holes

Collection system

The collection system of the bench scale design was used after all 10 gallons of oil emulsion were processed. A pipet was used to remove oil from the oil layer that accumulated on the surface of the water.

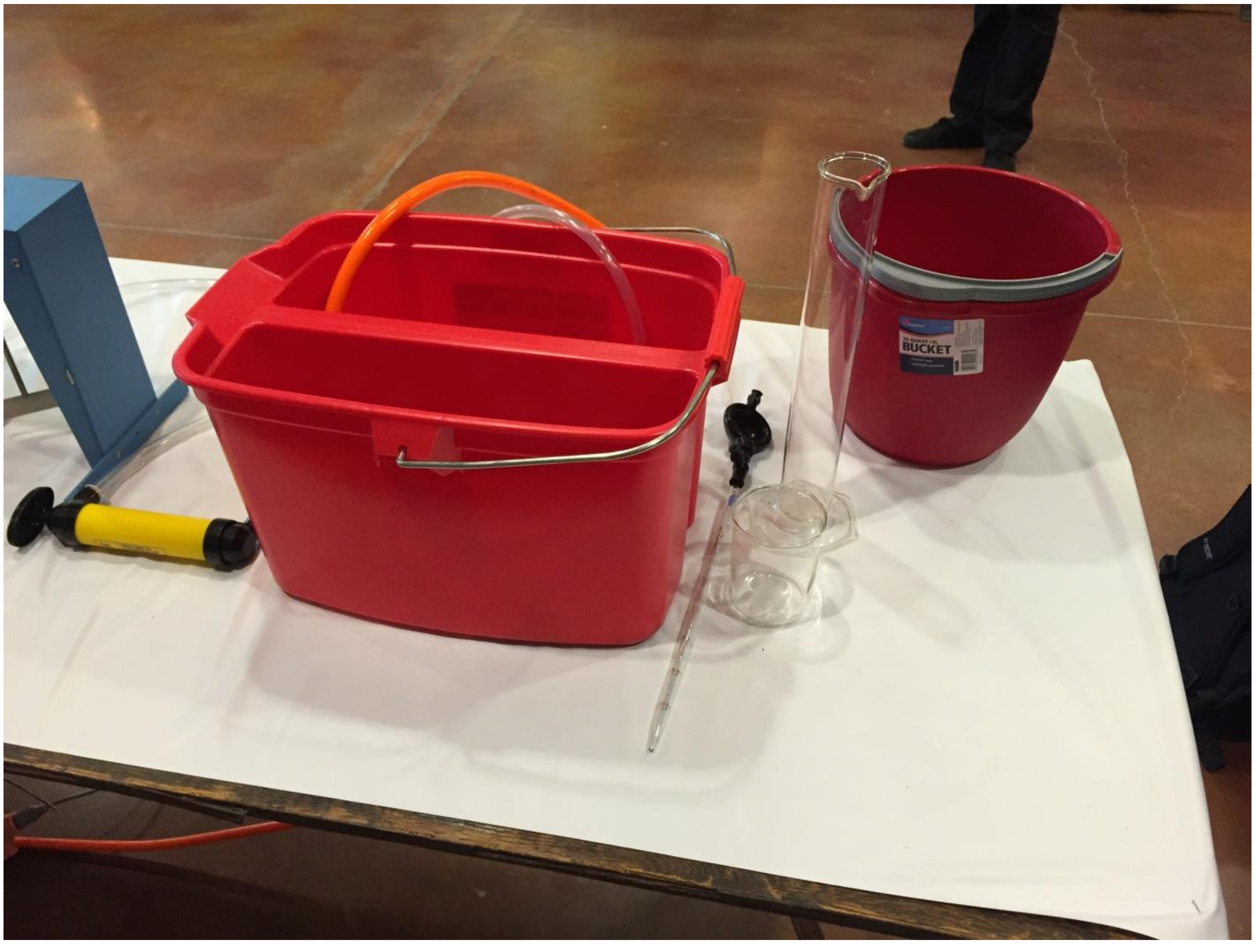

Figure 13: Glassware used for collection of oil and water samples

Analysis

This section will qualify the particle size classifications to quantify the terms used in the analysis. This information will then be followed by the properties and data tables that were used to analyze H2Oleum's design of the oil separation system.

Particle size classification

Two stationary immiscible liquids, such as free oil and water, will separate into a two-phase system which has the lighter liquid (oil) on top of the heavier liquid (water). Emulsified oil particles are so tiny that they will not separate from water over time as quickly as free oil. Figure 14 shows the classification and size range (microns) of oil droplets found in wastewaters.

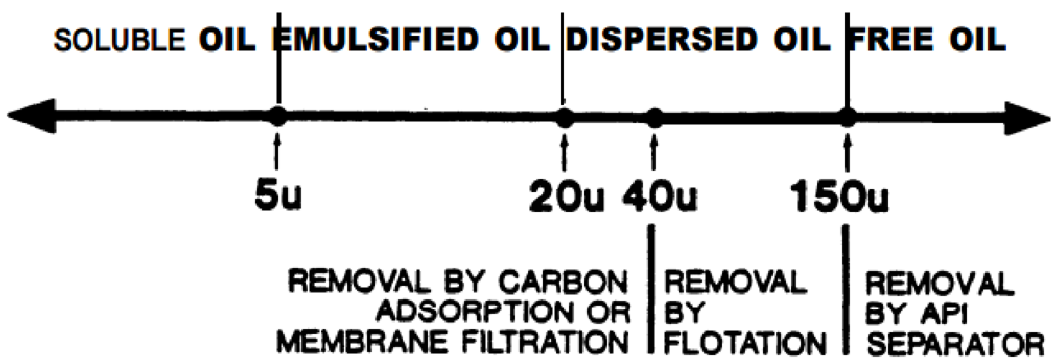

Figure 14 Classification and Size Range of Oil Droplets. [1]

As long as the oil particles in the emulsion are within the emulsified oil size range, they will take longer to separate over time. To remove the oil particles from the water, they must first be subjected to a method which will cause them to increase in size so that they can move to the surface of the water.

Properties of Emulsions

The physical properties of the water and oil are listed in Table 1.

Table 1: Physical Properties of Oil and Water for Calculations [10]

LSB type Oil Density [kg/m^3]	853.4
MDL type Oil Density [kg/m^3]	899.4
CLK type Oil Density [kg/m^3]	958.2
Vegetable Oil Density [g/mL]	0.920
Water Density [kg/m^3]	999.970
Water viscosity [g/m-s]	1.003

Although the assumed properties of the full and bench scale oil densities are different, the water density and viscosity are assumed to remain the same for simplicity. The differences between the two are assumed to be negligible.

Oil Particle size

The most important part of the analysis for the system was to determine whether each stage in the full scale design was increasing the size of the oil particle. The team created a graph that was used to calculate the rise rate of different oil particle size for each stage in the system.

An increase in the size of the oil particle will also increase the rise rate of the oil particle which will allow the oil to rise to the surface. The relationship between the rise rates and oil particle size can be seen in Figure 15.

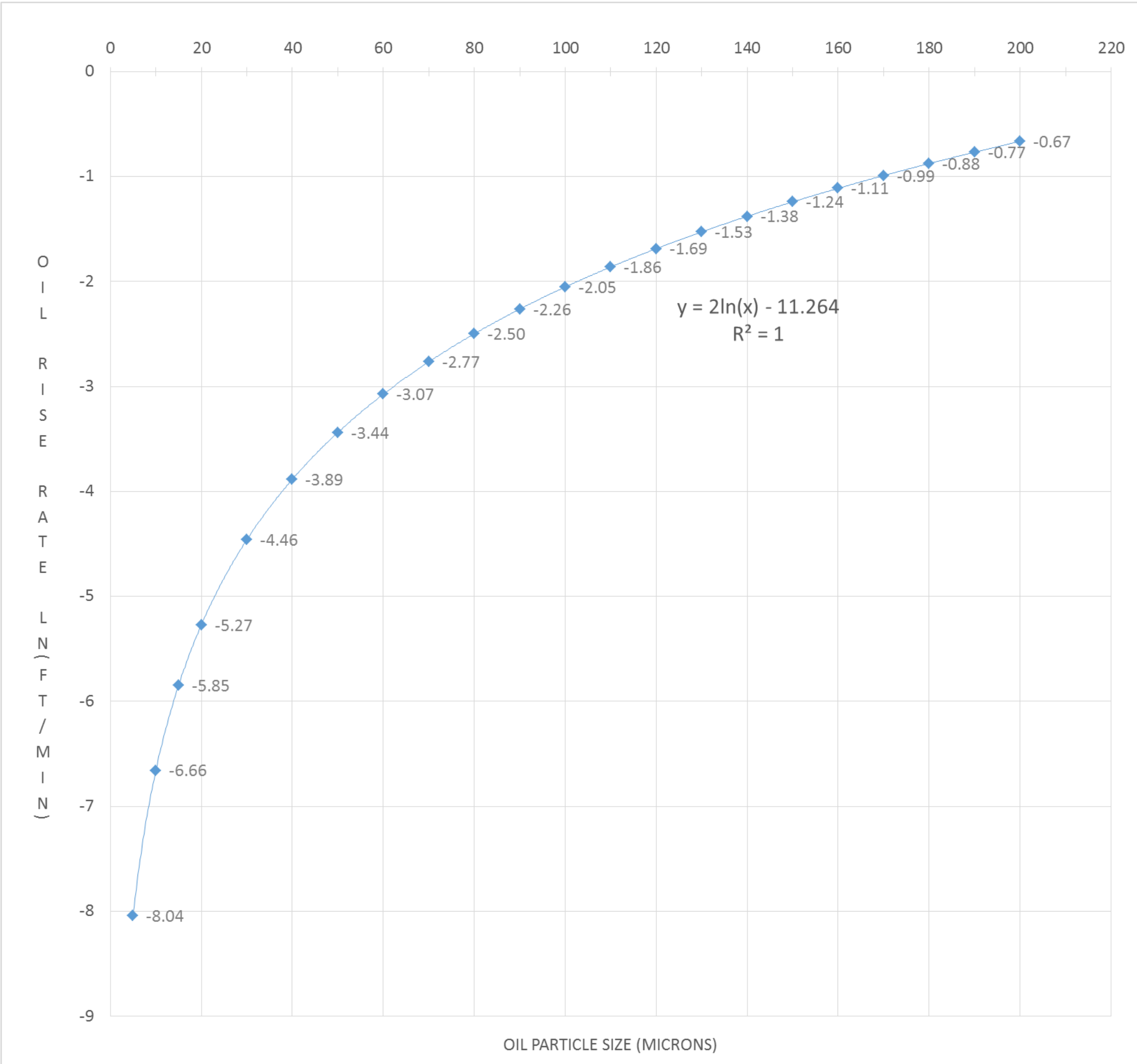

Figure 15: Semi-log plot of Oil Particle Rise Rate ln (ft. /min) vs. Oil Particle Size (Microns)

Figure 2 illustrates how the oil particle's rise rate increases with oil particle size through each stage in the system. The data from this graph confirms that each stage in the full scale design will increase the size of the system. Each marginal increase in rise rate for each stage was recorded in Table 2. The average time for the smallest oil particle to reach the surface of the water is 42 minutes.

Table 2 lists each calculated rise rate value for oil phase and particle size.

Table 2: System Stage, Particle Size, Rise Rate [1]

System Stage	Oil Phase	Size [Micron]	Rise rate [ft/min]	Marginal Rate Increase
Storage	Emulsified	5	3.21E-04	300.00%
Storage	Emulsified	10	1.28E-03	
Storage	Emulsified	15	2.89E-03	77.78%
Chemical	Emulsified	20	5.13E-03	
Chemical	Dispersed	30	1.15E-02	77.78%
Chemical	Dispersed	40	2.05E-02	
Gas Injection	Dispersed	50	3.21E-02	44.00%
Gas Injection	Dispersed	60	4.62E-02	
Gas Injection	Dispersed	70	6.29E-02	30.61%
Gas Injection	Dispersed	80	8.21E-02	
Gas Injection	Dispersed	90	1.04E-01	23.46%
Gas Injection	Dispersed	100	1.28E-01	
Gas Injection	Dispersed	110	1.55E-01	19.01%
Gas Injection	Dispersed	120	1.85E-01	
Gas Injection	Dispersed	130	2.17E-01	15.98%
Gas Injection	Dispersed	140	2.52E-01	
Collection	Free oil	150	2.89E-01	13.78%
Collection	Free oil	160	3.29E-01	
Collection	Free oil	170	3.71E-01	12.11%
Collection	Free oil	180	4.16E-01	
Collection	Free oil	190	4.63E-01	10.80%
Collection	Free oil	200	5.13E-01	

As the oil particle passes through each stage in the system, the oil particle increases in size from the emulsified phase to the dispersed phase, the marginal increase in oil particle rise rate is initially rapid; as the oil phase approaches the free oil phase, the marginal increase slows down (see Table 2, Marginal Rate Increase column). After reaching the gas injection stage, each batch would require 42 minutes before adding additional emulsion to the same tank.

Oil Layer Accumulation

The team did an analysis, using the different oil types with the properties previously listed in Table 1, to determine the number of batches each gas injection tank would need to run in order to accumulate an oil layer with the specified thickness of 25 mm (see Table 3).

Table 3: Number of batches to desired thickness of oil layer

Desired Oil Thickness [mm]	Batches to Desired Height (#)	Time required (hrs)	Oil Type
25	91	74	Light Sour blend crude oil (LSB)
25	96	78	Midale crude oil (MDL)
25	102	83	Cold Lake crude oil (CLK)

The information from Table 3 reinforces the overall process of H2Oleum's full scale design in being an effective method to recover the oil from an oil-in-water emulsion.

Water Sample

The analysis for the water sample and oil sample from the bench scale system was done on site by New Mexico State University chemical testing team. Images from the analysis are included in Figure 16.

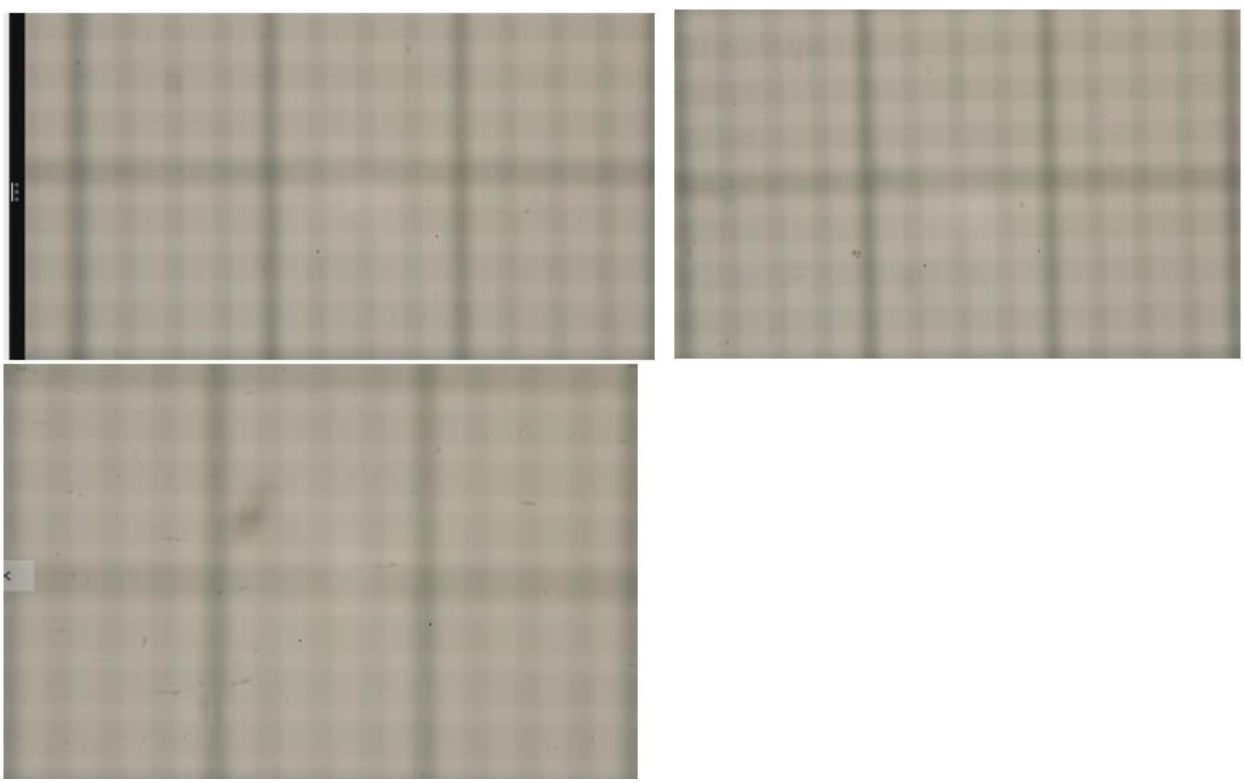

Figure 16: Treated Wastewater analysis, low lipid content

According to the NMSU chemical testing team, the “sample was analyzed in triplicate, under the microscope, no traces of oil bubbles visible. Suggesting no oil content in the treated water sample.” The bench scale system was able to provide oil free water which supports the team’s objective to design a system that is able to remove oil from industrial wastewater.

Oil Sample

The oil sample from recovered from the bench scale model was not visible after centrifuge in the oil sample (see Figure 17).

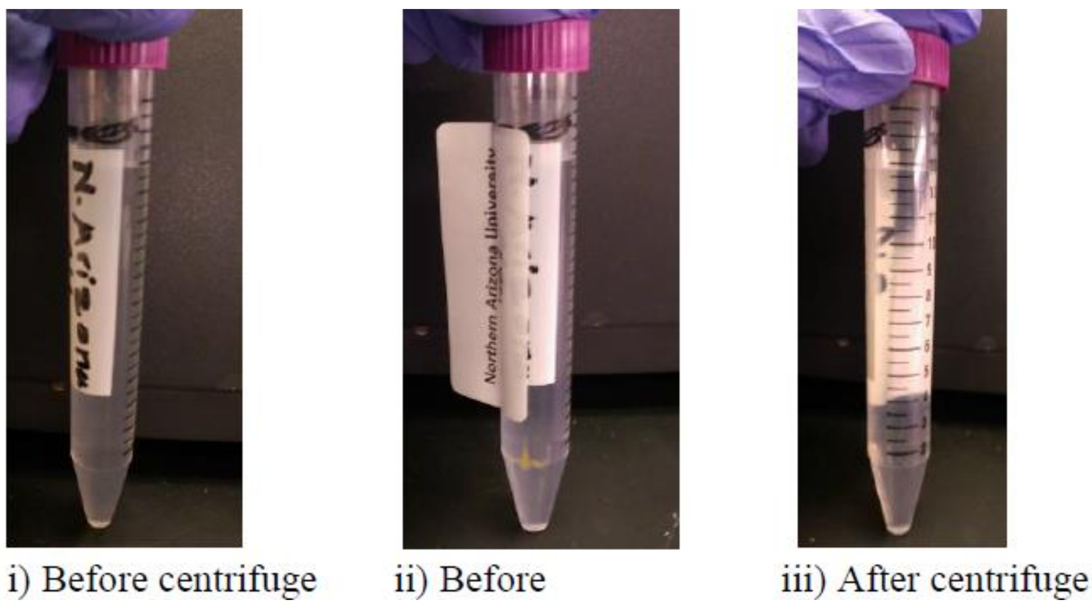

Figure 17: High lipid content analysis

The small oil layer was expected since the bench scale model would only use 1 cycle of emulsion through the entire bench scale system. If multiple cycles were done with more emulsion, the oil layer would increase in thickness.

Cost Considerations

The team looked into several sources for both tanks and parts for the system. The prices found are for the tanks or parts that most closely matched the team’s needs. In the final design if a custom tank needs to be built or if parts can be purchased at wholesale costs there may be fluctuations in the actual price. These are accounted for in the overhead. Labor costs are based on standard labor costs and the estimate of hours to build because a system like this has never been built the time to build was overestimated. In the following table you will find the final budget for the overall system design.

Operating costs are based on the price of Ferric Sulfate and Nitrogen in bulk. There will also be an operator on site 24 hours a day to make sure everything is running smoothly and to operate the skimming system when needed. In the table below you will find the estimated operating costs for one day

Table 4: Building Cost

Raw Building Materials	$56,230
Labor Cost	$72,000
Building Subtotal	$128,230
Contingency & Allowance (50%)	$64,115
Total Building Cost	$192,345

Table 5: Operation Cost per Day

Ferric Sulfate per Day	$4
Nitrogen per Day	$25
On-Site Operator per Day	$1,080
Energy Cost per Day	$20
Operation Subtotal	$1,129
Miscellaneous Costs (30%)	$339
Total Operation Cost per Day	$1,468

Conclusion

Particular systems that H2Oleum considered were chosen based on: cost (capital investment cost), separation efficiency (amount of oil in water, amount of water in oil), and robustness (system's ability to handle flow rate fluctuations when large volumes of oil or water that are fed to the treatment system unexpectedly).

H2Oleum's analysis of the full scale design was reinforced by the actual results from the bench scale competition analysis. Team H2Oleum was able to successfully remove the oil from the water in the oil-in-water emulsion. The impact of this design is that the water will be safer for the environment and the recovered oil can be used to offset costs for reuse or disposal.

References

[1] Rhee, CH. Martyn, PC. Krener, JG. Los Angeles County Sanitation Districts. Removal of oil and grease in oil processing wastewaters. J.M. Bell (Ed.), Industrial waste: 42nd: Purdue University conference proceedings (Purdue industrial Waste Conference Proceedings), CRC Press, West Lafayette, IN (1987), p. 143

[2] Megator. Megator Oil Water Separator Operational Theory [Web]. 10 Oct. 2014.

http://www.megator.com/download/Parallel%20plate%20USA.pdf

[3] Otzisk, Berthold. "Oil/water Separation Technologies." Oil/water Separation Technologies (2013): n. page. http://www.eptq.com. Kurita Europe, 2013. [Web] 16 Nov. 2014.

http://www.kurita.de/fileadmin/user_upload/artikel/Oil%20water%20separation_PTQ_Q22013.pdf

[4] Oil Demulsification." Petrowiki.org. SPE International, n.d. [Web]. 16 Nov. 2014.

http://petrowiki.org/Oil_demulsification

[5] Eow, John S., and Mojtaba Ghadiri. "Electrostatic Enhancement of Coalescence of Water Droplets in Oil: A Review of the Technology." Chemical Engineering Journal 85.2/3 (2002): 357. Academic Search Complete. Web. 16 Nov. 2014.

[6] Woo-Taeg Kwon. Kunyik Park. Et al. Investigation of water separation from water-in-oil emulsion using electric field. Journal of Industrial and Engineering Chemistry. Volume 16. Issue 5. 25 September 2010. Pages 684-687. ISSN 1226-086X.

http://dx.doi.org/10.1016/j.jiec.2010.07.018.(http://www.sciencedirect.com/science/article/pii/S1226086X10002121)

[7] Vitamix Corporation. "Vitamix 7500 | Machine." (2015) [Web] 3 Feb 2015

https://www.vitamix.com/Shop/7500.aspx

[8] Joy of Blending. "How fast does a Vitamix really spin? (Independent measurements of Vitamix RPM)." 10 June 2014. [Web] Feb 2015

http://joyofblending.com/vitamix-speed-measured/

[9] Al-Shamrani AA, James A, Xiao H. Destabilisation of oil-water emulsions and separation by dissolved air flotation. Water Res. 2002;36(6):1503–1512. doi: 10.1016/S0043-1354(01)00347-5

[10] Watkinson, AP. Heat Exchanger Fouling and Cleaning: Fundamentals and Applications: Comparison Of Crude Oil Fouling Using Two Different Probes. (2003) Engineering Conference International

[11] Nayyar, ML. Piping Handbook. ISBN 0-07-047106-1. McGraw-Hill Handbooks New York. 2002 Seventh edition

[12] Karassik, Igor. “Pump Handbook,” 3d ed., ISBN 0070340323, McGraw-Hill, New York, 2001.

[13] Ward, Stuart. Pollution Engineering. “Designing a DAF: DAF Designs, Three critical dissolved air flotation design parameters for successful aeration of wastewater are described” pp26-30. Journal Article. 16-19 May 2011. Chicago, IL.

Appendix

Figure 18: Vitamix 7500

Table 6: Material Building Cost

Item	Amount Required	Cost per Unit	Total Cost
4" PVC Pipe (10 ft sections)	10	$15	$150
Storage Tank (15,000 gallon tank)	1	$17,261	$17,261
Chemical Coagulation Tank	2	$407	$814
DAF Tank	6	$1,560	$9,360
Butterfly Valves	18	$395	$7,110
4" PVC Schedule 80 Flange	30	$38	$1,148
4" PVC Elbows 45 degrees	30	$9	$275
4" PVC Elbows 90 degrees	30	$9	$263
4" PVC Tee	30	$18	$551
Nitrogen Tank	4	$300	$1,200
Air Sparger	54	$250	$13,500
Floc Pump	2	$2,300	$4,600
		Total	$56,230