ABSTRACT

GALLIMORE, ERIN MICHELLE. Assessment of Internal and External Grease Interceptors for Removal of Food Based Fats, Oil, and Grease from Food Service Establishments. (Under the direction of Joel J. Ducoste.)

The objective of this study was to determine the removal efficiency of fats, oils and grease (FOG) of flow-based grease interceptors (FGI). Two FGI units were tested; one passive flow unit and one mechanical flow unit. Mechanical flow devices incorporate the use of an electrical functioning skimmer to aid with FOG removal and cleaning. Passive flow devices are not electrical and require manual cleaning. The results of the FGI tests were analyzed and compared to the performance of a Washington Suburban Sanitation Commission (WSSC) designed retention-based grease interceptor (RGI). Experiments involved multiple parameters; including three emulsion strengths (weak, medium, and strong), two influent temperatures (70ºF and 100ºF), variable flows (the maximum-flow and half the maximum-flow of each device), and air induction. The extent of emulsion was manipulated by utilizing a number of static mixers in series and measuring the influent FOG globule size distribution. Evaluation of the GI removal performance was based on measurement of the influent and effluent total oil and grease concentrations.

Overall, the WSSC RGI consistently achieved the highest FOG removal at approximately 80% removal or higher under all tested conditions. The passive flow-based GI (PFGI) and the mechanical flow-based GI (MFGI) performed at 50% or less under the tested conditions. One exception occurred during the PFGI average weak-emulsion testing

where removal reached approximately 80%, which was likely due to the relatively weak-emulsion generated and the extended residence time.

Experiments were conducted with the two FGI units under 70°F and 100°F conditions. Overall, the removal efficiency decreased with increased temperature, likely due to the decreased surface tension that lead to smaller globules/stronger emulsion.

Air entrainment prior to the FGI has been speculated to aid in removal efficiency. However, this study found no significant difference in FOG removal performance when an air entrainment device was utilized.

The current protocol for evaluating FGI separation efficiency focuses on design, installation, and maintenance. However, this study finds emulsion strength and sufficient residence time are two significant contributors to the efficiency of these devices. Therefore, further assessment of FGI devices beyond the current protocol should be implemented to assure FOG removal from food service establishment (FSE) effluent.

Assessment of Internal and External Grease Interceptors for Removal of Food Based Fats, Oil, and Grease from Food Service Establishments

by
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APPROVED BY:

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DEDICATION

To John,

your love and patience have carried me through.

BIOGRAPHY

Erin was born and raised in Asheboro, NC. She completed her undergraduate degree in Chemistry at North Carolina State University and pursued a Master of Science in Civil Engineering at North Carolina State University under advisor Dr. Joel Ducoste.

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1. INTRODUCTION

The performance of grease interceptors (GI) has become an area of elevated interest in recent years. Recently, the Water Environment Federation (WEF) has suggested a consistent terminology for grease abatement devices, which this study will follow. The heightened interest of GIs, whether below the sink or outside and below ground, is directly related to the number of Sewer System Overflows (SSOs) occurring in the United States. The EPA reported in its 2004 Report to Congress that approximately 40,000 SSOs occur every year in the United States, with 47% attributable to fats, oil, and grease (FOG) accumulation in the sewer lines (EPA 2004). When only including the municipalities that report 100 or more SSOs per year, the accumulation jumps to 74% of all SSOs (EPA 2004). Currently, GIs are the primary means of removing FOG from Food Service Establishment (FSE) effluent before reaching the sewer system.

The objective of this study was to determine the removal efficiency of FOG from flow-based grease interceptors (FGI). Two FGI units were tested; one passive flow unit and one mechanical flow unit. Mechanical flow-based GIs (MFGI) incorporate the use of an electrical functioning skimmer to aid with FOG removal and cleaning. Passive flow-based GIs (PFGI) are not electrical and require manual cleaning. The results of the FGI tests were analyzed and compared to the performance of a Washington Suburban Sanitation Commission (WSSC) designed retention-based grease interceptor (RGI). The experiments conducted sought to understand and quantify the removal performance of these FGI devices

under different flow conditions and emulsion strengths. These testing characteristics were designed to mimic potential real-world influent conditions of FGIs.

The present research explores how well FGIs are able to remove FOG globules over a range of globule sizes to understand the FOG removal efficiency of these devices beyond the Plumbing and Drainage Institute (PDI) testing procedure. In addition, this research will explore the impact of temperature and air entrainment on the separation performance of FGIs.

2. BACKGROUND

2.1 Fats, Oils and Grease (FOG)

The EPA has identified FOG as a pollutant of concern, listed alongside other pollutants such as fertilizers, pesticides, and herbicides (EPA 2004). The release of FOG into the environment can have a deleterious effect, causing objectionable odors and consumption of dissolved oxygen necessary for different aquatic life forms (Cheremisinoff *et al.* 1989). FOG is the leading cause of sewer system blockages and accounts for nearly half of all SSO discharges (EPA 2004). The first line of defense is to prevent, or at least substantially decrease, the volume of FOG discharged into the sewer collection systems.

The EPA recognizes effective management of FOG as an important technique for controlling SSOs (EPA 2004). FOG typically enters a FSE plumbing system via dish washing, equipment cleaning, or floor cleaning (NCDPPEA 2006). WSSC considers a FSE to be an establishment where food is served to or provided for the public, with or without

charge (WSSC 2009). These "establishments include, but are not limited to, restaurants, cafeterias, hotel kitchens, church kitchens, school kitchens, hospital cafeterias, bars, or any other commercial operation that has the potential to discharge grease laden wastewater (WSSC 2009)." While FOG may enter the sewer collection system from high density residential dwellings, no GI is currently required to reduce the FOG discharge from these locations.

There are two types of FOG common to wastewater systems; petroleum-, animal-, and vegetable-based (Brown and Caldwell 1999). This study focused on the effects of animal- and vegetable-based FOG. Cheremisinoff *et al*. (1989) described five ways in which oil can exist in water (Table 2.1):

Table 2.1. Description of types of oil in water (Cheremisinoff *et al*. 1989)

Type of oil in water	Description
Free oil	quickly rises to surface given a short quiescent settling period
Mechanical dispersions	fine oil droplets with stability due to electrical charges and other forces, but not due to surface active materials; size range from microns to fractions of a millimeter
Chemical stabilized emulsions	oil droplet distribution similar to mechanical dispersions, but with additional stability due to chemical interactions, typically surface active agents at the surface
"Dissolved" oil	oil dispersed in such fine droplets (<5 microns) that removal by normal physical means (i.e., filtration, coalescence, gravity settling) is impossible
Oil-wet solids	oil adhered to the surface of particulate materials

Given the ability of FOG to present itself in many forms, it is important to determine the typical characteristics of the FSE effluent in order to choose the proper separator device (Cheremisinoff *et al*. 1989). The characteristics to be determined should include: the oil and bulk fluid densities, the oil rise velocity, the oil droplet size distribution, the presence of emulsifying agents, and the suspended solids content and distribution (Cheremisinoff *et al*. 1989).

2.2 Emulsions/Globule Distributions

An emulsion is simply defined as two immiscible liquids, with one of the liquids being dispersed as small spherical droplets in the other liquid (McClements 2007). The two typical

immiscible liquids in the food industry are oil and water, which exist in two emulsion consistencies, oil-in-water (O/W) and water-in-oil (W/O) (McClements 2007). Examples of O/W emulsions include milk, mayonnaise, and soups, while W/O emulsions include butter and margarine (McClements 2007).

Emulsion stability is commonly referred to as the ability of an emulsion to resist changes to its physicochemical properties over time (McClements 2007). The physicochemical properties are strongly influenced by droplet characteristics, i.e., droplet concentration, size, charge, interfacial properties, and interactions (McClements 2007).

The American Petroleum Institute (API) considers oil globules below 150 microns capable of forming stable emulsions with further physicochemical treatment needed for separation of smaller globules (API 1969). Aziz (2010) further detailed the processes necessary to remove oil globules from suspension that included: gravity separation (>150µm), coagulation/flotation (40µm - 150µm), and adsorption/membrane filtration (<40µm). Considering the mean diameter of droplets in emulsified food products (i.e. butter, milk, ice cream) typically fall in the 0.1 to 100 micron range (McClements 2007), it is important to gain knowledge of the influent globule distribution.

2.3 Grease Interceptors (GI)

Currently, FGI and RGI devices are the primary means of preventing significant discharge of FOG from FSEs into sewer systems. Each device employs the principle of gravity separation and allows for the accumulation of FOG at the surface. The proper design and regular maintenance of GIs are essential for effective performance (EPA 2004). In order

to meet the goal of effective performance, the EPA has defined four design criteria for GIs (EPA 2004):

- Sufficient volume to allow the wastewater to cool for separation
- Proper retention time for the FOG to separate from the wastewater
- Low turbulence to prevent FOG and solids from re-suspending
- Adequate volume to handle the accumulation of FOG and solids between cleanings

RGIs and FGIs differ in numerous ways, with the greatest difference being volumetric size and residence time due to the design flow rate. Inadequate residence time can significantly hamper separation performance even for globules that are within the gravity separable range (greater than 150 µm) (Patterson 1985). Past research has also shown that temperature, internal geometry, and emulsion strength play a significant role in GI efficiency (Ducoste and Aziz, 2008; Ducoste *et al.*, 2008).

GIs are required for any establishment introducing FOG into the drainage or sewer system in quantities large enough to cause line blockages (Brown & Caldwell 1999). The devices are required to receive the drainage from fixtures and equipment with FOG-laden waste, including, but not limited to: pot sinks, pre-rinse sinks, fresh meat cutting and prepping work, wok stations, floor drains, floor sinks, and dishwashers (WSSC 2009). FGIs are required for small to medium volume FSEs operating 8–16 hrs/day and/or serving 100-400 meals/day (Brown and Caldwell 1999). RGIs are required for high volume FSEs

operating 16+ hrs/day and/or serving 500+ meals/day (Brown and Caldwell 1999). FGI and RGI sizing Best Management Practices (BMPs) focus on the operation hours and/or meals served, while some municipalities opt for other methods. One other method includes sizing based on the FSE plumbing configuration (Town of Cary, 2010). WSSC RGI sizing is based on the tally of FSE drainage fixtures connected to the interceptor with FGI sizing based on maximum flow rate (WSSC 2010).

There is currently no consensus or scientific basis on the acceptable effluent performance of GIs. The Town of Cary acceptable effluent concentration values range from 275 to 325 mg/L (depending on the sampling method) (Town of Cary 2002). WSSC mandates an acceptable threshold of 100 mg/L for every FSE effluent concentration (WSSC 2010).

2.3.1 Flow-based Grease Interceptors (FGIs)

PDI defines a FGI as a plumbing appurtenance installed in a sanitary drainage system to intercept non-petroleum FOG from a wastewater discharge and is identified by flow rate, separation, and retention efficiency (PDI 2008). The design should also incorporate air entrainment, hydro mechanical separation, interior baffling, and/or barriers in combination or separately, and an external flow control, with air intake (PDI 2008).

FGIs can vary in flow-based volume from 4gpm to 250gpm. The most common size is less than 100gpm, with most FGIs falling in the range of 35 to 50gpm (Movahed 2010). PFGIs are not electrical, have no mechanical grease removal feature, and are cleaned and maintained by the FSE or a pumping contractor. PFGIs are commonly referred to as ‘hydro-

mechanical' when designed and installed with a flow control device and air intake, and referred to a 'grease trap' without air intake (WSSC 2009). MFGIs incorporate the use of an electrical functioning skimmer to aid with FOG removal and cleaning. MFGIs are commonly referred to as 'grease removal (or recovery) devices' (WSSC 2009). The typical price with installation for a PFGI would fall in the range of $2,000 to $4,000, with MFGI pricing $5,000 to $10,000 (Movahed 2010).

PDI currently has 278 certified FGIs. The internal geometry of each certified device varies by manufacturer with regulations based solely on its grease retention capacity. Research into the efficiency of these devices is still in its infancy, with no known FGI research in the literature.

2.3.2. Retention-based grease interceptors (RGIs)

PDI defines a RGI as a plumbing appurtenance installed in a sanitary drainage system to intercept non-petroleum FOG from a wastewater discharge and is identified by volume, 30-minute retention time, baffle(s), a minimum of two compartments, a minimum total volume of 300 gallons, and gravity separation (PDI 2008). The interceptors are designed by a registered professional engineer and are generally installed outside (PDI 2008). RGIs may be sized based on the number of drainage fixture units connected to it with a minimum volume of 300 gallons (WSSC 2009). The most common RGI size is around 1,500 gallons with devices as large as 4,000 gallons (Movahed 2010), though required internal geometries vary with different municipalities. The range of cost for the purchase and installation of a RGI is $5,000 to $50,000 (Movahed 2010).

2.3.3. RGI Past Research

RGI research has produced a litany of results, with no consensus on performance. Effluent concentrations and/or percent removal efficiencies have been reported in numerous papers with various sampling methods and utilizing different FOG concentration analysis methods.

Lesikar *et al*. performed a field analysis for RGIs in 28 restaurants ranging in size and food fare (Lesikar *et al*. 2006). Samples were taken after the RGI with average FOG values of 123 +/- 107 mg/L, using the EPA 1664 method for analysis. No influent samples were taken. Aziz *et al*. performed a field analysis of a full-fare cafeteria-style FSE over a two day period (Aziz *et al*. 2010). The influent concentration range was 5-1,240 mg/L (avg. 399 mg/L +/- 540 mg/L) and 99-1,130 mg/L (avg. 396 mg/L +/- 491 mg/L) in the effluent on day one, using the EPA 1664 method. Overall, the results suggest no distinguishable trend between the influent and effluent FOG concentration (Aziz *et al*. 2010). Aziz et al. also pointed out possible inadequacies with the EPA 1664, specifically its ability to exclude non-FOG background constituents in its concentration determination (Aziz *et al*. 2010). A study by Garza also found variable effluent concentrations during field trials though no influent samples were taken during the study (Garza 2004).

Chu and Hsu performed a study on FOG content of the various kitchen operation stations of three fast food restaurants ranging in size from small to large (Chu & Hsu 1998). Examples of the eight kitchen operation stations include pot and pan washing, meat defrosting, pre-boiled broth, and floor washing. The average effluent concentration range of

the stations was 12 to 23,579 mg/L with more than 60% of the FOG originating from pot, pan, and dish washing. No sample analysis method was mentioned. A significant decrease in RGI FOG loading was noted once kitchen practices were modified (Chu & Hsu 1998), such as scraping all food residues from dishes prior to washing and discarding all solidified FOG as solid waste.

Nisola *et al*. performed a study on the FOG removal efficiency of a lab-scale and full-scale RGI (Nisola *et al*. 2009). The laboratory and full-scale studies were then duplicated with the addition of an isolated microbial lipolytic strain to degrade the FOG (Nisola *et al*. 2009). The laboratory-scale research utilized soybean oil, which was emulsified in a 100 L container using a mixer at 250 rpm. The emulsion created was likely weak, with almost all globules falling into the readily separable range (>150 microns). The study found FOG removal efficiencies (microbial lipolytic non-treated RGI) of 90-99.9% during influent feeds up to 1,000 mg/L, while causing effluent concentrations to fall below the standard (i.e. 100 mg/L (Nisola *et al*. 2009)) when the influent feed was increased beyond 1,000 mg/L (Nisola *et al*. 2009). Nisola *et al*. utilized a partition gravimetric method to determine total FOG concentrations. The full-scale study found FOG removal efficiencies to be very unstable at 74.6 +/- 27.13%. It is unclear how this value was calculated considering the two sets of average influent values listed; 894 +/- 37.1 mg/L and 463.4 +/- 296.86 mg/L (Nisola *et al*. 2009).

2.4 FGI/RGI Certification Standard

The recognized standard for the maximum-flow rate and FOG retention rate of FGIs (defined by the PDI as 'hydro mechanical grease interceptors') was established in 1949. This standard is known as PDI-G101, which was most recently revised in March 2010. The American Society of Mechanical Engineers (ASME) has a similar standard, known as A112.14.3. These standards only apply to grease abatement devices designed for FOG laden waste; the standards do not incorporate fixtures carrying sanitary waste (PDI 2010^{B}). Essentially, the standard requires the heating of lard, which is a solid fat at room temperature. The liquid lard is poured atop the surface of one of the two compartment sinks filled with hot water. The water is drained from both sinks into the FGI located approximately 10 feet below. Flow rate is evaluated by the drainage time of a certain volume from the test sink (the tested unit includes a flow control valve to safeguard against the flow exceeding the maximum-flow rate). The effluent from the FGI is drained into a skimming tank where readily separable FOG is collected from the surface.

Skimming initiates five minutes after the sinks have been drained into the FGI and continues until negligible FOG is present on the surface. Consequently, only skimmed FOG is quantified and no knowledge of FOG in suspension is measured. The collected FOG is weighed and compared with the initial lard added to determine removal, giving the FOG retention rate. This process is repeated continuously until two consecutive average efficiencies reach less than 90% or an incremental efficiency reaches less than 80%; which is considered test failure or breakdown point of the device. The grease retention capacity is

determined by pounds of grease retained. The grease retention capacity rating is established at the point where grease retained falls below two times the maximum-flow rate.

PDI literature also addresses the use of baffle walls and air entrainment to improve FOG removal efficiency. Given that PDI certified FGIs are relatively small, they rely on accomplishing the separation efficiency by the use of specially engineered internal baffling arrangements used in conjunction with an external vented flow control device (PDI 1998).

Historically, RGIs (defined by PDI as 'gravity grease interceptors') have not had an established standard. However, PDI published recommendations on RGI sizing, procedures, and installation in March 2010. The sizing is based on either influent pipe size or fixture compartment size with the requirement of a one or two minute drainage period (PDI 2010[B]).

3. METHODS

3.1 Grease Interceptors

Three devices were analyzed in this study; a 10gpm rated PFGI (residence time of 30 seconds), a 25gpm rated MFGI (residence time of 1 minute), and a bench-scale WSSC designed RGI rated at a maximum 0.9gpm flow to produce a residence time of 30 minutes.

The 10gpm PFGI is a PDI certified device. The internal design incorporates an L-shaped, uniformly holed metal dispersion plate at the inlet and is otherwise empty (Figure 3.1a).

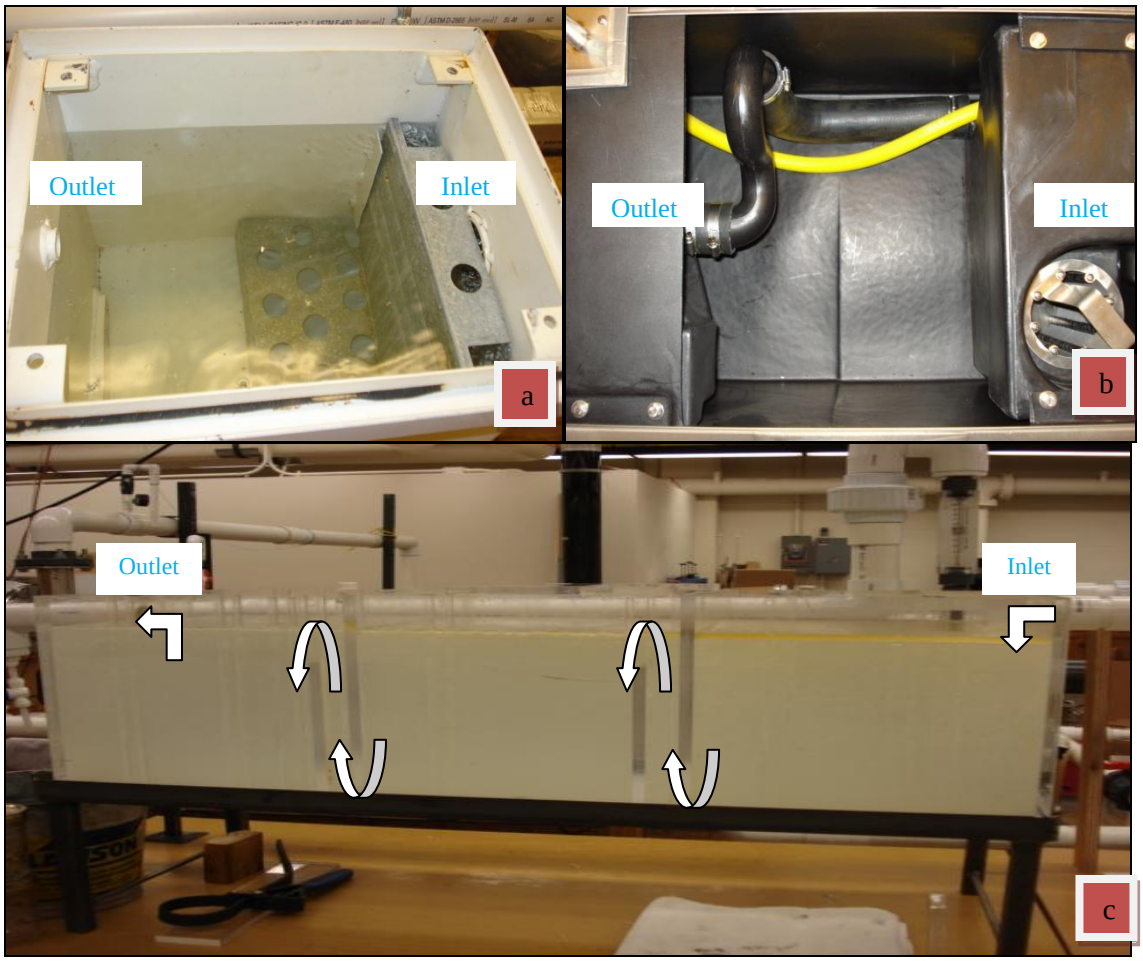

Figure 3.1. Internal views of the a) PFGI, b) MFGI and c) RGI.

The 25gpm MFGI (Figure 3.1b) is an ASME certified device. The internal design of this device is quite complicated when compared to the PFGI. Once the flow enters the MFGI at the inlet, it flows upward through a strainer basket and over a 'baffle wall' in the direction of the inlet. The flow travels down and under the baffle wall to the main compartment of the MFGI. Once the flow reaches the outlet end, it travels up another 'baffle-like' component into the outlet. The MFGI used in this study incorporates an automatic solids transfer (AST)

device meant to extinguish food from the inlet compartment and a heating unit with an electric skimmer. These components, however, were not used during this study.

The WSSC RGI is a 27 gallon bench-scale model with two pairs of internal baffle walls. The two pairs of baffle walls converted the RGI into a three compartment device where flow must travel under the first baffle and up and over the second (Figure 3.1c). The WSSC RGI model has been used in the field for more than 10 years and is a modification of the typically utilized two compartment RGI.

3.2 Pilot Model Design

Figure 3.2 displays a detailed schematic of the pilot system testing facility.

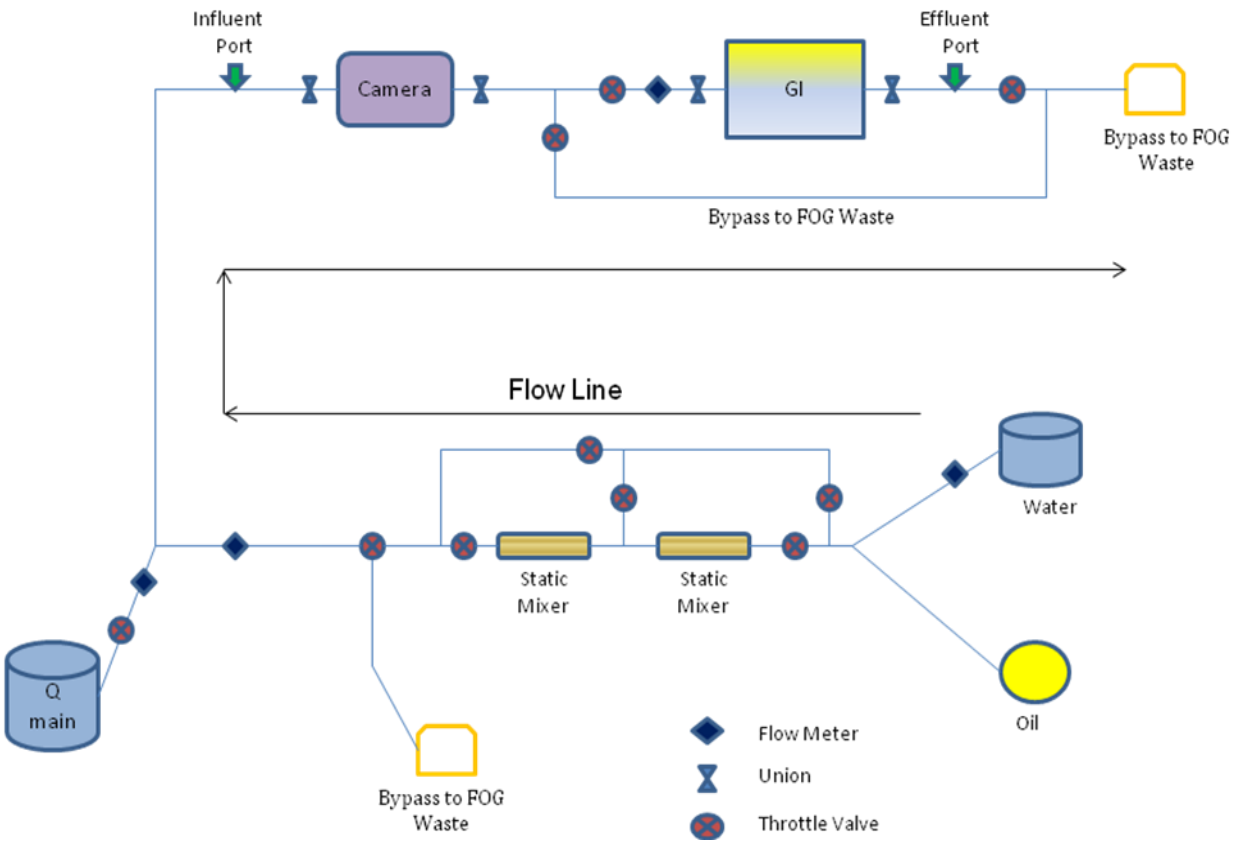

Figure 3.2. Pilot Scale Schematic.

In this study, corn oil was used to represent FOG. Static mixers were incorporated in the setup to produce the FOG emulsion. The static mixer assembly is complete with throttle valves to allow for bypass or inclusion of one or two static mixers. Flow meters were included at the two pure water inflows, just before the emulsion joins the main flow and also just before the GI. The oil flowed through a peristaltic pump before joining the pure water inflow at the junction before the static mixers. There is an influent port just before the camera setup and an effluent port just after the GI. The influent port location was positioned just before the camera setup to establish a direct relationship between the oil concentration and globule size. The camera section has a larger pipe diameter than the incoming PVC piping. This difference in pipe diameter also played a part in the placement of the influent port. The emulsion contribution to the flow was maintained throughout the experiment. To maintain steady state mixing conditions, a constant oil/water ratio was used during emulsion generation. The necessary concentrations were then regulated by wasting from the pre-mixed oil/water emulsion line. The camera section incorporated an acrylic three inch tube where FOG globule pictures were taken. This setup allowed the camera to easily focus and capture the relatively fast flowing, small oil globules. After each experiment, pictures were transferred to computer software, which evaluated and enumerated the oil globules. Refer to Appendix A – Pilot Model Experiment Setup Checklist and Appendix B – Experimental Process for further description.

3.3 Emulsion Generation

Three different emulsions were generated; weak, medium, and strong. The strong-emulsion was created by utilizing two of the static mixers in series (Figure 3.2). The

medium-emulsion was created by utilizing one static mixer, which produced intermediate emulsion strength. The weak-emulsion was created by bypassing the flow around both static mixers and allowing the background pipe turbulence to create an emulsion. The goal influent concentration for each experimental condition was 1250 mg/L. Though the emulsion generation in each FGI experiment was consistent, variations in flow and temperature caused differences in the globule sizes. In other words, the weak-emulsion condition for the 25gpm FGI experiments produced smaller globules due to the shearing of the increased water flow compared to the weak-emulsion condition for the 10gpm FGI experiments. A relatively stronger emulsion was produced for RGI testing than the emulsion produced for the FGI testing, due to a higher emulsion generation flow needed for RGI testing. However, image analysis of the FOG globules was performed for each experimental condition, whether caused by increased or decreased flow or altered oil inputs during emulsion generation. Therefore, all experimental influent globule size distributions were quantified.

3.4 Flow Variation/Residence Time

Each GI was challenged with two flows; maximum and average. The maximum-flow is the maximum-flow through the device at steady state. The average-flow is approximately half of the maximum-flow. The maximum-flow for the FGI devices was based on PDI certified maximum-flow rates. The RGI maximum-flow was based on the suggestion that an HRT of 30 minutes or greater is necessary for adequate FOG removal (Metcalf and Eddy 1991).

Table 3.1 outlines the flows and residence times of each FOG separation device.

Table 3.1. Flows of each device.

Device	Maximum-flow (Residence Time)	Average-flow (Residence Time)
PFGI	10 gpm (30 seconds)	5 gpm (1 minute)
MFGI	25 gpm (1 minute)	12.5 gpm (2 minutes)
RGI	0.9 gpm (30 minutes)	0.45 gpm (60 minutes)

It is important to challenge the devices with different flows to simulate the potential nature of variable FSE kitchen flows. Different flow conditions (i.e. different residence times) may produce significant changes in FOG removal efficiency.

3.5 Air Induction

PDI literature (PDI 1998) suggests the inclusion of an air induction device to improve the FOG removal efficiency in the FSE effluent stream. The air induction device is meant to cause negative pressure and thus entrain air under atmospheric conditions. The induced air bubbles are thought to aid in the separation of the FOG globules from the flow stream by attaching to the bubbles and subsequently increasing the rise velocity.

The air induction device was installed into the PFGI setup (Figure 3.3). A plastic tube was attached to a metal nipple screwed into the hole on the top portion of the device.

Figure 3.3. Air Induction device with PFGI setup.

3.6 Temperature Variation

Experiments were conducted at room temperature (~70°F) and at an elevated temperature condition (~100°F). The variation in temperature was an important characteristic to analyze of the FSE waste stream to determine any changes in FOG removal efficiency with temperature variations.

3.7 Total Oil and Grease (TOG) Sample Preparation

Influent and effluent grab samples were taken during each experiment. Samples were taken after three hydraulic residence times (HRT) (i.e., three minutes for the 25 gpm flow condition and six minutes for the 12.5 gpm flow condition) to assure a steady state FOG effluent concentration. The samples were immediately acidified with hydrochloric acid to a pH less than 2 per recommendation of common FOG extraction procedures (EPA Method 1664, Standard Methods 5520B). The samples were refrigerated at 4°C until use. Samples

were deemed invalid if they remained refrigerated for greater than one month prior to testing (EPA Method 1664, Standard Methods 5520B). Each experimental condition was completed and analyzed three times to verify results.

3.8 Liquid-Liquid Extraction

During the extraction phase, the samples were poured from the 400 mL sample jars to a 500 mL separatory funnel. 30 mL of n-hexane (Optima, 95%) was then added with a 10 mL volumetric pipette to the empty sample jar. The contents of the jar were then added to the 500 mL separatory funnel. The separatory funnel was shaken vigorously for exactly two minutes with periodic venting. Following this mixing/venting step, the sample was left stationary for exactly 10 minutes to allow clear phase separation. After 10 minutes, the water layer was drained back into the sample jar via the stopcock at the bottom of the separatory funnel. A very small quantity of the extracted (organic) layer was allowed to pass into the sample jar to minimize the residual water in the organic layer. The above procedure describes the process for a single extraction of a sample. A single sample underwent two extractions with marginal FOG recovery noted beyond the second extraction. Refer to Appendix D – Sample Analysis (Liquid-Liquid Extraction and Distillation) for further description.

3.9 Distillation

Distillation of the extracted material was performed through procedures specified in standard oil and grease measurement guidelines (EPA Method 1664, Standard Methods 5520B). As the solvent used was n-hexane, the samples were distilled in a water bath. A boiling flask was connected to a Claisen-type distillation head and a West-type condenser. A

thermometer within the distillation head ensured that the appropriate temperature was achieved for distillation (~70°C). Generally, the solvent was fully evaporated after approximately 15 minutes within the water bath. After 15 minutes, the flask was dried and put on a vacuum for a few minutes to ensure the removal of n-hexane vapors. The boiling flask was then placed in an oven at 70 °C for thirty minutes. After this drying step, the flask was placed in a dessicator until room temperature was achieved. The dried flasks were then weighed to determine the extracted mass. Refer to Appendix D – Sample Analysis (Liquid-Liquid Extraction and Distillation) for further description.

3.10 Extraction Calculations

The oil concentration of each grab sample was calculated using Equation 3-1.

$$\text{Oil Concentration } (mg/L) = \frac{(\text{Dried Flask Wt.} - \text{Clean Flask Wt.})}{\text{Grab Sample Volume}}$$

Equation 3-1

The oil concentration of the influent and effluent grab samples were compared to determine percent removal performed by the FGI/RGI using Equation 3-2.

$$\text{Percent Removal } (\%) = \frac{(\text{Influent Conc.} - \text{Effluent Conc.})}{\text{Influent Conc.}} * 100$$

Equation 3-2

3.11 Image Analysis

Pictures were taken during each emulsion, flow, and temperature condition. The pictures were taken with a Canon EOS Rebel XSI digital camera equipped with a Canon EF-

S60mm f/2.8 Macro USM lens. A 10 mm scale was utilized to scale the pictures with the oil globules within the acrylic tube. Globule sizes were then quantified using ImageJ software (Rasband 2009). The ImageJ image analysis software enumerated at least 400 globules for each image. In a study of oil droplet breakup by Clark, it was found that in order to produce a 95 percent or better confidence interval for the average droplet size, the total number of droplets measured must be greater than 90 (Clark 1985).

Figure 3.4 displays a picture of the globules captured during a maximum-flow weak-emulsion experimental run. The 10 mm scale can be seen in the center of the picture. Refer to Appendix C – Experimental Photography Process for further description.

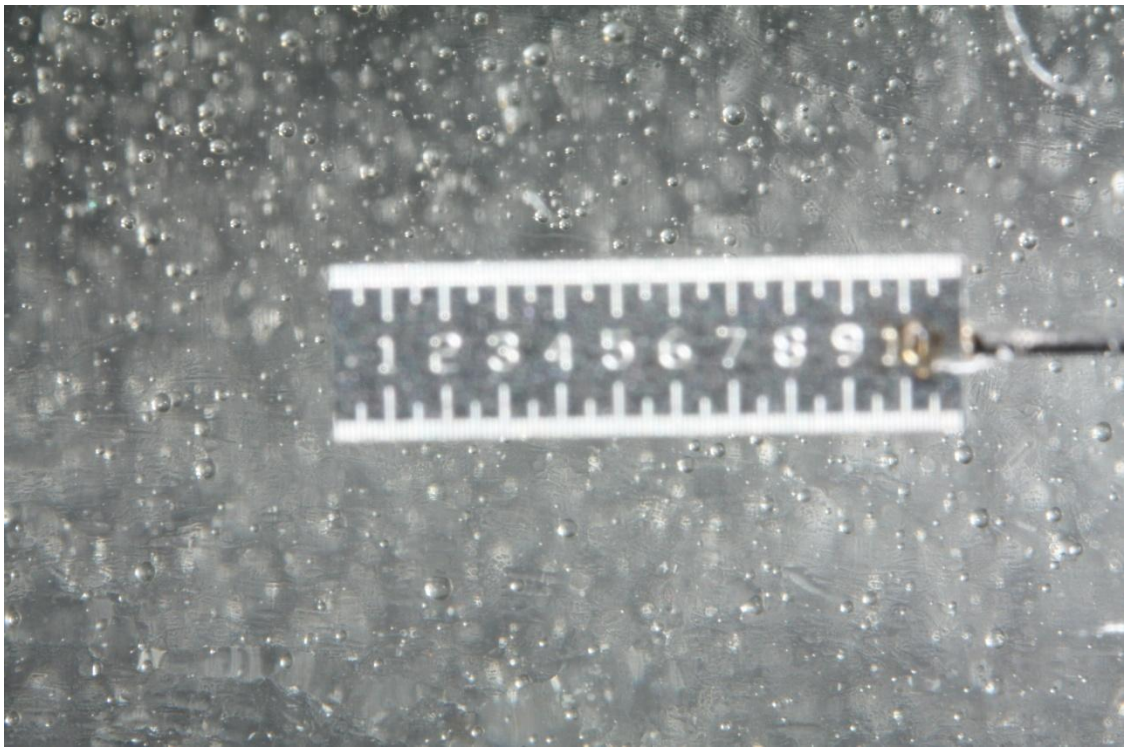

Figure 3.4. Picture of oil globules a maximum-flow weak-emulsion experimental run.

The volume weighted mean was chosen to analyze the globule distribution due to its sensitivity to larger particles/globules (McClements 2007). The volume-weighted mean is one of the most commonly used mean particle size values; in addition to the number-weighted mean diameter ($d_{1,0}$) and the surface-weighted mean diameter ($d_{3,2}$) (McClements 2007). The volume weighted mean diameter ($d_{4,3}$) was calculated using the globule diameters enumerated by ImageJ software, using Equation 3-3.

$$\bar{d}_{4,3} = \sum\left(\frac{d^3 * d}{\Sigma d^3}\right).$$

Equation 3-3

where d^3 stands for the globule volume and d stands for the globule diameter.

The volume fraction was utilized, in lieu of the number fraction, to represent the particle/globule concentration of each particular size class. McClements found that using a number fraction to present the data can essentially delete the contribution of the larger globules, since the relatively larger globules may make-up an appreciable amount of the overall volume, often greater than 25 % (McClements 2007).

4. JOURNAL ARTICLE

Title: Assessment of Internal and External Grease Interceptors for Removal of Food Based Fats, Oil, and Grease from Food Service Establishments.

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ABSTRACT

The objective of this study was to determine the removal efficiency of fats, oil, and grease (FOG) of flow-based grease interceptors (FGI). Two FGI units were tested; one passive flow unit and one mechanical flow unit. Mechanical flow-based devices incorporate the use of an electrical functioning skimmer to aid with FOG removal and cleaning. Passive flow-based devices are not electrical and require manual cleaning. The results of the FGI tests were analyzed and compared to the performance of a Washington Suburban Sanitation Commission (WSSC) designed retention-based grease interceptor (RGI). Experiments involved multiple parameters; including three emulsion strengths (weak, medium and strong), two influent temperatures (70ºF and 100ºF) and two flow rates (the maximum-flow and half the maximum-flow of each device). Oil/water emulsion consists of passing corn oil through in-line static mixers located upstream from the FGI inlet. The extent of emulsion was manipulated by utilizing a number of static mixers in series and measuring the FOG globule size distribution. Evaluation of the FGI removal performance was based on measurement of the influent and effluent total oil and grease concentrations.

Overall, the WSSC RGI consistently achieved the highest FOG removal at approximately 80% removal or higher under all tested conditions. The passive FGI (PFGI) and the mechanical FGI (MFGI) performed at 50% or less under the tested conditions. One exception occurred during the PFGI average weak-emulsion testing where removal reached approximately 80% and was likely due to the relatively weak-emulsion and the extended residence time.

This study also sought to determine the impact of temperature and air induction on FGI FOG removal performance. Experiments were conducted with the two FGI units under 70°F and 100°F conditions. Overall, the removal efficiency decreased with increased temperature. This study also found no significant difference in FOG removal performance when an air entrainment device was utilized.

The current protocol for evaluating GI separation efficiency focuses on design, installation, and maintenance. However, this study finds emulsion strength and sufficient residence time are two significant contributors to the efficiency of these devices. Therefore, further assessment of FGI devices beyond the current protocol should be implemented to assure FOG removal from food service establishment (FSE) effluent.

4.1 INTRODUCTION

The EPA has identified FOG as a pollutant of concern, listed alongside other pollutants such as fertilizers, pesticides, and herbicides, and as the leading cause of sewer system blockages accounting for nearly half of all Sewer System Overflow (SSO) discharges (EPA 2004). The first line of defense is to prevent, or at least substantially decrease, the volume of FOG discharged into the sewer collection system. There are three types of FOG common to wastewater systems; petroleum-, animal-, and vegetable-based (Brown and Caldwell 1999). This study will focus on the effects of animal- and vegetable-based FOG.

FOG typically enters a Food Service Establishments (FSEs) plumbing system via dish washing, equipment cleaning, or floor cleaning (NCDPPEA 2006). Cheremisinoff *et al*. defined five ways in which oil can exist in water; free oil, mechanical dispersions, chemical stabilized emulsions, "dissolved" oil, and oil-wet solids (Cheremisinoff *et al*. 1989). Cheremisinoff et al. (1989) mentioned that the selection of the appropriate FOG separator device will depend on the form of discharged FOG by the FSE. The characteristics of FOG that should be analyzed include: the oil and bulk fluid densities, the oil rise velocity, the oil droplet size distribution, the presence of emulsifying agents, and the suspended solids content and distribution (Cheremisinoff *et al*. 1989). Given that emulsions will impact the droplet size and oil rise velocity, this study employed tests with varying emulsion strengths.

The American Petroleum Institute (API) considers oil globules below 150 microns capable of forming stable emulsions with further physicochemical treatment needed for separation of smaller globules (API 1969). Considering the mean diameter of droplets in

emulsified food products (i.e. butter, milk, ice cream) typically fall in the 0.1 to 100 micron range (McClements 2007), it is important to gain knowledge of the influent globule distribution when testing the removal efficiency of the grease abatement device.

Currently, grease abatement devices, whether below the sink or outside and below ground, are the primary means of removing FOG from FSE effluent before reaching the sewer system. Recently, the Water Environment Federation (WEF) suggested a consistent terminology for grease abatement devices, which this study will follow. Therefore, devices located within the FSE and under the sink will be referred to as flow-based grease interceptors (FGI), whereas, devices located outdoor-underground will be referred to as retention-based grease interceptors (RGI). Each device works under the principle of gravity separation and allows for the accumulation of FOG at the surface with proper design and regular maintenance critical for effective performance (EPA 2004).

RGIs and FGIs differ in numerous ways, with the greatest difference being volumetric size (i.e. residence time based on the design flow rate). Inadequate residence time can significantly hamper separation performance even for globules that are within the gravity separable range (greater than 150 µm) (Patterson 1985). Past research has also shown that temperature, internal geometry, and emulsion strength play a significant role in GI efficiency (Ducoste and Aziz 2008, Ducoste *et al.* 2008). Aziz et al. (2010) observed the changes in RGI efficiency with the use of different inlet designs. Understanding the complexity of RGI designs and utilizing knowledge of the flow pattern, flow type, and quantity of influent FOG and solids are essential for the proper RGI design (Aziz et al. 2010).

FGIs can vary in flow-based volume from 4gpm to 250gpm and are defined as either passive-flow or mechanical-flow. The most common size is less than 100gpm, with most falling in the range of 35 to 50gpm (Movahed 2010). Passive FGIs (PFGIs) are not electrical and have no mechanical grease removal feature. PFGIs are commonly referred to as 'hydro-mechanical' when designed and installed with a flow control device with air intake and referred to a 'grease trap' without air intake (WSSC 2009). Mechanical FGIs (MFGIs) incorporate the use of an electrical functioning skimmer to aid with FOG removal and cleaning. MFGIs are commonly referred to as 'grease removal (or recovery) devices' (WSSC 2009).

The Plumbing and Drainage Institute (PDI) currently has 278 certified FGIs. The standard is known as PDI-G101, which was most recently revised in March 2010. The American Society of Mechanical Engineers (ASME) has a similar standard, known as A112.14.3. These standards only apply to GIs designed for FOG laden waste; the standards do not incorporate fixtures carrying sanitary waste (PDI 2010[B]). Essentially, the standard requires the heating of lard (solid fat at room temperature) that is poured atop the surface of a two compartment sink filled with hot water. The water and heated lard are drained to a FGI unit below. The internal geometry of each certified device varies by manufacturer with regulations based solely on its grease retention capacity. Research into the efficiency of these devices is still in its infancy, with no known FGI research in publication. The most common RGI size is around 1,500 gallons with devices as large as 4,000 gallons (Movahed 2010).

Currently, no certification test includes any procedure to evaluate the performance of FGIs or RGIs to remove influent FOG concentration in the form of oil/water emulsions.

4.2 METHODS

4.2.1 Grease Interceptors

Three devices were analyzed in this study; a 10gpm rated PFGI (residence time of 30 seconds), a 25gpm rated MFGI (residence time of 1 minute), and a WSSC designed RGI rated at a maximum 0.9gpm flow to produce a residence time of 30 minutes (Figure 4.1).

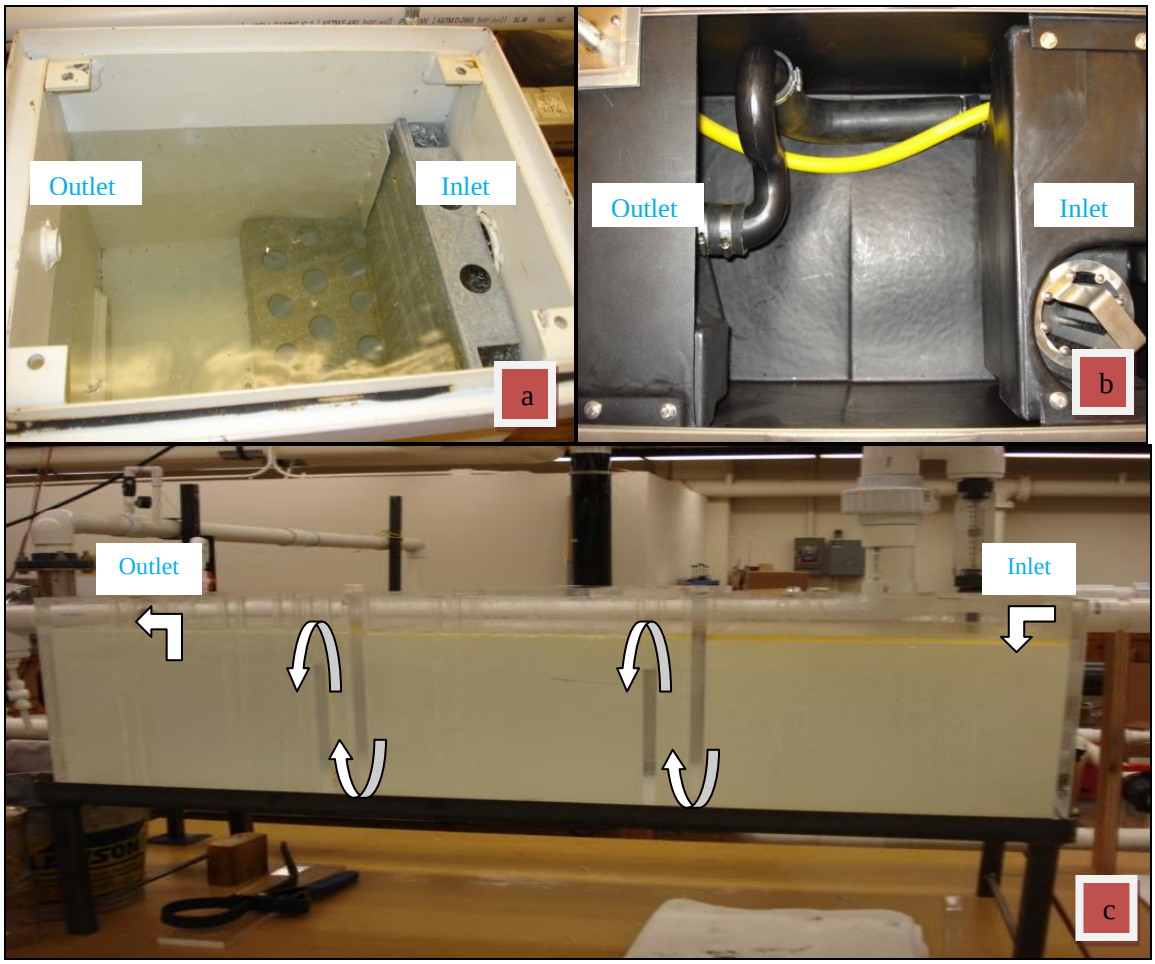


Figure 4.1. Internal views of the a) PFGI, b) MFGI, and c) RGI.

The 10gpm PFGI (Figure 4.1a) is a PDI certified device. The internal design incorporates an L-shaped, uniformly holed metal dispersion plate at the inlet and is otherwise empty. The 25gpm MFGI (Figure 4.1b) is an ASME certified device. The internal design of this device is quite complicated when compared to the PFGI. Once the flow enters the MFGI at the inlet, it flows upward through a strainer basket and over a 'baffle wall' in the direction of the inlet. The flow travels down and under the baffle wall to the main compartment of the MFGI. Once the flow reaches the outlet end, it travels up another 'baffle-like' component

into the outlet. The MFGI used in this study incorporates an automatic solids transfer (AST) device meant to extinguish food from the inlet compartment and a heating unit with an electric skimmer. These components, however, were not used during this study. The WSSC RGI (Figure 4.1c) is a 27 gallon bench-scale model with two pairs of internal baffle walls. The two pairs of baffle walls converted the RGI into a three compartment device where flow must travel under the first baffle and up and over the second. The WSSC RGI model has been used in the field for more than 10 years and is a modification of the typically utilized two compartments RGI.

4.2.2 Pilot Model Design

Figure 4.2 displays a detailed schematic of the pilot system testing facility.

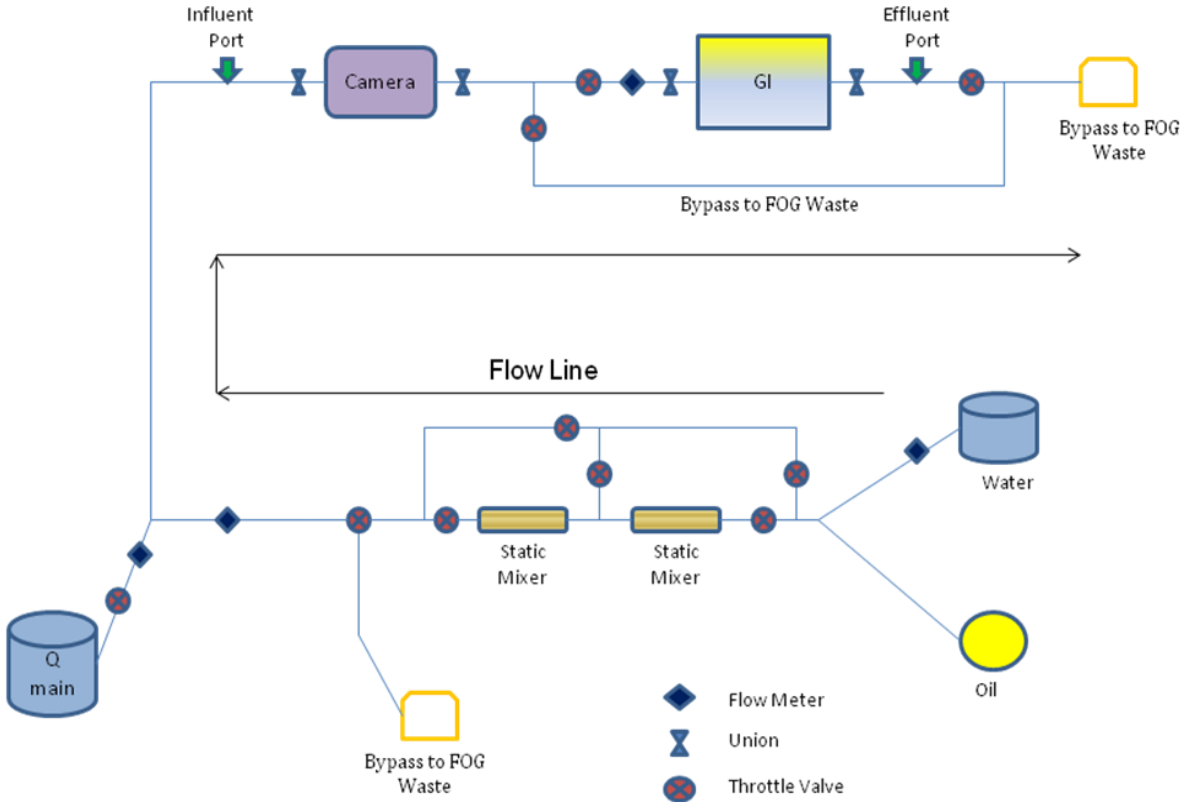


Figure 4.2. Pilot Scale Schematic.

In this study, corn oil was used to represent FOG. Static mixers were incorporated in the setup to produce the FOG emulsion. The static mixer assembly is complete with throttle valves to allow for bypass or inclusion of one or two of the static mixers. Flow meters were included at the two pure water inflows, just before the emulsion joins the main flow and also just before the GI. The oil flowed through a peristaltic pump before joining the pure water inflow at the junction before the static mixers. There is an influent port just prior to the camera setup and an effluent port just after the GI. The influent port location was positioned just before the camera setup to establish a direct relationship between the oil concentration and globule size. The camera section has a larger pipe diameter than the incoming PVC piping. This difference in pipe diameter also played a part in the placement of the influent port. The emulsion contribution to the flow was maintained throughout the experiment. To maintain steady state mixing conditions, a constant oil/water ratio was used during the emulsion generation. The necessary concentrations were then regulated by wasting from the pre-mixed oil/water emulsion line. The camera section incorporated an acrylic three inch tube where FOG globule pictures were taken. This setup allowed the camera to easily focus and capture the relatively fast flowing, small oil globules. After each experiment, pictures were transferred to computer software, which evaluated and enumerated the oil globules.

4.2.3 Emulsion Generation

Three different emulsions were generated; weak, medium, and strong. The strong-emulsion was created by utilizing two of the static mixers in series (Figure 4.2). The medium-emulsion was created by utilizing one static mixer, which produced intermediate emulsion strength. The weak-emulsion was created by bypassing the flow around both static

mixers and allowing the background pipe turbulence to create an emulsion. Though the emulsion generation in each FGI experiment was consistent, variations in flow and temperature caused differences in the globule sizes. However, image analysis of the FOG globules was performed for each experimental condition, whether caused by increased or decreased flow or altered oil inputs during emulsion generation. Therefore, all experimental influent globule size distributions were quantified.

4.2.4 Flow Variation/Residence Time

Each grease abatement device was challenged with two flows; maximum and average. The maximum-flow is the highest flow through the device at steady state. The average-flow is approximately half of the maximum-flow. Table 4.1 outlines the flows and residence times of each FOG separation device.

Table 4.1. Flows of each device.

Device	Maximum-flow (Residence Time)	Average-flow (Residence Time)
PFGI	10 gpm (30 seconds)	5 gpm (1 minute)
MFGI	25 gpm (1 minute)	12.5 gpm (2 minutes)
RGI	0.9 gpm (30 minutes)	0.45 gpm (60 minutes)

4.2.5 Air Induction

PDI literature (PDI 1998) suggests the inclusion of an air induction device will improve the FOG removal efficiency in the FSE effluent stream. The air induction device is meant to cause negative pressure and thus entrain air under atmospheric conditions. The induced air bubbles are thought to aid in the separation of the FOG globules from the flow

stream by attaching to the bubbles and subsequently increasing the rise velocity. The air induction device was installed into the PFGI setup approximately two feet prior to the inlet.

4.2.6 Temperature Variation

Experiments were conducted at room temperature (~70°F) and at an elevated temperature condition (~100°F). The variation in temperature was an important characteristic to analyze of the FSE waste stream to determine any changes in FOG removal efficiency with temperature variations.

4.2.7 Total Oil and Grease (TOG)

Influent and effluent grab samples were taken during each experiment at maximum and average-flows. To assure a steady state FOG effluent concentration, samples were taken after three hydraulic residence times (HRT). The samples were immediately acidified with hydrochloric acid to a pH less than 2 per recommendation of common FOG extraction procedures (EPA Method 1664, Standard Methods 5520B). The samples were refrigerated at 4°C until use. Samples were deemed invalid if they remained refrigerated for greater than one month prior to testing (EPA Method 1664, Standard Methods 5520B). Each experiment was completed three times to verify results.

During the extraction phase, the samples were poured from the 400 mL sample jars to a 500 mL separatory funnel. 30 mL of n-hexane (Optima, 95%) was then added with a 10 mL volumetric pipette to the empty sample jar. The contents of the jar were then added to the 500 mL separatory funnel. The separatory funnel was shaken vigorously for exactly two minutes with periodic venting. Following this mixing/venting step, the sample was left stationary for

exactly 10 minutes to allow clear phase separation. After 10 minutes, the water layer was drained back into the sample jar via the stopcock at the bottom of the separatory funnel. A very small quantity of the extracted (organic) layer was allowed to pass into the sample jar to minimize the residual water in the organic layer. The above procedure describes the process for a single extraction of a sample. A single sample underwent two extractions with marginal FOG recovery noted beyond the second extraction.

Distillation of the extracted material was performed through procedures specified in standard oil and grease measurement guidelines (EPA Method 1664, Standard Methods 5520B). As the solvent used was n-hexane, the samples were distilled in a water bath. A boiling flask was connected to a Claisen type distillation head and a West type condenser. A thermometer within the distillation head ensured that the appropriate temperature was achieved for distillation (70°C). Generally the solvent was fully evaporated after approximately 15 minutes within the water bath. After 15 minutes, the flask was dried and put on a vacuum for a few minutes to ensure the removal of n-hexane vapors. The boiling flask was then placed in an oven at 70 °C for thirty minutes. After this drying step, the flask was placed in a dessicator until room temperature was achieved. The dried flasks were then weighed to determine the extracted mass.

The oil concentration of each grab sample was calculated using Equation 4-1.

$$\text{Oil Concentration } (mg/L) = \frac{(\text{Dried Flask Wt.} - \text{Clean Flask Wt.})}{\text{Grab Sample Volume}}$$

Equation 4-1

The oil concentration of the influent and effluent grab samples were compared to determine percent removal performed by the FGI/RGI using Equation 4-2.

$$\text{Percent Removal}\,(\%) = \frac{(\text{Influent Conc.} - \text{Effluent Conc.})}{\text{Influent Conc.}} * 100$$

Equation 4-2

4.2.8 Image Analysis

Pictures were taken for each emulsion condition during maximum and average-flows of each experiment. The pictures were taken with a Canon EOS Rebel XSI digital camera equipped with a Canon EF-S60mm f/2.8 Macro USM lens. A 10 mm scale was utilized to scale the pictures with the oil globules within the acrylic tube. Globule sizes were then quantified using ImageJ software (Rasband 2009). The ImageJ image analysis software enumerated at least 400 globules for each image. In a study of oil droplet breakup by Clark, it was found that in order to produce a 95 percent or better confidence interval for the average droplet size, the total number of droplets measured must be greater than 90 (Clark 1985).

The volume weighted mean was chosen to analyze the globule distribution due to its sensitivity to larger globules (McClements 2007). The volume weighted mean diameter ($d_{4,3}$) was calculated using the globule diameters enumerated by ImageJ software, using Equation 4-3.

$$\bar{d}_{4,3} = \sum\left(\frac{d^3 * d}{\Sigma d^3}\right),$$

Equation 4-3

where d^3 stands for the globule volume and d stands for the globule diameter.

Volume fraction was utilized to represent the globule concentration of each particular size class. McClements (2007) found that using a number fraction to present the data can essentially delete the important contribution of the larger globules, towards the separated amount of total oil and grease.

4.3 RESULTS AND DISCUSSION

4.3.1 Passive Flow-based Grease Interceptor

4.3.1a Maximum/Average-flows at 70°F Condition

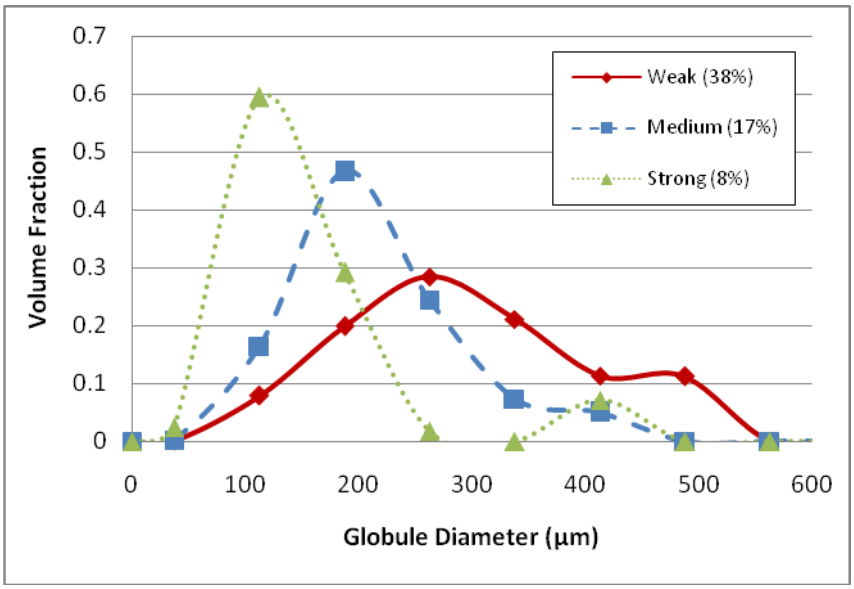
The percent removal results of the 70ºF PFGI experiments are listed in Table 4.2.

Table 4.2. Percent removal data from 70°F PFGI experiments, with standard deviations.

Emulsion Strength	Maximum-flow (10 gpm)	Average-flow (5 gpm)
Weak (0 static mixers)	38% +/- 7%	82% +/- 2%
Medium (1 static mixer)	17% +/- 3%	46% +/- 0.2%
Strong (2 static mixers)	8% +/- 0.3%	38% +/- 2%

In Table 4.2, the strong-emulsion strength experiments produced the least FOG removal while the weak-emulsion strength produced the greatest FOG removal. The strong versus weak-emulsion strength removal trend is apparent in both the maximum and average-flow conditions. It is also important to observe the impact on FOG percent removal when flow is decreased from maximum to average. The weak-emulsion strength displays a greater increase in percent removal (~40%) when flow is reduced to average conditions, whereas, the

stronger emulsion strengths display a smaller increase in percent removal (~30%). The relatively low percent removal of the stronger emulsion strengths, during maximum and average-flow conditions, displays the difficulty of removing smaller oil globules from FSE wastewater regardless of the FGI residence time. Figure 4.3 displays the image analysis data for the PFGI 70ºF experiments at maximum conditions, with $d_{4,3}$ values listed in the adjacent chart.



Emulsion strength	$d_{4,3}$ (µm) with standard deviation
Weak	288.3 +/- 83.9
Medium	210.4 +/- 58.4
Strong	150.7 +/- 40.2

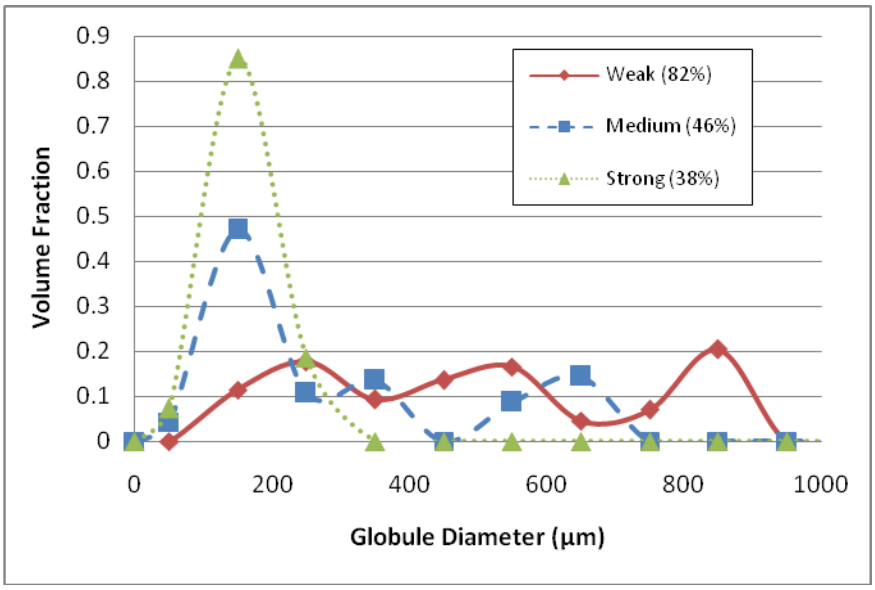
Figure 4.3. PFGI at 70ºF maximum-flow condition (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

The three emulsion strengths under the maximum flow condition produce similar trends with each producing a large peak between 150 and 300 microns and another smaller peak between 400 and 500 microns. Below 200 microns, the strong-emulsion contains the largest fraction of globules followed by the medium-emulsion and then the weak-emulsion. The $d_{4,3}$ values for each emulsion strength supports the decrease in removal as the emulsion strength increases (weak – 38% removal ($d_{4,3}$ = 288.3µm), medium – 17% removal ($d_{4,3}$ =

210.4µm), strong – 8% ($d_{4,3}$ = 150.7µm)). The opposite trend was found when comparing the fraction of large globules above 350µm with the strong-emulsion containing the smallest fraction followed by the medium-emulsion then the weak-emulsion. The strong-emulsion produced the largest peak in the smaller globule range (approximately 150 microns), which is an expected result with the use of two static mixers during emulsion generation. The medium-emulsion gave an initial peak at approximately 200 microns with the weak-emulsion peak around 275 microns.

The globule size results displayed in Figure 4.3 paints a complex picture within the influent pipe. With the medium and strong-emulsions, a fluid shear globule size interaction is setup such that the smaller globules produced can readily coalesce at a faster rate with increasing fluid shear but the large globules undergo more breakup due to those same forces. Consequently, the globule size distribution tends to narrow (i.e., a decreasing statistical variance) with increasing emulsion strength. Figure 4.3 also suggests that under the weak-emulsion condition, the low fluid shear does not cause any significant breakup of the larger globules. In addition, the presence of larger globules with the weak-emulsion condition may allow for additional slow coalescence with the larger globule sizes and result in the formation of an oil layer at the flow surface. Once globules coalesce and seek the surface, they cannot be captured by image analysis, meaning the larger globules may not all be represented in Figure 4.3. If the globules could be captured by image analysis the weak-emulsion curve would be more skewed to the right (i.e., to the larger globule range).

Figure 4.4 displays the PFGI average-flow condition at 70ºF for the weak, medium, and strong-emulsion strength.



Emulsion strength	$d_{4,3}$ (µm) with standard deviation
Weak	501.5 +/- 111.1
Medium	327.3 +/- 53.1
Strong	143.5 +/- 40.6

Figure 4.4. PFGI at 70ºF average-flow condition (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

The weak-emulsion strength condition displayed a larger fraction of globule sizes above 200 microns when compared to the medium and strong-emulsion strength conditions, which is supported by the measured percent removals. It is also important to note the observation of a thick oil layer, which accumulated at the surface of the flow during the weak average condition. As mentioned before, the coalesced globules at the surface may not be represented by image analysis. If these coalesced globules were captured, the weak curve in Figure 4.4 would likely produce an even larger peak beyond 900 microns. It is also important to compare the $d_{4,3}$ of each emulsion strength at average-flow with its $d_{4,3}$ at maximum-flow. The weak emulsion produced a $d_{4,3}$ of 288.3µm at maximum-flow and 501.5µm at average flow. The significant increase in globule size, along with the increased residence time, is the major factor in the improved removal, from 38% (maximum) to 82%

(average). The medium-emulsion also produced an increase in globule size from maximum flow ($d_{4,3}$ of 210.4µm) to average flow ($d_{4,3}$ of 327.3µm). The medium-emulsion increase in globule size was not as significant as the weak-emulsion, though still producing a percent removal increase of 17% (maximum) to 46% (average). The strong-emulsion $d_{4,3}$ values are similar; with 150.7µm (maximum) and 143.5µm (average). The similar $d_{4,3}$ values give credence to the ability of the two static mixers to create a relatively stable emulsion. Given the similarity of the $d_{4,3}$ values, the increased residence time at average flow (RT = 1 min. (38% removal)) compared to maximum flow (RT = 30 sec. (8% removal)) would be the main factor in the increased percent removal at the strong emulsion condition.

4.1.3b Maximum/Average-flows at 100°F Condition

Table 4.3 lists the percent removals for the 100ºF PFGI experiments.

Table 4.3. Percent removal data from 100ºF PFGI experiments, with standard deviations.

Emulsion Strength	Maximum-flow (10 gpm)	Average-flow (5 gpm)
Weak (0 static mixers)	29% +/- 4%	69% +/- 7%
Medium (1 static mixer)	-	-
Strong (2 static mixers)	14% +/- 2%	34% +/- 2%

Water temperature variations during 100°F experiments were within 5ºF. The 100ºF experiments produced a lower FOG percent removal than the 70ºF experiments at the weak-emulsion maximum and average-flows (29% vs. 38% and 69% vs. 82%, respectively). These results run contrary to what is typically expected when comparing gravity separation performance at two different temperature conditions. One possible explanation is that the FOG globule size may have changed under the two temperature conditions. Stokes Law

(Equation 4-4) could be used to simply describe the influence of globule size and fluid temperature for a quiescent separation process with no interaction between globules (i.e. coalescence).

$$V_s = \frac{2}{9} \frac{(\rho_p - \rho_f)}{\mu} g R^2,$$

Equation 4-4

where the migration velocity is V_s, the particle (globule) density is ρ_p, the fluid density is ρ_f, the fluid viscosity is μ, gravity is g, and the particle (globule) radius is R. In Equation 4-4, when temperature is increased the fluid viscosity (μ) decreases and increases the migration velocity (V_s) of the oil globules, thus aiding in oil globule separation. However, one additional complication not described by this equation is the well recognized relationship developed by Hinze (1955), listed below as Equation 4-5.

$$\frac{(d_{max})_0}{D} = 0.55 \left(\frac{\rho_c u_c^2 D}{\sigma} \right)^{-0.6} f^{-0.4},$$

Equation 4-5

where the maximum emulsion droplet diameter is d_{max}, the velocity of the continuous phase is u_c, the density of the continuous phase is ρ_c, the interfacial tension is σ, the friction factor (measure of turbulence) is f, and the pipe diameter is D. Hinze showed, in Equation 4-5, that the maximum diameter size (d_{max}) of an emulsion is proportional to the interphase surface tension (σ) and inversely proportional to the level of turbulence. Assuming a constant turbulence level, Hinze's relationship suggests that the maximum oil globule size will

decrease with increasing temperature since increasing temperature will also decrease the interphase surface tension. A decrease in oil globule diameter will produce a stronger emulsion and a lower FOG percent removal, as seen in all experimental trends except one. The 100°F maximum-flow strong-emulsion produced a greater percent removal (14%) than the 70°F maximum-flow strong-emulsion percent removal (8%).

The percent removals for the 100ºF and the 70ºF strong-emulsion conditions did not display as large a difference between the maximum and average-flows (14% vs. 8% (maximum) and 34% vs. 38% (average), respectively). These results were expected due to the strong-emulsion generation of the two static mixers. Once a certain oil globule size threshold has been achieved, the increased temperature would have very little, if any, impact on removal efficiency (i.e., the maximum-flow strong-emulsion condition produces mostly globules on the relatively smaller range and very few relatively larger globules). Aziz (2010) states globules much less than 150 microns may form stable emulsions that are not readily separable. Therefore, the strong-emulsion created by the two static mixers produced a stabilizing effect and the globule size was well maintained even though the residence time changed between maximum and average-flow conditions. Other processes would have to be imposed to remove oil globules much smaller than 150 microns as shown in Figure 4.5 (Aziz 2010).

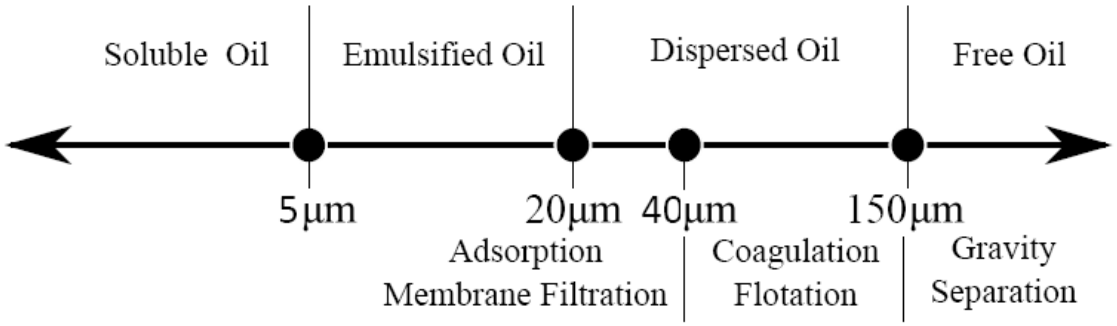
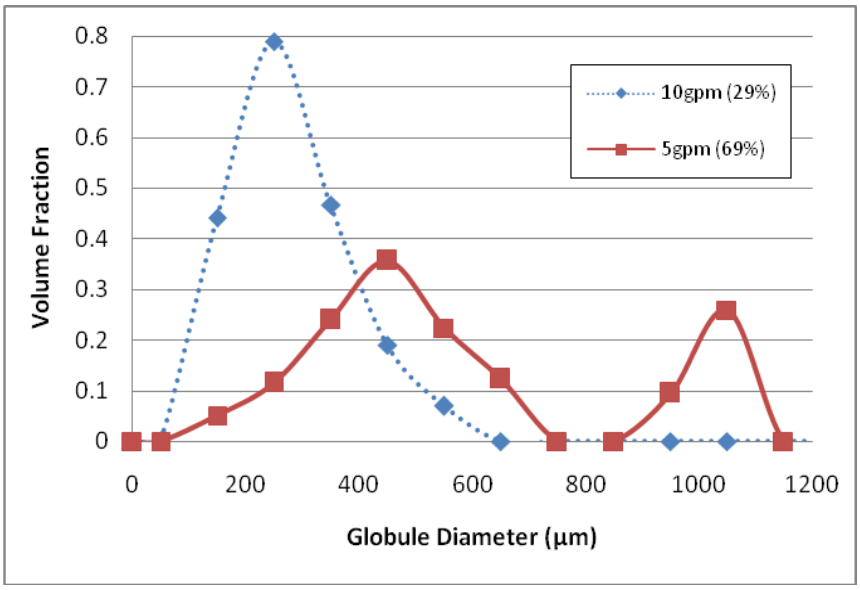


Figure 4.5. Chart of Droplet Size, Characterization of droplet, and the proposed effective treatment technology (Aziz, 2010)

Figure 4.6 displays the results of the 100ºF experiments at weak-emulsion strength conditions.



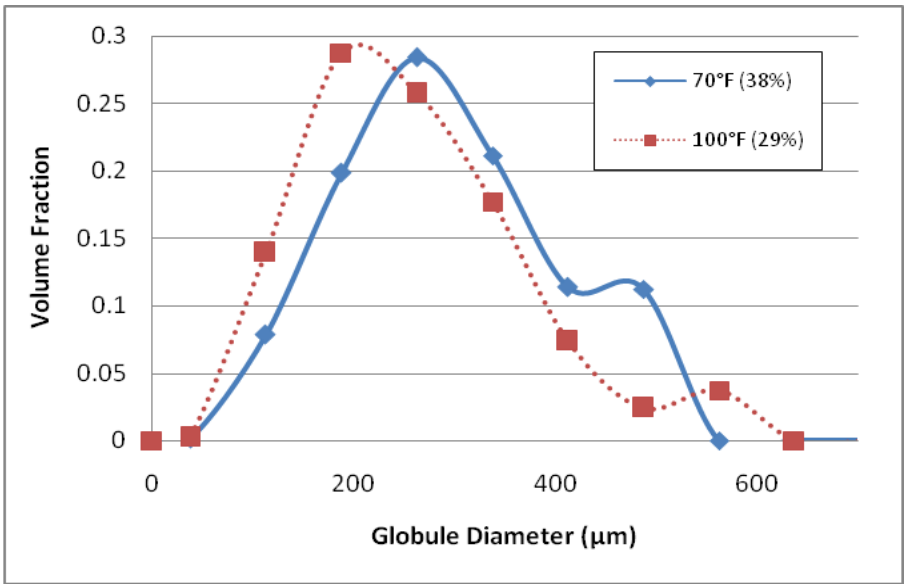
Emulsion strength	$d_{4,3}$ (µm) with standard deviation
10gpm	256.6 +/- 70.0
5gpm	544.94 +/- 149.1

Figure 4.6. PFGI at 100ºF weak-emulsion strength condition (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

The maximum-flow ($d_{4,3}$ = 256.6µm) produced smaller globules leading to a lower percent removal than the average-flow ($d_{4,3}$ = 544.94µm) operating condition. In addition,

the maximum-flow condition reduced the residence time by half compared to the average-flow condition, which also plays a critical role in percent removal.

Figure 4.7 displays a comparison between the 70°F and 100°F weak-emulsion strength condition during maximum-flow.



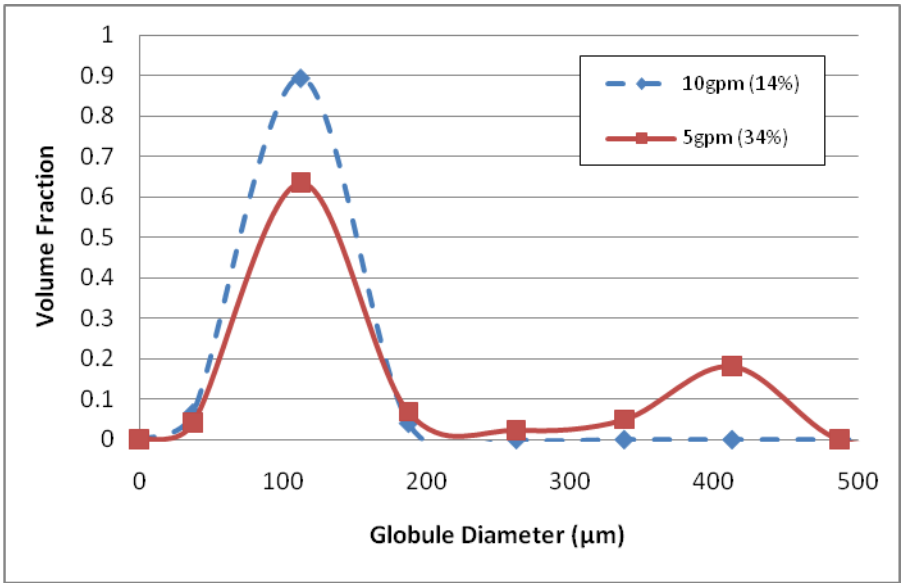
Temp.	$d_{4,3}$ (µm) with standard deviation
70°F	288.3 +/- 83.9
100°F	256.6 +/- 70.0

Figure 4.7. PFGI results for 70ºF vs. 100ºF at weak-emulsion strength (0SM) condition (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

The image analysis of the 70ºF and the 100ºF experiments at weak-emulsion maximum-flow conditions support the percent removal values; 38% removal and $d_{4,3}$ of 288.3µm at 70ºF and 29% removal and $d_{4,3}$ of 256.6µm at 100ºF. Both temperatures produce two peaks; 300 and 500 microns for the 70ºF condition and 200 and 550 microns for the 100ºF condition. The low percent removal for both cases is indicative of the short residence time of the PFGI under the maximum-flow condition. As discussed earlier, the comparison of the globule size distribution with increasing temperature suggests that the higher

temperature may allow for the breakup of the larger globules. The overall loss of the larger globules with increasing temperature, $d_{4,3}$ value of 288.3µm (70°F) and 256.6µm (100°F), lead to a decrease in removal efficiency.

Figure 4.8 displays the results of the 100ºF experiment at strong-emulsion strength conditions.



Temp.	$d_{4,3}$ (µm) with standard deviation
10gpm	93.1 +/- 23.6
5gpm	178.6 +/- 32.8

Figure 4.8. PFGI 100ºF results at strong-emulsion strength condition (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

As expected the average-flow produced larger globules overall than the maximum-flow (avg: $d_{4,3}$ of 178.6µm, max: $d_{4,3}$ of 93.1µm). A significant portion of the globules are present around 125 microns for the maximum and average-flow with an additional peak at 400 microns for the average-flow.

4.3.1c Air Induction – Maximum-flow at 70°F Condition

The air induction device was incorporated into the PFGI device to test whether FOG removal efficiency will increase with entrained air. During these experiments, a slight suction was noted with the attached plastic tube, giving credence to the creation of negative pressure within the device causing air entrainment. An increase in small bubbles at the inlet surface within the device was also noted during these experiments, proving the existence of the air entrainment.

The PFGI experiments conducted without air induction during 70°F maximum conditions produced a removal efficiency of 38%. Tests were repeated with the same conditions using air induction and found similar results (~38%). For this PFGI device, air induction did not seem to enhance the separation of FOG. No change in globule size distribution was noted due to the induction of the air stream.

4.3.2 Mechanical Flow-based grease interceptor

4.3.2a Maximum/Average-flows at 70°F Condition

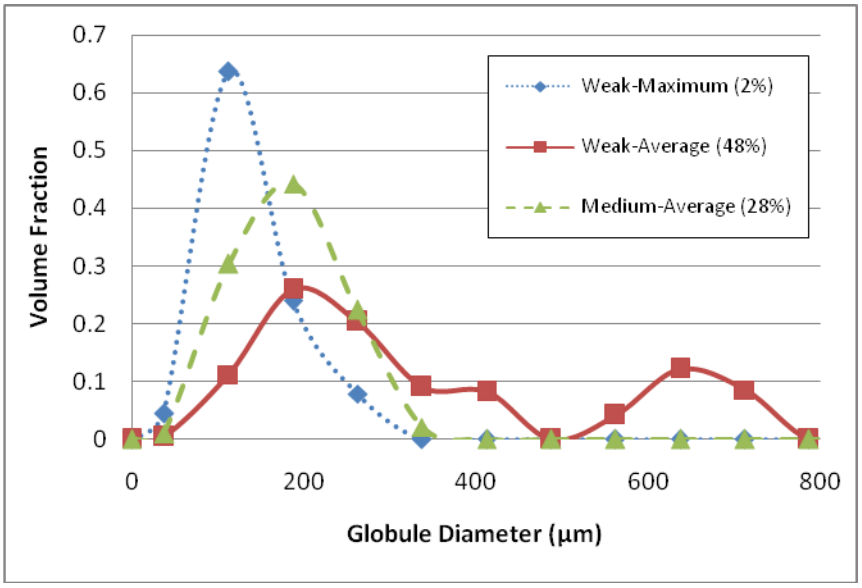
Table 4.4 displays the results of the 70ºF MFGI experiments.

Table 4.4. Percent removal data from 70ºF MFGI experiments, with standard deviations.

Emulsion Strength	Maximum-flow (25 gpm)	Average-flow (12.5 gpm)
Weak (0 static mixers)	2% +/- 3%	48% +/- 1%
Medium (1 static mixer)	-	28% +/- 0.2%
Strong (2 static mixers)	-	-

The maximum-flow for the MFGI displayed approximately no removal. The weak-emulsion strength average-flow percent removal trend was similar to the PFGI percent removal trends, where tests displayed an improvement of 40% or more over the maximum-flow. Due to the removal result of the weak-emulsion strength at maximum-flow, it was deemed unnecessary to run experiments at the medium and strong maximum-flow levels. The medium-emulsion strength average-flow experiment did display a 28% removal. The image analysis for the MFGI displayed similar trends to the PFGI for the same set of experimental conditions.

Figure 4.9 displays the MFGI during 70ºF weak-emulsion maximum and average-flow conditions and the medium-emulsion average-flow conditions.



Emulsion strength	$d_{4,3}$ (µm) with standard deviation
Weak – Max.	129.6 +/- 33.8
Weak – Avg.	346.2 +/- 76.6
Med. – Avg.	174.9 +/- 51.9

Figure 4.9. MFGI 70ºF results at weak-emulsion strength conditions and medium-emulsion strength conditions (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

The 25gpm system at 70ºF maximum-flow conditions displays one major spike at 120 microns giving significant support to the approximately 0% removal result. The $d_{4,3}$ results

of the maximum-flow condition produced a globule range of 95.8µm to 163.4µm, placing it almost completely in the stable-dispersed oil region (Figure 4.5 (Aziz, 2010)). It is also important to account for the impact of the MFGI internal geometry, which directs the flow in multiple directions during its one minute residence time, thus potentially causing more turbulent mixing. This turbulent mixing can lead to shearing and cause a shift in the globule size distribution (Figure 4.9) to the smaller globule size range, thus creating a situation where a large fraction of the globules are at or less than 150 microns. The 20% decrease in FOG removal efficiency from the weak average-flow to medium average-flow condition was an expected result due to the production of smaller globules with the use of a static mixer.

4.3.2b Maximum/Average-flows at 100°F Condition

Table 4.5 lists the results of the 100ºF MFGI experiments.

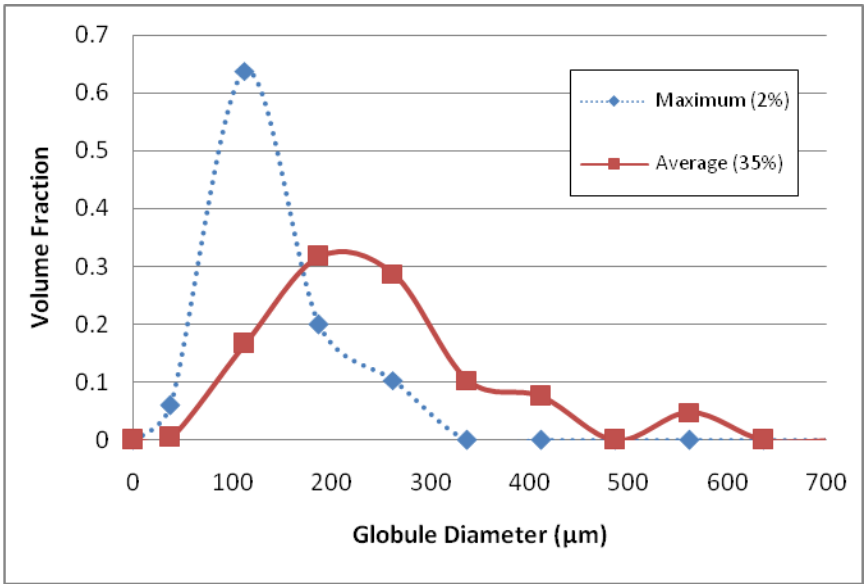
Table 4.5. Percent removal data from 100ºF MFGI experiments, with standard deviations.

Emulsion Strength	**Maximum-flow (25 gpm)**	**Average-flow (12.5 gpm)**
Weak (0 static mixers)	2% +/- 2%	35% +/- 9%
Medium (1 static mixer)	-	-
Strong (2 static mixers)	-	-

The elevated temperature had no effect on the weak-emulsion strength maximum-flow removal efficiency and displayed 2% FOG removal, similar to the 70ºF result. The 100ºF weak-emulsion average-flow condition did display a higher percent removal compared to the maximum-flow and is likely due to the longer retention time as well as the increased fraction of larger globules as shown in Figure 4.10. However, the average-flow saw a

decrease in percent removal from the 70ºF to the 100ºF condition; from 48% to 35%. The decrease in removal efficiency when influent temperatures were elevated was also noted between the 70ºF and the 100ºF experiments of the PFGI. An increase in temperature produces smaller oil globules compared to the same conditions at 70°F.

Figure 4.10 displays the MFGI at 100ºF weak-emulsion maximum and average-flow conditions.

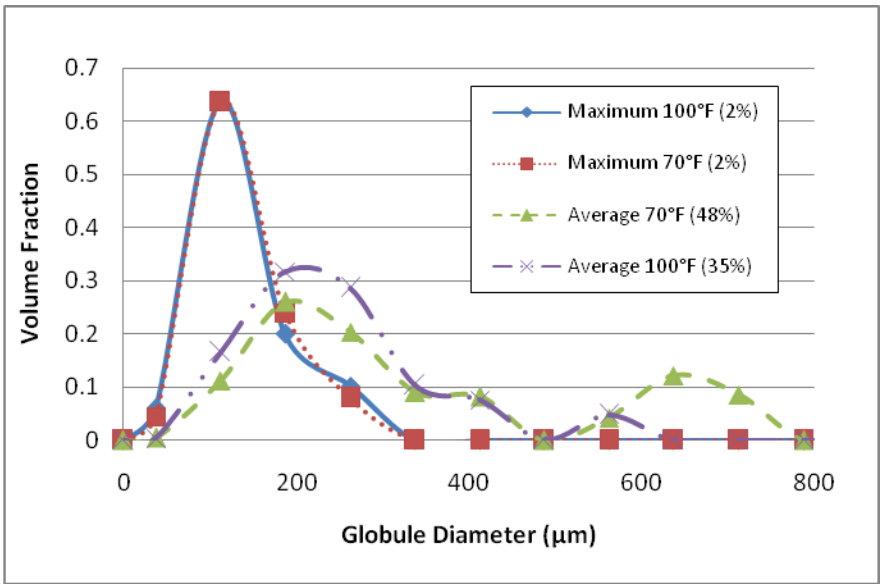


Flows	$d_{4,3}$ (µm) with standard deviation
25gpm	125.8 +/- 30.2
12.5gpm	241.8 +/- 65.5

Figure 4.10. MFGI 100ºF results at weak-emulsion strength conditions (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

The average-flow condition displayed a significant improvement over the maximum-flow, producing a 35% FOG removal efficiency. However, the improvement at 100°F was not as significant as the 70ºF condition, where the removal improved from 2% to 48%.

Figure 4.11 displays a comparison of the maximum and average conditions at 70°F and 100°F to better visualize the change in globule distribution.



Flows	$d_{4,3}$ (µm) with standard deviation
Max. 100°F	125.8 +/- 30.2
Max. 70°F	129.6 +/- 33.8
Avg. 70°F	346.2 +/- 76.6
Avg. 100°F	241.8 +/- 65.5

Figure 4.11. MFGI 70°F and 100°F results at weak-emulsion strength conditions (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

Figure 4.11, the maximum condition globule size distributions both produced a peak at 120 microns (giving similar $d_{4,3}$ values of 125.8µm (100°F) and 129.6µm (70°F)) with each curve displaying a volume fraction of ~0.6. The comparison of the two average globule size distributions displays why a greater performance increase from the maximum-flow at 70°F condition (2%, maximum to 48%, average) than with the maximum-flow at 100°F condition (2%, maximum to 35%, average) was observed. The $d_{4,3}$ values clearly displayed that there was a larger difference in the range of globule sizes between the 70°F average and maximum-flow conditions (346.2µm and 129.6µm, respectively) compared to the 100°F average and maximum-flow curves (241.8µm and 125.8µm, respectively). Hence, the FOG removal performance difference would be larger for the 70°F flow conditions compared to the 100°F flow conditions.

4.3.3 WSSC Retention-based grease interceptor

4.3.3a Maximum/Average-flows at 70°F Condition

The RGI produced a significant improvement in percent removal compared to the PFGI and MFGI. Table 4.6 details the RGI percent removals during maximum and average conditions at the weak and strong-emulsion generation conditions at 70°F, along with the previous 70°F PFGI and MFGI results.

Table 4.6. Percent removal data from 70° F PFGI, MFGI & RGI experiments; with standard deviations.

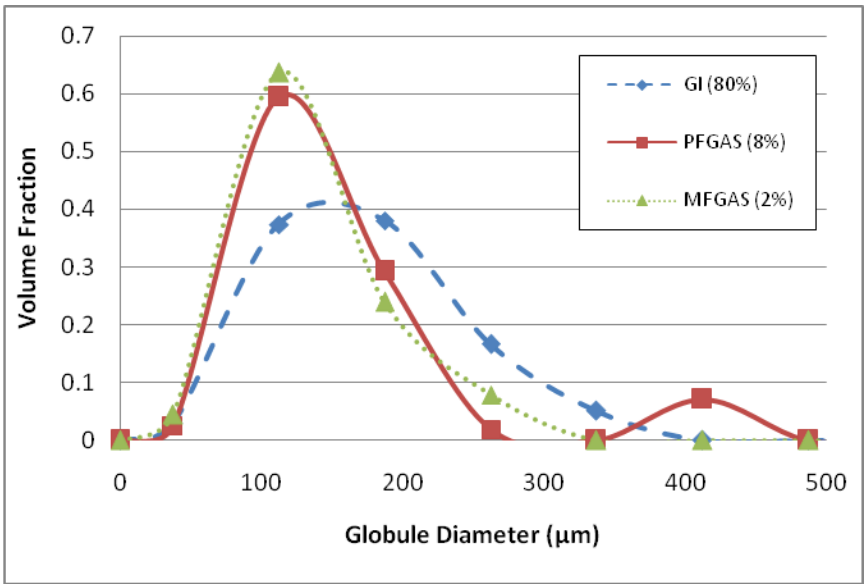
	PFGI		**MFGI**		**RGI**	
Emulsion Strength (# of static mixers)	**Maximum-flow (10 gpm)**	**Average-flow (5 gpm)**	**Maximum-flow (25 gpm)**	**Average-flow (12.5 gpm)**	**Maximum-flow (0.9 gpm)**	**Average-flow (0.45 gpm)**
Weak (0)	38% +/- 7%	82% +/- 2%	2% +/- 3%	48% +/- 1%	80% +/- 1%	88% +/- 2%
Medium (1)	17% +/- 3%	46% +/- 0.2%	-	28% +/- 0.2%	-	-
Strong (2)	8% +/- 0.3%	38% +/- 2%	-	-	77% +/- 3%	84% +/- 0.1%

The RGI produced a significantly improved percent removal during weak-emulsion maximum-flow as compared to the PFGI and MFGI under similar conditions (RGI (80%), PFGI (38%), MFGI (2%)). The increased performance is primarily due to the significantly longer residence time with additional contribution likely due to the quiescent flow through the RGI during maximum-flow conditions. The PFGI and MFGI displayed more significant mixing conditions when operated at maximum-flow. As mentioned earlier, the internal

geometry of the MFGI is quite complex and may cause additional shearing of the floc, which can hinder efficient separation.

The RGI also produced an increased percent removal during weak-emulsion average-flow (RGI (88%), PFGI (82%), MFGI (48%)). The RGI and PFGI percent removal at average-flow under weak-emulsion conditions are similar (RGI (88%), PFGI (82%)). At average-flow conditions, the flow within the PFGI was more quiescent and may have produced a favorable environment for coalescence and separation. The comparisons detailed above focus on percent removals under similar experimental conditions (i.e. flow and emulsion). However, it is more important to compare these separation performances based on the influent emulsion condition (i.e. globule sizing).

Figure 4.12 displays the globule size distribution of the RGI at the maximum-flow weak-emulsion condition along with the PFGI globule size distribution at the maximum-flow strong-emulsion condition and the MFGI globule size distribution at the maximum-flow weak-emulsion condition.

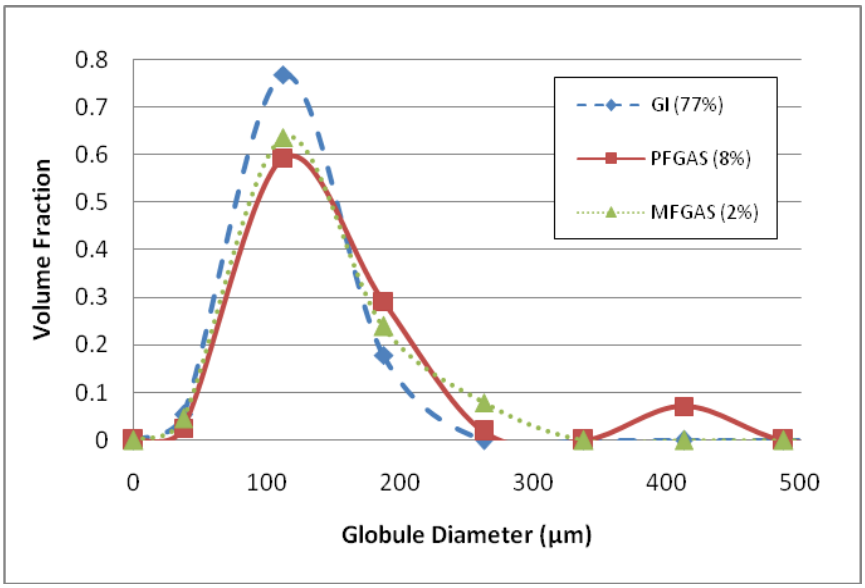


Device	$d_{4,3}$ (µm) with standard deviation
RGI	169.3 +/- 47.1
PFGI	150.7 +/- 40.2
MFGI	129.6 +/- 33.8

Figure 4.12. RGI (Maximum-flow/Weak-emulsion) w. PFGI (Maximum-flow/Strong-emulsion) & MFGI (Maximum-flow/Weak-emulsion), (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

The globule size/emulsion strength of the RGI (maximum-flow/weak-emulsion) produced a size distribution that contains a slightly higher fraction of larger globules compared to the globule size/emulsion strength of the PFGI (maximum-flow/strong-emulsion) and the MFGI (maximum-flow/weak-emulsion) size distribution curves. Considering the relatively similar peak regions of globule sizes between the three curves, it would be expected that the RGI would produce a similar low percent removal. However, the RGI produced a significantly greater percent removal of 80% compared to 8% for the PFGI and 2% for the MFGI. The most significant difference between the three devices and likely the component that produces the greatest difference in their removal efficiencies, is the residence time. The RGI allows for a residence time of 30 minutes, whereas the PFGI and MFGI allow for residence times of 30 seconds and one minute, respectively.

The RGI was also challenged with a strong-emulsion at maximum conditions, as seen in Figure 4.13.



Device	$d_{4,3}$ (µm) with standard deviation
RGI	111.2 +/- 30.9
PFGI	150.7 +/- 40.2
MFGI	129.6 +/- 33.8

Figure 4.13. RGI (Maximum-flow/Strong-emulsion) w. PFGI (Maximum-flow/Strong-emulsion) & MFGI (Maximum-flow/Weak-emulsion), (percent removal in parenthesis); with adjacent $d_{4,3}$ chart, including standard deviations.

The RGI (maximum-flow/strong-emulsion) curve is similar to the MFGI (maximum-flow/weak-emulsion) and PFGI (maximum-flow/strong-emulsion) curves though with significantly different removal efficiencies (RGI (77%), MFGI (2%), PFGI (8%)). As previously mentioned, the difference in removal efficiencies is likely due to the difference in residence time, the turbulent nature of the flow created in the MFGI, and possibly the internal geometries of the devices. The residence time argument is further supported by analyzing the $d_{4,3}$ values in Figure 4.13. The RGI removed more oil globules with $d_{4,3}$ of 111.2µm, which was smaller than the MFGI $d_{4,3}$ at 129.6µm and the PFGI $d_{4,3}$ at 150.7µm. The RGI was able to produce a higher percent removal due to the longer HRT, especially considering

it was challenged with a stronger emulsion than the MFGI or PFGI. The globule distribution for the RGI experiments was the same for the maximum and average-flow of each tested condition (weak and strong-emulsion).

Recall that the PFGI produced an 82% FOG removal performance when operated at the 70°F weak-emulsion-average-flow condition. One could argue that the PFGI can achieve similar results to the RGI but at a significantly reduced HRT. However, it should be noted that a significantly large fraction (90%) of the globule sizes were above 200 microns with 40% above 600 microns (Figure 4.3). So this specific PFGI result suggests that the PFGI may achieve a high percent removal when operated under average-flow conditions (i.e., provided enough residence time under quiescent separation conditions) when the FOG is in a readily separable form (i.e., much greater than 150 microns).

The PF/MFGI devices are considered to be a convenient and cost effective resource for removing the FOG from FSE effluent, often in lieu of installing a RGI. However, the 'effective' point of these devices may need to be reconsidered due to their low removal performance when challenged with an emulsion of globules that are considered to be gravity separable (i.e., greater than 150 microns).

As mentioned previously, the increased RGI percent removal is not only due to the longer residence times but also due to the quiescent internal geometry of the RGI that are maximized with two pairs of baffles with a distributed opening between the compartments. The quiescent nature is critical, particularly for FOG that is in the form of an emulsion for improved separation and stable collection at the surface. A previous study showed that changing the internal geometry can have a significant impact on the FOG removal

performance of RGIs and that sufficient residence time and geometric configuration should be considered in any FOG separation (Ducoste *et al.* 2008). Note that sufficient residence time was recommended as these researchers also noted the difficulty of higher FOG removal performance (i.e., larger than 90%) beyond 20 minutes for a well optimized RGI. It's likely that the remaining fraction of effluent FOG globules is in the size range that is difficult to remove through gravity separation.

4.4 CONCLUSION

This study focused on the performance of two FGI units and one RGI unit under three emulsion strengths (weak, medium and strong), two influent temperatures (70ºF and 100ºF) and variable flow rates (the maximum-flow and half the maximum-flow of each device). The results of this study clearly showed a decreased removal performance with increasing flow rate and increasing emulsion strength, which is not captured with the current PDI rating protocol. Sufficient residence time along with internal design configuration was identified as major factors in the performance of these units.

Overall, the WSSC RGI performed with the highest FOG removal at approximately 80% removal or higher under each tested condition. The PFGI and the MFGI performed at 50% or less under each tested condition. Pictures were taken of the emulsion during each experiment prior to entering the grease abatement unit to determine the strength of the emulsion (i.e. FOG globule size distribution).

Image analysis revealed similar emulsion strengths (i.e. FOG globule size distributions), with the PFGI emulsion strength being weaker compared to the RGI emulsion

strength that produced ~80% removal and the PFGI produced 8% removal. Considering that a large portion of globules in both distribution were in the gravity separable range (greater than 150 µm) the removal results suggest the longer residence time of the RGI (30 minutes) compared to the PFGI (30 seconds) was the major factor in the significant removal difference. One exception occurred during the PFGI average weak-emulsion testing where removal reached approximately 80%. However, the FOG globules produced under these conditions for the PFGI were highly separable (i.e., 40% of the FOG globules were above 600 microns in size).

The effects of temperature on FGI performance were determined with the two FGI units challenged under 70°F and 100°F conditions. Overall, the removal efficiency decreased with increasing temperature. Although the removal efficiency decreased, the difference in the removals was not significant; a decrease of approximately 10% was produced under most conditions. Temperature testing was not conducted for the RGI in this study.

Air entrainment prior to the FGI has been speculated to aid in removal efficiency and was tested in this study. The air entrainment device produced an increase in air bubbles at the FGI inlet. However, this study found no difference in FOG removal performance when an air entrainment device was utilized.

Further assessment of FGI devices beyond current protocol should be implemented to assure FOG removal (whether readily separable or emulsified FOG) from FSE effluent. Attaining a complete understanding of FGI devices and how they perform is essential in the future health and longevity of sewer collection systems.

5. FUTURE WORK

Future research should initially include a review of the current PDI/ASME FGI certification procedure. PDI states that certified grease abatement devices are capable of removing almost all FOG from FSE effluent, with the ability to remove the most stringent of FOG limits at 50 ppm (approximately 50 mg/L) (PDI 2010[A]). PDI literature lists the design, installation, and maintenance of the device as being the critical aspects of FOG separation (PDI 2010[A]) and does not address the emulsion strength of FSE effluent or the importance of retention time. This present study clearly shows that both emulsion strength/globule distributions and retention time play a major role in the ability of an abatement device to remove FOG.

The suggested review should focus on:

- Should lard be the FOG of choice?
- What is the appropriate process for effluent determination? More specifically, should a whole effluent sample be taken in lieu of the skimming tank process?
- What is the appropriate process for influent determination? More specifically, should a sample be taken prior to the FGI instead of assuming the lard poured atop of the sinks traveled in its entirety to the FGI?

FGIs are essentially a 'black boxes' with very little known about their internal behavior. Computational Fluid Dynamic (CFD) models should be utilized to observe the

performance of FGIs. The CFD results could provide information on how each emulsion strength globule size class performs, possible shortcomings, and how to improve the device.

A better understanding needs to be focused on the content of the wastewater from FSE kitchens. Grease abatement design values for FSEs historically do not consider the influence of management practice and cuisine type leading to insufficiently designed systems (Garza *et al.* 2005).

The 25% rule, which requires cleaning once FOG and solids accumulation reaches 25% of the systems liquid retention capacity (WSSC 2009), should also be reviewed. It is unknown whether this rule can be applied across the board to all GIs and FSE circumstances.

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APPENDIX

Appendix A – Pilot Model Experiment Setup Checklist

1. Fill 500 gallon and 50 gallon tanks with water; you must start with full tanks to maintain the proper pressure throughout the experiment.

2. Make sure to have the proper amount of corn oil. This value can be back-calculated based on the wanted oil concentration at the influent.

3. Purge the acrylic GI, 60 gallon holding tank and the 600 gallon holding tank of any wastewater, making sure to skim FOG off the surface as needed. *Skimmed FOG is disposed in the EHS provided hazardous waste 60 gallon drum. *The purging of the acrylic tank cannot occur during an experimental run – the circuit will become overloaded.

4. Prepare two mason jars for each sample to be taken during the experiment. Mason jars should be labeled with the date, experiment title with variables, and type of sample. For example: 2/15 (date), RGI 0SM, 70°F (title), maximum flow (type of sample).

5. Calibrate Peristaltic pump. Using back-calculation from the mass balance equation for the experiment the rate of oil per unit time can be determined. Detach the oil-feeding tube from the pilot model and insert into a 100 mL Erlenmeyer flask. Use a stopwatch to determine the time it takes to fill a certain volume of the flask to determine the rate of oil inflow. For example: If 20mL oil per 15 sec. will give the proper influent concentration, then the peristaltic pump speed should be modified until this rate is reached.

6. Fill the grease abatement device to be tested with clean water.

7. Adjust the static mixer section to the appropriate setting based the emulsion strength needed. Example: Bypass static mixers if weak emulsion needed, two static mixers if strong emulsion needed.

Appendix B – Experimental Process

1. Close/Open valves as needed to define a clear path of flow to the acrylic RGI, bypassing the grease abatement device to be tested.

2. Open the 500 gallon water valve.

3. Turn on the 500 gallon water tank pump.

4. Modify the valve until the appropriate flow is reached.

5. Open the 50 gallon water valve. Make sure there is an open path for the water from the 50 gallon tank to where it reaches the main flow.

6. Turn on the 50 gallon water tank pump.

7. Modify the valve until the appropriate flow is reached. Adjustment the of 50 gallon valve with the 60 gallon holding tank (bypass) valve will need to be done in unison. *The emulsion generated was always greater than what was needed, except for one experiment. This was done to maintain a constant emulsion generation (globule size), regardless of the other experimental variables.

8. Turn on the peristaltic pump. *Make sure the 4000 mL corn oil container is full.

9. Recheck all flowmeters to make sure of proper flows.

10. Allow the system to reach steady state. Three minutes was the utilized rule of thumb.

11. Open the valve to the grease abatement device and close the valve to bypass.

12. Allow the emulsion to pass through the grease abatement device for three hydraulic residence times. *HRT=Volume/Flow

13. Samples can be taken at the influent and effluent ports. Purge the ports for 20 seconds prior to taking samples.

14. Take 200 mL samples; original and duplicate samples should be taken consecutively. Take the influent samples first, followed by the effluent samples. *No jar prepping is needed – FOG residue could be transferred with the prep rinse and give unrepresentative concentration values.

    *If this is the end of the experiment, defer to number 18. If switching to a different setting and continuing then continue to number 15.

15. Open the valve to bypass main flow to acrylic RGI and close valve to grease abatement device.

16. Reset flows and/or static mixers as needed to achieve the wanted flow and/or emulsion strength. *Be sure to always leave a path open for the water to travel. If not, the pump will be choked and back pressure will develop.

17. Follow steps 9-14.
18. Turn off peristaltic pump and pinch oil feeding tube with a clip.
19. Allow clean water to continuously run through system for three minutes.
20. Turn off pumps first, and then close valves.
21. Acidify samples, with hydrochloric acid, to pH. Use litmus paper to determine pH.
22. Store is refrigerator unless to be tested within 24 hours.

Appendix C – Experimental Photography Process

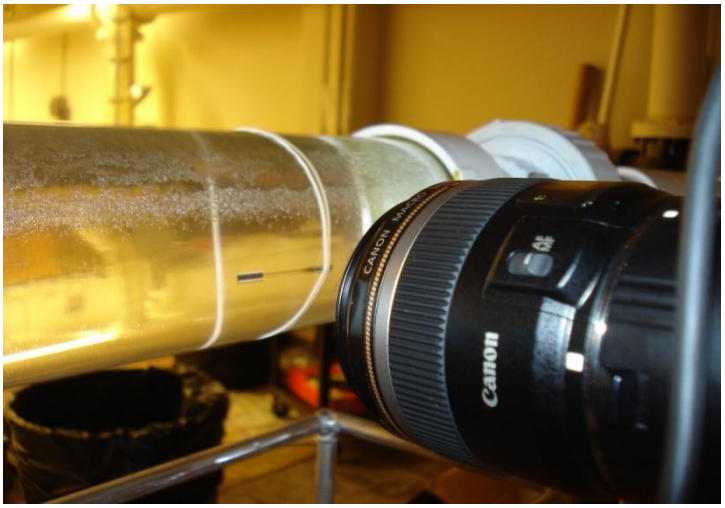

Figure 0.1. Photography Process - Camera/Acrylic tube orientation.

1. Purge camera of all old images, making sure to load needed photos onto computer first.
2. Make sure flash batteries are charged.
3. Attach 10 mm calibration bar to acrylic tube with tape. Tape should only be used on the handle portion and not on the measured portion.
4. Setup camera with tripod. Make sure level of camera is flush with level of calibration bar. Camera lens should be 3-5 inches from acrylic tube.
5. Hold flash within 2 inches of acrylic tube in the upper right orientation with the camera.

6. Take many pictures, reviewing them as you go to gain knowledge of technique.
7. Pictures can be taken any time after the three minute steady state step.
8. If pictures will be taken during two experiments at one experimental run, then take note of the picture numbering. For example: Maximum flow, 0SM – Pics 1-10; Average flow, 0SM – Pecs 11-20.
9. Load pictures onto computer and organize as soon as possible.

Appendix D – Sample Analysis (Liquid-Liquid Extraction and Distillation)

Supplies Needed:

- 500 mL separatory funnel, with top
- 2 funnels
- 1000 mL beaker
- Claisen-type distillation head, with thermometer
- West-type condensing tube
- 2 clack clips
- One boiling flask
- ~2 T. sodium sulfate
- 120 mL hexane
- 4-6 boiling chips (depending on size)
- 2 filters
- Hot plate/stirrer
- Stirrer
- Thermometer, with wire attachment

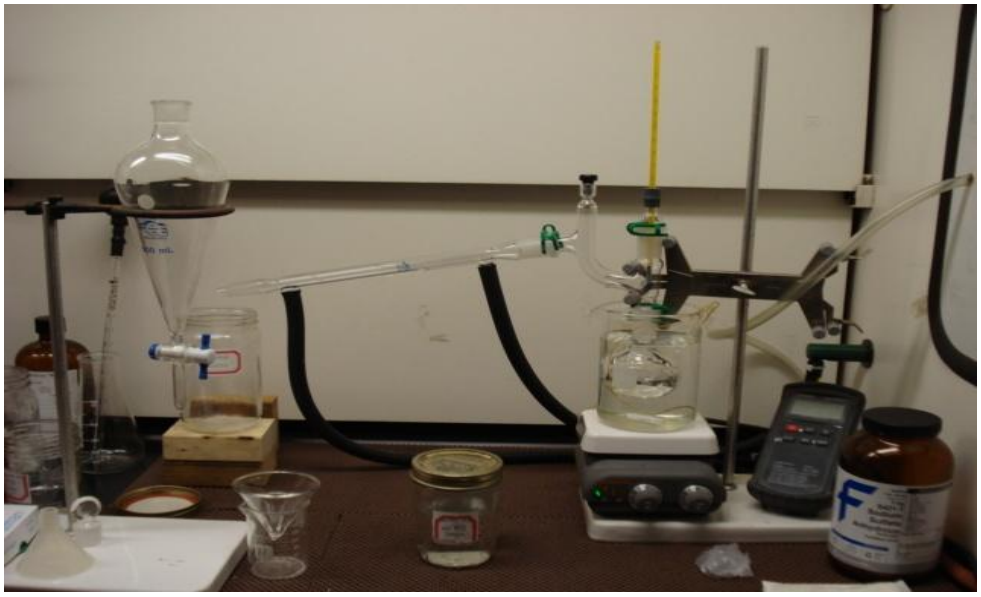

Figure 0.2. Experimental analysis setup

1. Samples must be at room temperature to be tested. *Remove from refrigerator 24 hours in advance, if applicable.
2. Fill 1000 mL beaker with water and set on hot plate/stirrer. Insert stirrer and turn on hot plate/stirrer to heat: 6, stir: 5. (The settings may need to change depending on specific hot plate/stirrer.)
3. Turn on thermometer and insert wire attachment into water bath.
4. Attach an insulation device around beaker to better maintain temperature. *A towel was used for insulation, taped around the beaker.
5. Monitor thermometer for a temperature of 95°F (will take around 25 minutes). *This setup required a water bath temperature of ~95°F to achieve the goal volitization temperature of 70°F.
6. Close seperatory funnel stopcock and place funnel in top of separatory funnel.
7. Record mason jar sample volume.
8. Shake mason jar sample vigorously for a few seconds.
9. Pour sample into separatory funnel.
10. Add 30 mL hexane into sample jar.

11. Screw on mason jar lid securely and shake (~3-5 sec.), making sure to contact hexane with all surfaces.

12. Unscrew lid and pour into separatory funnel. (At this point, the 200 mL sample volume and 30 mL hexane volume should both be in separartoy funnel.)

13. Stopper separatory funnel.

14. Remove separatory funnel from holder and shake vigorously for 2 minutes. *Be sure to vent the separatory funnel (via the stopcock) within 5-10 seconds of shaking initiation or risk the stopper being forced off due to building internal pressure. Venting should continue every 20 to 30 seconds after the first venting.

15. Set separatory funnel back in holder and remove stopper. *Glass stoppers should never be twisted to remove – pull straight up.

16. Allow seperatory funnel to sit for 10 minutes, giving time for separation.

17. Fold filter paper in half – twice. *Crease the filter paper softly.

18. Add ~1 tablespoon of sodium sulfate to the filter paper.

19. Place filter paper cone with sodium sulfate into glass funnel and set in a beaker that will allow the funnel to rest on the lip of the beaker.

20. Prep the sodium sulfate by passing thru 10 mL of hexane.

21. Drain content of separatory funnel into original mason jar allowing a very small amount of hexane to pass. *The hexane will be on top, producing a distinct layer.

22. Place the funnel with hexane prepped sodium sulfate atop a pre-weighed boiling flask with boiling chips and drain the hexane from the separatory funnel into it. *Set the stopcock to drain slowly.

23. Close separatory funnel stopcock and add 10 mL hexane.

24. Stopper separatory funnel and shake allowing the hexane to make contact with all surfaces.

25. Remove stopper from separatory funnel and drain hexane into same funnel/boiling flask combo used in step 22.

26. Purge sodium sulfate by passing thru 10 mL hexane, while still sitting atop boiling flask.

27. Discard sodium sulfate to trash container, within vent hood.

28. Set boiling flask aside.

29. Repeat steps 6 thru 28 for second extraction. *Using same sample volume, same boiling flask, no need to wash separatory funnel, will need new sodium sulfate and filter paper.

    After completion of second extraction, continue to step 30.

30. Attach Claisen tube to boiling flask, via clack clip. *Make sure not to allow any water vapor to settle within Claisen tube – it will alter results.

31. Want beaker water at 95°F and Claisen thermometer at 70°F.

32. Attach condensing tube, via clack clip.

33. Lower boiling flask into beaker water.

34. Monitor temperature via thermometer attached to Claisen tube. Want 70°F +/- 2°F.

35. Turn on cold water to run thru outer tube of condenser.

36. Hexane volitization should take 15 to 30 minutes.

37. Take setup apart.

38. Vacuum off any residual hexane from boiling flask.

39. Place boiling flask in oven at 70°F +/- 2°F for 30 – 45 minutes.

40. Move to dessicator for cooling for 30 – 45 minutes.

41. Weigh boiling flask.

42. Repeat steps 39 thru 41 until weight value levels off.