

CRANFIELD UNIVERSITY

Martin Fairley

Fats, oils and grease management in separators

School of Water, Energy and Environment

PhD

Academic Year: 2016 - 2017

Supervisors: Prof. Bruce Jefferson & Dr Raffaella Villa

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degree of PhD

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Abstract

The fat, oil and grease (FOG) problem may be the 21st Century's 'perfect storm': an outcome of urbanisation, population and economic growth, compounded by changing weather patterns causing inundation and exceedance of sewerage infrastructure capacity. FOG dramatically affects sewer capacity by gradually coating sewer walls with what is frequently termed a FOG compound. Often hard and difficult to remove, large aggregated masses of FOG combined with other 'non-flushable' product make headline news when they do break away and the term 'fatberg' has been coined to describe the enormity and destructive potential of the phenomenon. For food service establishments (FSEs), FOG presents hygienic issues, cost and operational disruption. Despite the global significance to developing economies, FOG mitigation management is challenged by inadequate knowledge of fundamentally important factors such as wastewater character and flow rates: factors that are essential to any attempt to improve mitigation efficiency.

Source control can be taken as a central tenant and clear progress can be made in developing device test protocols that accommodate variable flows and particle size distributions (PSD) that are representative of actual loads. A number of positive outcomes may result: improved product performance standards, greater 'trust' in the product marketplace leading to wider market application serving small but ubiquitous FSEs. Innovation and product development will follow; ultimately it is hoped, turning the problem into a resource.

This study seeks to characterise real wastewater FOG using a combination of microscopy and image processing to reveal the underlying PSD which directly translates to the extent to which FOG might be treated by separation. Separation and retention of FOG is then influenced by flow rate, which in turn drives the physical device size required. Spatial limitations in many FSEs prevent use of the large separators that are qualified under the only current Euronorm Standard. This work illustrates that FOG flow in real systems might be more appropriately conceived as a pseudo batch separation process, the full ramifications of which will be explored in FOG mitigation product development. Finally the use of a novel recirculating separator

test platform is shown to facilitate study of both capture and retention of FOG present in droplets: the median size of which has been considered untreatable by conventional (low cost) separation technology.

Key words: FOG, fats oils and grease, BS EN 1825, PSD, separator

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Abbreviations

BS	British Standard
CF	Circle fit
COD	Chemical oxygen demand
DTNN	Distance to nearest neighbour
EG	Edge gradient
ESD	Equivalent spherical diameter
FOG	Fats, oils and grease
FSE	Food service establishment
HRT	Hydraulic retention time
PSD	Particle or droplet size distribution

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Chapter 1. Introduction

1.1 Background

The problem of fats oils and grease (FOG) produced from food preparation and cooking processes and its impact in drainage is of concern in many advanced economies. FOG may reduce capacity in drainage systems, particularly in so called FOG ‘hotspots’ where food service establishment (FSE) density, combined with other factors may lead to sewer surcharge and flooding. Estimates on actual costs in the UK are few, however recent estimates of sewer blockage cost are £88 million, and it is suggested that more than 50% relate to FOG or other ‘non-flushable’ product (Dyson, 2015). Thames Water Utilities alone cleared 55,000 blockages and cite 223 pollution incidents were caused by FOG blockages in 2014 (Thomas, 2015).

Similar issues are evident at a global level especially in advanced or rapidly developing economies. For example Williams et al., (2012) note food oil consumption per capita increases from 20 kg per annum in less developed countries to over 50 kg per annum in developed regions. Countries such as Hong Kong exhibit large numbers and high densities of FSEs: Chen et al., (2008) note over 9000 restaurants and 200 fast food shops use over half a million tonnes of water per day with subsequent impact on the receiving sewer system. FOG adheres to the sewer pipe wall and constricts the pipe cross sectional area (He et al., 2011), reducing capacity and contributing to tens of thousands of sanitary sewer overflows per annum (*ibid*). In the USA FOG blockages are thought to account for between 50 and 75% of all sanitary sewer overflows (Ducoste et al., 2008). The problem is compounded where sewer systems are aged and designed for significantly lower populations; for example Wallace et al., (2017) note a population increase of 340% in the City of Dublin from 1841 – 2011.

FOG further impacts waste water treatment plant operation. Wallace et al (*ibid*) note that FOG can block plant infrastructure, impede treatment processes in settlement and clarification leading to higher operational and maintenance costs, and further affect micro-organism activity slowing the degradation of organic material. The authors cite as much as 25% of treatment costs are attributable to the FOG component.

The control of FOG at source is required in England by Building Regulations Part H (2002) which cite the current British Standard BS EN 1825 (2002/2004) and further suggest ‘or other effective means of grease removal’. There are many products marketed to control FOG; a large proportion rely on physical separation and might be classified into 3 sub types with a further classification distinction for bio-degradation used independently of a separator or ‘residence time’ providing tank (Figure 1.1). Of the 4 sub types, the BS EN Standard applies to only one - type *a*; the physical dimensions of such products is spatially problematic for many smaller FSEs. Of the two other sub categories of separation reliant products type *b* has some form of continuous FOG removal – either electro-mechanical or passive to an external container, but requires periodic sludge / sediment removal. Type *c* encompasses a range of devices that might be simply smaller versions of the BS EN 1825 conceptualisation – which are therefore unqualified to a reference standard, or represent a hybrid of separation coupled with biological agents – equally unqualified. Of concern to the FSE, is the hygienic operation of any product – thus some type *c* products now incorporate FOG / Sludge containment – facilitating periodic removal, or are removed and exchanged for a fresh unit. Despite the profusion of non-EN 1825 products, agreed standards of performance, testing regimes and associated application guidance does not exist.

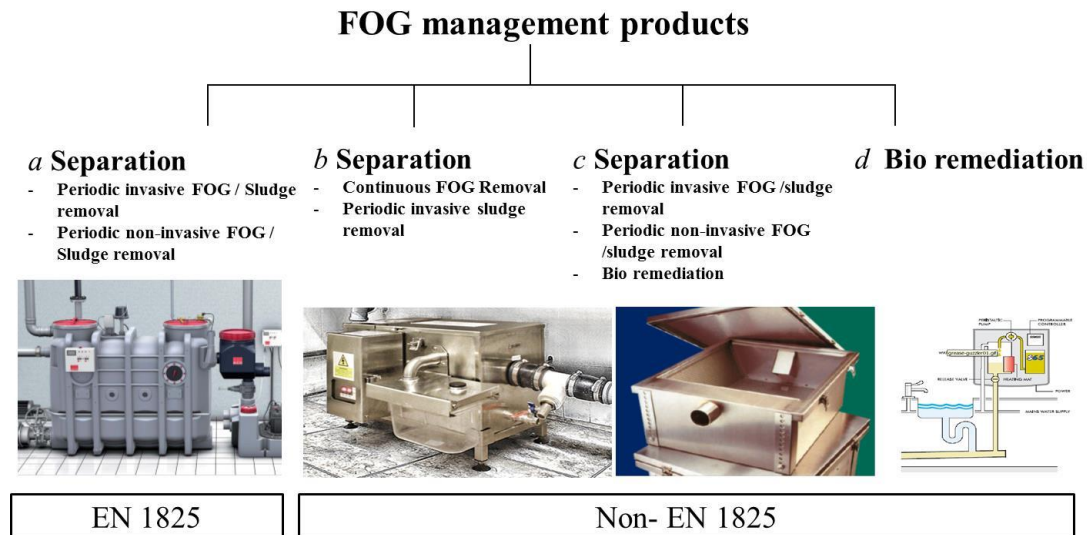


Figure 1-1 Illustration of treatment options.

1.1.1 Basic separation theory

When liquid FOG in wastewater exists in two principle forms: free oil and dispersed partially emulsified droplets. The former is easy removed but the latter is currently considered difficult to remove (Gallimore et al., 2011). The separation of spherical droplets in quiescent conditions is known to follow Stokes' law:

$$V^t = \frac{(\rho_f - \rho_p)g.d^2}{18\mu} \quad \text{Equation 1-1}$$

Where V^t = Terminal velocity of separating particle (m/s), ρ_f = density of continuous medium (kg/m^3), ρ_p = Density of separating particle (kg/m^3), g = Gravity (m/s^2), d = diameter (m), μ = dynamic viscosity (kg/m.s). Accordingly, the size of the droplets that form is critical in defining removal efficiency. However, current practice is not to measure the size of droplets, in part as suitable techniques are not easily available.

1.1.2 Sizing of Passive gravity separators

In Europe only one product Standard exists which is for large gravity separators (BS EN 1825 2002/2004). In the market, preferred solutions are smaller but rely on proprietary guidance only. The design of separators according to the standard is based on the residence time necessary to achieve a stated separation performance of the test media at a given flow

rate. As such the current guidance requires assessment of wastewater flow in order to calculate the required size of separator. Four methods of assessing flow are provided: by actual knowledge of the equipment flow rate; by reference to cited equipment types; by reference to assumed flows based on generalised facility type, or, by special calculation. BS EN 1825 (2002) provides methods for determining the Nominal Size (NS) of the separator (Equations 1-2, 1-3)

$$NS = Q_s f_d f_t f_r \quad \text{Equation 1-2}$$

Where NS = nominal size of separator (the tested flow rate in L/s), Q_s = maximum wastewater flow in litres per second, f_d = density factor, f_t = influent temperature factor, f_r = impediment factor for cleaning and rinsing agents. Calculation of the design flowrate (Q_s) based on the second method utilises stated flows from kitchen equipment together with a ‘frequency’ factor to be used if more than one item is present:

$$Q_s = \sum_{i=1}^m n q_i Z_i(n) \quad \text{Equation 1-3}$$

where i = dimensionless counter, m = reference number of fittings or equipment, n = number of fittings or equipment, q_i = maximum discharge from fittings or equipment in litres per second, $Z_i(n)$ = frequency factor established from Table 1.1 A1 in BS EN 1825-2. Implied in the calculation is that all equipment is draining continuously at a maximum rate of 45% of a units design flow and that the probability of simultaneous drainage is less as the equipment number increases.

Table 1-1 BS EN 1825 Example of flow assessment table using standardised discharge units

Type of kitchen equipment	m	q L/s	$Z_i(n)$					
			n=0	n=1	n=2	n=3	n=4	n=5
Boiling pan								
25mm outlet	1	1.0	0	0.45	0.31	0.25	0.21	0.2
50mm outlet	2	2.0	0	0.45	0.31	0.25	0.21	0.2
Tilting boiling pan								
70mm outlet	3	1	0	0.45	0.31	0.25	0.21	0.2

The third alternative bases the flow rate on the type of establishment:

$$Q_s = \frac{VF}{3600t} \quad \text{Equation 1-4}$$

where V = average wastewater volume per day calculated as $V=MV_m$, M = number of meals per day, V_m = volume of water used per meal as given in the standard, F = peak flow coefficient for equipment type (given in the standard) and t = time in hours. Clearly the NS size obtained depends on the calculation method used. As an example for a small restaurant serving approximately 100 meals per day, with a rinse sink and dishwasher the Standard gives two sizes NS2 or NS4 based on method 2 or 3. The working volume of the selected separators are 0.75 m^3 and 1.5 m^3 respectively. The resultant separator will include volume for grease collection, separation and silt all based on the design flow rate (Figure 1.2). The volume of grease separation can be significant, up to 63% of the working volume but is not an essential requirement of the standard and might be reduced whereas both grease collection and silt volumes are fixed requirements.



Figure 1-3 BS EN 1825 test apparatus – light fuel oil introduction to water flow (Forty 2005)

The use of maximum design flow is perhaps also open to debate. However current evidence on flow rates from FSEs is scarce. In one rare study across 24 FSEs the average flow was reported a maximum flow of 2.84 L/s with 90 – 95% of rates below 0.63 L/s^{-1} (Ducoste et al., 2008, Aziz et al., 2012). Furthermore, the study highlighted that the flows were highly intermittent in nature with the majority of flow events substantially below the maximum flow measured. For instance, the 90% percentile flow rate was only 33% of the peak value. Additionally, long periods of time occur when the flow is very low or non-existent during which time it is posited the separator will operate as a quiescent batch separator rather than a continuous flow separator.

Overall the current testing procedures do not appear to effectively reflect the actual operation of separators in FSEs. However a lack of characterisation data in regards to flow patterns and the size of droplets restrict a proper assessment of the efficacy of the current testing procedure.

1.1.4 Performance considerations

Taking the simplified example in Figure 1.4, a single baffle plate prevents continuous phase oil escaping. The influent comprises oil and water whilst the effluent is proposed to contain less oil. Droplet d_3 is the target droplet size insomuch that its size and associated rise rate offsets its trajectory under flow conditions to the extent that it joins the separation zone designated by the area above the base of the baffle. Droplet d_3 vector is a consequence of all aspects of Stokes' law and flow rate. Droplet d_3 is posited as the minimum droplet size that is tested in current test regimes. Any position to the right will mean it escapes under a maximum flow condition. Under the current Euronorm the test influent sum volume of d_3 is not known but at 98.4 % removal success it is unlikely to be a significant sum volume. Larger still droplet d_2 and d_1 are of less concern in new apparatus without oil or sediment; d_1 size is such that separation occurs under any conditions. Although droplet d_2 is larger than d_3 and illustrated here at a position within the separation zone, it might be subject to disruptive turbulence under flow conditions plus separator oil / sediment inundation and get re-entrained. In effect Droplets d_1 to d_3 constitute *separable* oil en-route to the *free* oil continuous phase with d_3 constituting the boundary droplet size between non-separable emulsions and separable free oil droplets. Its size and vectors imparted by flow, are the key concerns of this project.

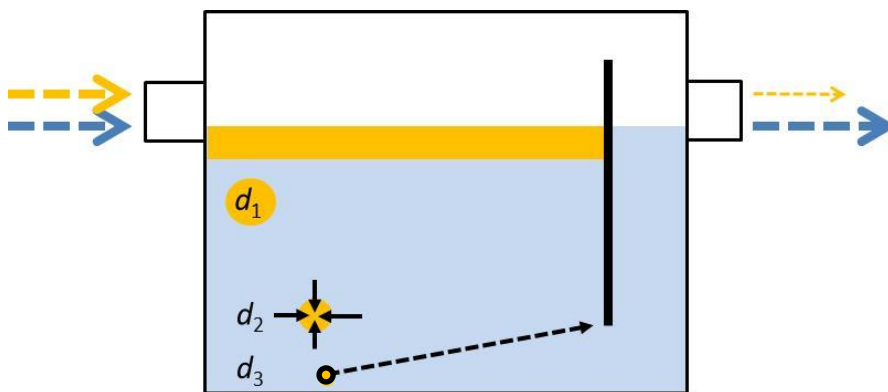


Figure 1-4 Simple FOG separator – droplet size d_2 is smaller than d_1 reducing to d_n . Solid arrows indicate turbulent forces a droplet might experience dashed arrow the vector resulting from convective flow

1.2 Aim and Objectives

The overall aim of the research was to understand and critically evaluate the key characteristics of FSE wastewater that impact on removal mechanisms and hence performance in passive gravity separators.

As such it was hypothesised that the current testing procedure for passive gravity separators does not appropriately reflect actual operation of the devices in FSEs. Therefore an alternative testing procedure is required to better reflect the main characteristics and pathways that control the effective removal of FOG in passive gravity separators. To test the hypothesis and deliver against the overall aim the following objectives were set:

Objective 1: To develop a method for selectively sizing FOG droplets in FSE wastewater

Objective 2: To determine the size of FOG droplets and other debris in FSE wastewater from different source types

Objective 3: To determine the dynamics of flow in FSEs to establish a basis for understanding the impact of temporal variance in flow rate and volume discharged

Objective 4: To understand the impact of oil layer thickness of the potential for re-entrainment of previously captured FOG and the capture of new droplets.

1.3 Thesis Plan

The thesis is presented as a series of chapters formatted as journal papers. All papers were written by the primary author Martin Fairley and edited by Prof. Bruce Jefferson and Dr Raffaella Villa. All experimental work was designed, co-ordinated and completed by Martin Fairley with contributions from Caroline Gurd in terms of FOG measurement, and Anna Cermakova in terms of COD measurement in Chapter 3.

Chapter 2 develops a method for the discrimination of FOG droplets within real food service establishment wastewater. (Chapter 2, Paper 1 - in preparation: Fairley, M., Villa, R. and Jefferson, B. Measurement of the size distribution and volume of FOG droplets within food service establishment wastewater. *Water and Environment Journal*.). The work demonstrated

that the system is dominated by non-FOG debris and as such only techniques that can selectively size the FOG droplets can effectively determine real droplet size data.

The method developed in Chapter 2 was then utilised to measure the size distribution of FOG droplets in real FSE wastewater as well as samples from a domestic washing up sink. (Chapter 3, Paper2 – in preparation: Fairley, M., Gurd, C., A Cermakova., Villa, R. and Jefferson, B. Characterisation of food service establishment wastewater in terms of droplet size distribution. *Waste Management*). This is the first time the size of FOG droplets from FSEs has been reported and indicated that the droplet sizes were smaller than previous trial work had been based on. Findings provide insight to the size of droplets that are required during testing in order to appropriately assess separator performance.

Chapter 4 then compliments Chapter 3 by assessing flow rate profiles within a real FSE to establish the appropriateness of current testing procedures that operate at the maximum design flow of the tested separator. (Chapter 4, Paper 3 – in preparation: Fairley, M., Villa, R. and Jefferson, B. Measurement of the dynamic flow profile of discharges from food service establishments. *Waste Management*).

The experimental work concludes by examining the impact of retained FOG layers on the re-entrainment of previously captured FOG and the additional removal of new droplets. (Chapter 5, Paper4 - Fairley, M., Villa, R. and Jefferson, B. Understanding the impact of retained oil on the efficacy of FOG separation in a continuous flow passive gravity separator. *Water Research*).

Finally, Chapter 6, brings together the findings from the different aspects of the work to conclude on the overall appropriateness of the current basis for design and testing as well as offering suggestion of a more appropriate way forward. Table 1.2 summarises this thesis.

Table 1-2 Thesis plan

Chapter	Paper	Objective	Title	Journal	Status
2	1		Measurement of the size distribution and volume of FOG droplets within food service establishment wastewater	Water and Environment Journal	In preparation
3	2		Characterisation of food service establishment wastewater in terms of droplet size distribution	Waste Management	In preparation
4	3		Measurement of the dynamic flow profile of discharges from food service establishments	Waste Management	In preparation
5	4		Understanding the impact of retained oil on the efficacy of FOG separation in a continuous flow passive gravity separator	Water Research	In preparation
6			Conclusions and Future Work		

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Chapter 2. Measurement of the size distribution and volume of FOG droplets within food service establishment wastewater

M Fairley, R. Villa, B. Jefferson*

Cranfield University, Bedfordshire, MK43 0AL

Abstract

Fats, oils and greases (FOG) management technologies include separation devices which rely on gravitational displacement, the efficiency of which depends to some extent on the particle or droplet size distribution (PSD). Currently limited data exists on the size of particles found in food service establishment wastewater with existing data based on techniques that cannot discriminate between particle types and hence measure more than just the FOG component. The current study investigates the use of optical sizing as an effective way of discriminating FOG components from other debris to provide fresh insights in terms of the total FOG volume and the size distribution of the droplets. The free droplet fraction was readily measured through use of a circle fit filter (>0.9), sizing precision was enhanced by use of a minimum edge gradient of 100. More complex filters were able to estimate the volume of FOG held within the FOG / debris mixture fraction. Testing of an environmental sample revealed FOG represented 5% of the total particle volume in the sample held within a size range of 2-300 μm . The use of discriminated FOG measurement is proposed as a more appropriate basis for innovative design and testing of separator systems.

Keywords: Fats oil and grease, FOG, particle size distribution (PSD), optical sizing, FSE, food service establishment wastewater

2.1 Introduction

There are many potential sources of fats, oils and greases (FOG) in Food Service Establishment (FSEs) wastewater including rinse sinks, dishwashers, combination ovens, wok ranges and extraction filters. The different source devices impart different levels of energy and/or surfactants such that the characteristics of the FOG to be treated vary significantly. For instance, prewash rinsing of wares and evacuation of liquors from large bulk cooking equipment such as tilting kettles are thought to generate predominately non emulsified free oil. In contrast, dishwashers and combination ovens, both of which utilize automated cleaning processes with chemical or biologically active agents are thought to generate mainly emulsified FOG. Management technologies to control such FOG discharges in FSEs include separation devices which rely on gravitational displacement and hence is

driven by a density difference with a rise velocity that follows Stokes' law. Accordingly, the size of the droplets is likely to be a key parameter in understanding the efficiency of removal and hence product design. However, no specific guidance is provided on the impact of droplet size on the design and efficacy of separators used in FSEs (BS EN 1825 part 2, 2002). Guidance from the American Petroleum Institute suggests a critical separable size of 150 μm (López-Vasquez and Fall, 2004). More recently Gallimore et al., (2011) have worked with a range of laboratory derived droplet dispersions to determine the mitigation efficiencies of passive and mechanical separation and created dispersion with reported median diameters of $143.5 \pm 40.6 \mu\text{m}$ to $501.5 \pm 111.1 \mu\text{m}$. Additionally, current testing procedures (BS EN 1825 part 1, 2004) do not consider FOG droplet size such that it is unknown whether the droplets formed during the testing procedure reflect real environmental samples.

To date there is paucity of data related to the size of FOG droplets encountered in FSEs. One study, using laser diffraction, identified median sizes of 48-56, 9-123, 23-274 and 31-138 μm from four different FSE wastewaters (Barton, 2012). However, the data relates to all components in the FSE wastewater, FOG and other debris, due to the sizing approach. In order to discriminate out only the FOG components optical approaches would be required as they enable selection through identified specific morphological features such as shape and transparency (Zölls et al., 2013). In the case of FSE wastewater discrimination it is possible as the FOG droplets exist as spherical objects whereas the non-FOG debris will have irregular morphological features. Consequently, discrimination and selection can be achieved through the use of relatively simple filters such as circle fit (CF), defined as a particles deviation from a best fit circle normalised to the range of 0-1, where 1 is a perfect fit. Further, images in focus tend to appear with a hole in the centre and so can be filtered from the background through use of skeleton functions which render the image down to its simplest single pixel width form (Jefferson, 1997).

Optical based approaches capture a series of images of individual objects and then size them according to a specific parameter: e.g. surface area, perimeter or ferret diameter (Jarvis et al., 2005a). Statistically robust determination of any resulting particle size distribution requires a sufficient number count (625) in order to be considered representative of the particle system (BS 3406 1963). Automated systems utilising image processing software enable such count numbers to be routinely achieved and have been applied to a number of sizing applications including: enumeration and sizing of plankton (phytoplankton, nano and micro planktonic

organisms) (Buskey and Hyatt, 2006; Alvarez et al., 2011; Zetsche et al., 2014); protozoa (Day et al., 2012), protein particles (Zölls et al., 2013), atmospheric wet and dry deposition of particulate matter in alpine environments (Goss et al., 2013), *Microcystis* colonies (Wang et al., 2014) aggregates formed during coagulation (Jarvis et al., 2005a,b) and bubble sizing (Jefferson, 1997). In addition to sizing, the optical technique also provides information of number count, morphological information such as Fractal dimension (Jefferson and Jarvis, 2005a) and can be used to measure settling or rise velocities when used in controlled systems (Jarvis et al., 2005b).

The current paper investigates the potential to measure FOG droplet size distributions in real FSE wastewaters through the use of optical sizing to enable selective sizing of the FOG component. The work will explore the accuracy of the method and report for the first time the PSD of FOG droplets in FSE wastewater.

2.2 Materials and Methods

Optical based sizing was conducted on a Flowcam VSI – Portable, with external syringe pump (Meritics, Dunstable, UK). An overview of the Flowcam system, set up, effect of key adjustable parameters and the deployment of filters is provided in Appendix 1 to 3. Appendix 4 describes the operating procedure used during initial and subsequent analyses. The system draws a fluid sample through a flow cell at a predefined rate of 1.8 mL/s with images captured through a camera configured with an LED light source set to record at 22 frames per second. Groups of pixels representing particles are segmented out of the raw image and saved as set of separate collage images. The images are then processed utilizing the in-built software to filter images according to a set of user defined parameters. The system was operated with a 40x magnification on a 300 μm cell such that the manufacturer specific sizing range was 12-300 μm although visual inspection of the images suggested that a lower detection limit of 5 μm was appropriate. The instrument was calibrated with microsphere size standards suspended in ultraclean diluent at a concentration of 3000 particles / mL ($\pm 10\%$). (Thermo-Scientific COUNT-CALTM, Meritics, Dunstable, UK). The manufacturer specific sizes of the test sphere were 10 ± 0.08 ; 19.99 ± 0.25 and 50.2 ± 1 μm for the test spheres CC10-PK; CC20-PK and CC50-PK respectively. In addition, synthetic samples of FOG and

bubbles were generated by adding 0.5% v/v oil or detergent into DI water (820 mL total) and dispersed at 580 rpm for 15 minutes with a Eurostar digital stirrer (IKA, Oxon, UK). In order to emulate a food service sink wash situation an environmental sample was generated from a domestic washing operation utilizing 3 L of water into which 3 mL of commercial washing up liquid was added. At the point of generation the washwater temperature was 52°C, pH 8.2. Crockery and utensils used to cook a 2 person curry and rice meal were then washed. At point of sample extraction the temperature had decreased to 34°C and pH 7.7. Samples were extracted from the sink and filtered through a 300µm mesh into a beaker where the sample was stirred prior to extraction for measurement. Illustrations of the arrangement are provided in Appendix 5.

After cessation of stirring, samples were transferred to the instrument where a 1 mL sample was utilised per measurement. The image processing software was then utilized to process the images through alteration of key parameters to enable a series of discrete images to be sized (Table 2.1). The size of each individual component was based on the mean feret diameter measured at 5° intervals calibrated to a known scale.

The initial image set was defined through application of a threshold filter set to a value of 18 based on a visual assessment to provide the most effective identification of available particles. Discrimination of FOG droplets, from within the whole particle set, was accomplished by testing potential filters and establishing which provided the most effective selection. Individual FOG droplets were selected through a combination of CF (>0.9) and an edge gradient (EG) of ≥ 100 which was visually checked to ensure it selected all available FOG only droplets. A subsequent filter set was established to identify FOG contained within FOG-debris combined images. All potential filters were tested against known images of FOG, debris and coupled FOG-debris. Filters that did not discriminate or were reciprocals of other filters were deselected. A further check was made to establish any significant correlation between a filter parameter and reported particle volum., The final set of filter parameters had an R^2 coefficient of determination ≤ 0.22 indicating non-significant correlation. Final filter values were generated through analysis of a pre-selected set of 577 images of FOG like droplets that would evade selection by a simple CF filter (CF<0.9 and EG ≥ 100).

Four filters were generated by ordering the 577 particle population by its fit to each of six selected parameters in turn (Appendix 3 provides information on parameter selection). Seven images were taken from each parameter to create a total library of 42 particles in each filter. Filter one was based on the first seven from the image collage – therefore the best fit to the parameter selected, filter two the last seven – the worst fit, filter three the mean seven, filter four the median particles from the image collage. It would be expected that filter 1 performed best and filter 2 the worst. The filters were applied by absolute value and the inbuilt statistical option to establish the order of preference. A value filter would be limited by the highest value of the parameters evident in the library, whereas the statistical function uses the library of particles to generalise a target particle. The effectiveness of the filters was analysed through application to the 100 largest particles, based on mean diameter, in order to calculate the FOG volume compared to the total volume. The identified fractional component was then applied to the total volume identified to establish the volume of FOG held within the FOG-debris components. FOG equivalence was determined through visual inspection.

Application of the different stages enabled identification of three fractions: the total systems (all particles), the free FOG droplets (filtered by CF) and the total FOG volume (Free FOG and FOG contained within a FOG-Debris mixture).

Table 2-1 Summary of key processing parameters utilised during the measurements.

Parameter	Range (as used)	Purpose
Threshold level - particle boundary	0-255 (18 dark only)	Removal of background
Dilution	$10^3 - 10^7$ particles/mL	Avoid occlusion
Distance to nearest neighbour	0+ (0)	Avoid sizing overlapping particles as one
Acceptable region constraints	1280 x 960 (1278 x 958)	Avoid images on edge on image field
Circle fit	0-1 (>0.9 for FOG)	Select only round objects
Edge gradient	0 – 255 (≥ 100 for PSD)	Select only objects in focus
Sigma Intensity	≥ 0	Selected on the basis of discrimination potential when applied to a FOG / non FOG data set (see Appendix 3)
Fibre Curl	≥ 0	
Transparency	0-1	
Elongation	≥ 1	

2.3 Results and discussion

2.3.1 Optimisation of image processing

The measured particle count from four separate environmental samples was $5.6 \times 10^4 \pm 3 \times 10^3$ particles/mL, $5.9 \times 10^4 \pm 6 \times 10^3$ particles/mL, $1.9 \times 10^5 \pm 7.7 \times 10^3$ particles/mL and $7.7 \times 10^5 \pm 4.6 \times 10^4$ particles/mL. This compares to previously defined appropriate ranges of 4×10^3 to 1×10^6 particles/mL with underestimation of between 10-25%, due to occlusion, occurring when the count exceeded 4×10^6 particles/mL (Zolls et al., 2013). Similarly, in tests with microcystis across a concentration range of 2.5×10^3 to 2.5×10^7 cells/mL the mean percentage error compared to direct microscope counts was 2% (Wang et al., 2015). The proximity of neighbouring particles is more significant in particle velocimetry where observation of multiple objects in the same field of observation is known to impact on the measured velocity (Jarvis et al., 2005a). In the current application, the measurement of FOG falls within the low end of the particle concentration ranges and indicates that the samples can be analysed without dilution with minimal error.

Objects in close proximity risk being analysed as combined components reducing number counts and shifting the size distribution towards larger sizes. Minimisation of this impact was assessed through use of the *distance to nearest neighbour (DTNN)* function that alters the interpretation of the particle boundary. Alteration of the DTNN from 10 μm to 1 μm increased the number count by 16% from 12923 to 14925 particles /mL, identifying close but discrete droplets. Similarly, inclusion of a boundary limit of 1 pixel ensures only complete objects are selected. To illustrate, a 1 pixel boundary filter reduced the particle count from 12772 to 12545 and the median from 93.83 μm to 86.15 μm .

2.3.2 Comparison to standard spheres

The impact of measuring images across the depth of field of the microscope was demonstrated with the test spheres through the use of the EG function to define the sharpness of the transition from an object to the background. To illustrate, in the case of the 10 μm test spheres ($10 \pm 0.8 \mu\text{m}$), both the median size and the variance decreased as the EG threshold was increased (Figure 2.1). Lower EG values occur if the particle is out of focus, the subsequent blur is then interpreted as a larger boundary and is related to thresholding. The

median particle size decreased from 11.65 μm at an EG of 80-85 to 9.98 μm at an EG of 130-135, with an average of 11.03 μm at EG 100-105 representing a 9.4% error on the known size. Equivalent trials with the 20 μm test spheres ($19.99 \pm 0.25 \mu\text{m}$) revealed a similar impact where the mean size decreased from $32.05 \pm 0.42 \mu\text{m}$ at an EG of 80-85 to $20.8 \pm 1.1 \mu\text{m}$ at an EG of 120-125, an error of 4%. All samples remained within the expected particle count per mL of $3000 \pm 10\%$ with the exception of one test. Whilst high EG affords precision it reduces particle count: an EG of ≥ 130 reduces count by 90%, an EG of ≥ 100 only reduces the count by 31%. Subsequent measurements utilized a minimum EG of 100.

The manufacturer advocates use of the most frequent bin range, or mode, rather than mean (Flowcam 2012). Analysis of the size distribution measured when the three test spheres are mixed resulted in mode sizes of 9.75, 20.25 and 50.75 μm (Figure 2.2), whilst mean sizes of 9.82, 20.15 and 50.99 μm were similar to the mode. Variation around the mode for counts ≥ 2 particles was 9 – 11, 19.5 – 21.75 and 50 – 52.5 μm respectively, congruent with the impacts of depth of field. Importantly, the mode sizes were not influenced by the presence of the other test spheres.

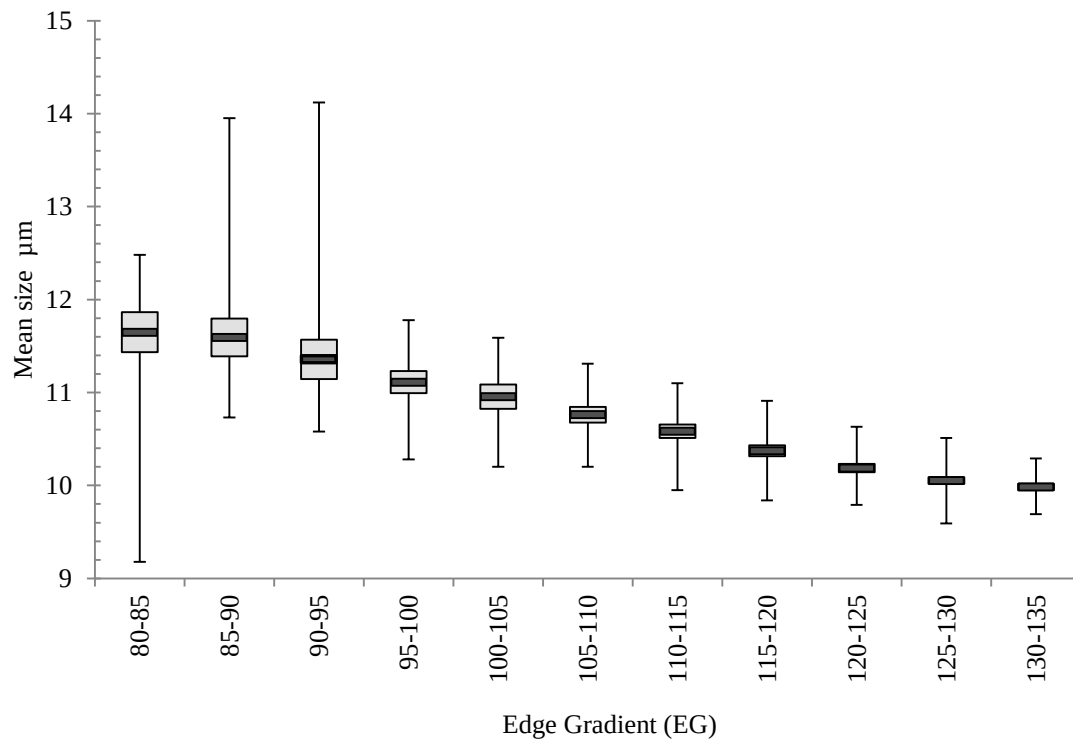


Figure 2-1 Impact of EG on the mean particle size of a 10 μm test sphere (10 ± 0.8 μm). Bin ranges with less than 35 particles excluded. Mean denoted by X, box boundaries sit at 95% confidence interval, whiskers represent data bin range. (607 particles)

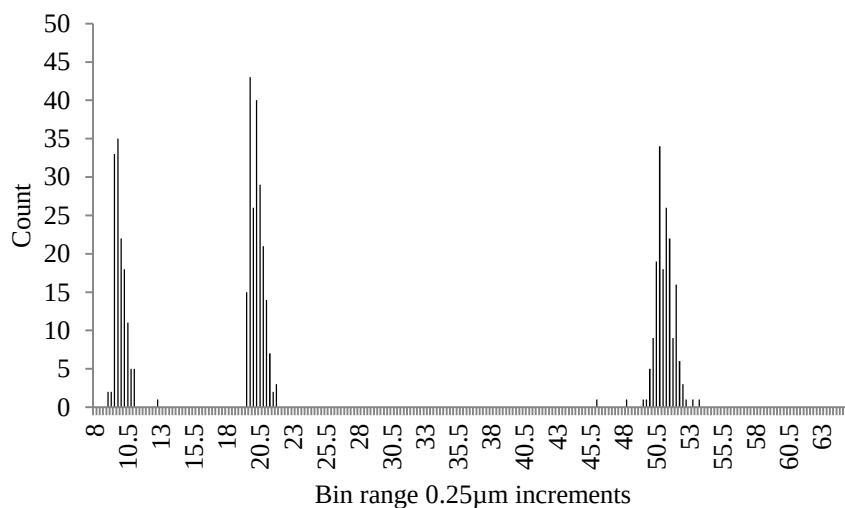


Figure 2-2 Particle size distribution of the 10, 20, and 50 μm test microspheres using an EG of ≥ 100 (508 particles).

2.3.3 FOG discrimination

The primary function for discriminating FOG droplets was the combination of a CF of greater than 0.9 at an EG of ≥ 100 . Analysis of an environmental sample revealed application of the filter to effectively segregate out FOG droplet only images. To illustrate, 92075 individual images were captured from the sample of which 3771 were filtered out as FOG droplets easily by use of the circle fit filter. Further filters were used to address occlusion by other FOG or food debris. These additional quantities were added to the final FOG PSD analysis. Visual inspection of the images selected confirmed that only individual FOG droplets were selected enabling direct sizing of the FOG droplet component of real FSE wastewaters to be conducted. However, it was thought that air bubbles could also be present in the samples and these would not be filtered out. To assess the impact a series of trials were conducted where samples containing air bubbles (i.e. no oil) and FOG droplets were measured over a time series of up to 100 minutes as it was posited that the air bubbles would separate out more quickly than the FOG droplets due to their appreciably lower density (Figure 2.3). The FOG number count decreased from 5.6×10^4 to 2.3×10^4 particles / mL compared to a decrease from 4.6×10^3 to 94 in the case of the bubbles, representing a potential error of 8% at time 0 to less than 1% once 30 minutes had passed in terms of the number count. The mean of the generated size distributions were 20.65 μm and 20.99 μm , for the bubbles respectively at time points $t=0$ and $t= 100$ minutes. In comparison, the change in the mean of the FOG droplets changed from 24.12 μm to 19.18 μm over the same time. Overall, the presence of gas bubbles is not expected to impart a significant error on the generated size distribution due to the relatively low proportional number count but will influence estimates of total volume more with an error of up to 6%.

The importance of this is related to whether estimation of total droplet volume could be used as a surrogate for oil concentration. This idea was tested with a synthetic solution using COD as a measure of total oil. The use of proxy measurements of FOG such as COD is considered valid when no other constituents are present but cannot be used on environmental samples. The total FOG volume per mL decreased from 121 to 52.3 nL/mL over the course of the experiment with a corresponding decrease in COD from 5220 to 3115 mg/L (Figure 2.4). Analysis of the comparison of the FOG volume with the COD yielded a correlation coefficient of 0.96 indicating that this morphological approach to the measurement of FOG was an effective measure of the concentration with minimal potential of false positive

identification. The application of using the image based estimate FOG concentration is considered most effective to compliment sizing data in that it provides insight into changes of overall volumetric load.

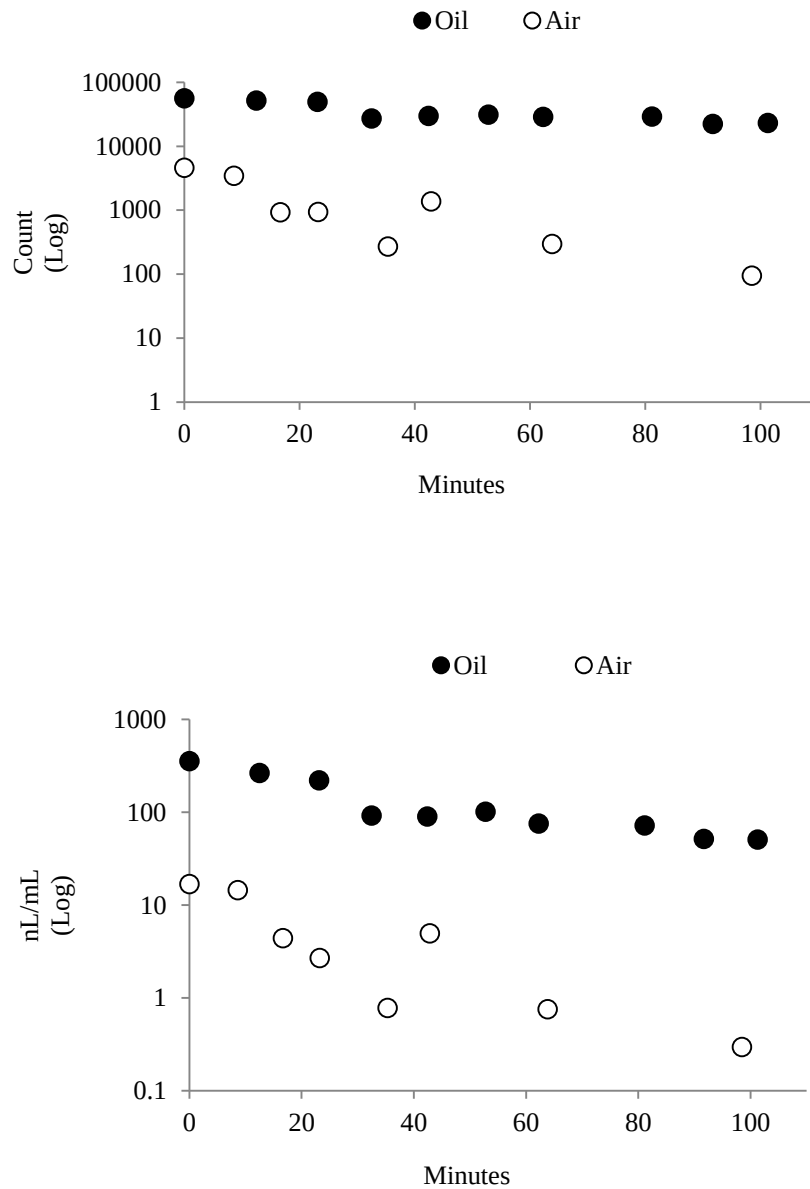


Figure 2-2 Time sequential analysis of oil droplet and detergent based air bubbles

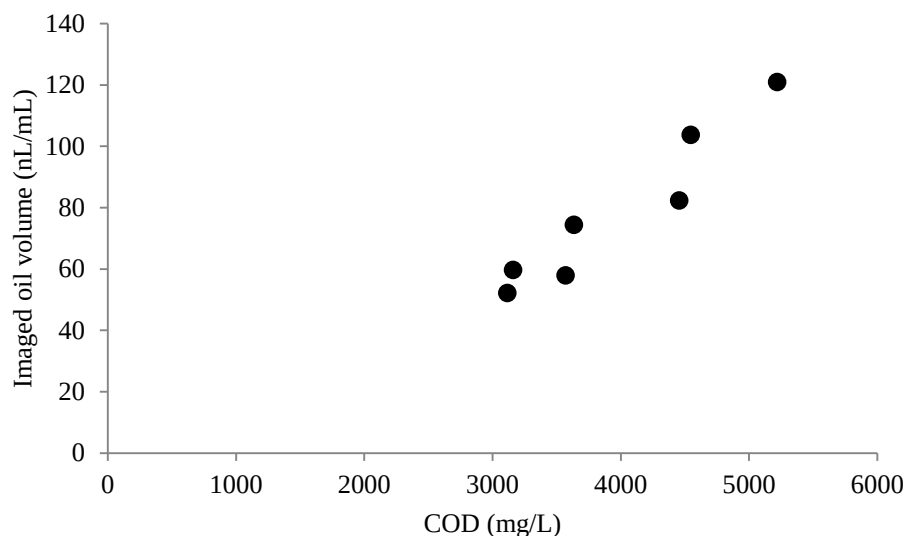


Figure 2-3 Oil droplet total volume for high circle fit droplets (CF>0.9) and COD evolution over time

Application to environmental samples

Application of the sizing method outlined in the paper is illustrated on a sample of domestic washing up water generated post a takeaway chicken curry and rice meal. In total the instrument identified 92075 individual images of which 85% v/v were identified as non-FOG debris with sizes between 100-300 μm (Table 2.2, Figure 2.5). The remaining volume fraction was split into 3.27% as readily identifiable FOG droplets (individual droplets), 1% was optically unresolvable (2-8 μm range) with 10.67% comprising FOG-debris mixtures. Further analysis of the final fraction identified images with near, overlaying or touching circular FOG droplets and/or adjacent debris (Appendix A3). Application of the developed filter estimated an additional 1.75% of the total volume was FOG. This compared to visual analysis of the images which estimated the volume as 1.6% indicating that the filter was effective. Combined with the free droplets, the total volume of FOG represented 5% of the total volume and 36% of the volume held within the 8-100 μm fraction.

Table 2-2 Summary of example data from analysing an environmental FOG sample.

Item	Criteria	Particle count	Volume mL	% of total particle volume	% of 8-100µm fraction	FOG Sample
1	< 300 µm	92075	4.67E-04	100%	NA	Sample FOG/Food
2	100-300 µm	126	3.99E-04	85.44.%	NA	Non FOG
3	2-8 µm	83129	2.91E-06	0.62%	NA	Undefinable particles
4	8-100µm CF >0.9	3771	1.53E-05	3.27%	23.47%	Easily visually qualified FOG
5	8-100µm CF <0.9	5049	4.98E-05	10.67%	76.53%	FOG / Food
6	Visually qualified FOG from CF <0.9 segment (mean of two assessments)	1242	7.49E-06	1.60%	11.51%	Target 'additional' FOG (assessed from row 5)
7	L1 Statistical filter	2850	1.33E-05	2.85%	20.46%	FOG filter
8	L1 Statistical x accuracy coefficient	NA	8.15E-06	1.75%	12.52%	FOG filter coefficient
9	Reported FOG	NA	2.34E-05	5.02%	35.99%	Total FOG (Item 4+8)
10	Reported FOG	6621	2.86E-05	6.12%	43.92%	Total FOG (item 4+ 7)

The size distribution of the identified FOG droplets fell within the 8-100 µm fraction with the largest FOG droplet having a diameter of 95.7 µm (Figure 2.6). Comparison of the total PSD, the free FOG droplets and the total FOG samples revealed median sizes of 213.83, 37.82 and 67.44 µm respectively indicating that inclusion of the FOG component held within the FOG-Debris mixture fraction altered the PSD to larger sizes. Overall the analysis identified that the

overall PSD is dominated by non-FOG debris (Figure 2.5) that biases the sizing to larger particles sizes. This confirms that use of instruments such as laser diffraction are inappropriate for informing about the size of FOG droplets in real FSE wastewater. In contrast the use of an optical sizing approach as detailed here provides a simple way of discriminating and sizing the free FOG droplets. Whilst more complex, the use of more advanced filters also enables determination of the total FOG volume held within the samples. The importance of understanding the different fractions is related to development of separators and understanding the fate of the FOG with free droplets being separate through flotation and FOG combined with debris more likely to settle. Importantly, determination of the actual size distribution of real FOG droplets in FSE wastewater can inform a more appropriate testing procedure to ensure that separator designs can remove the FOG they are intended to remove.

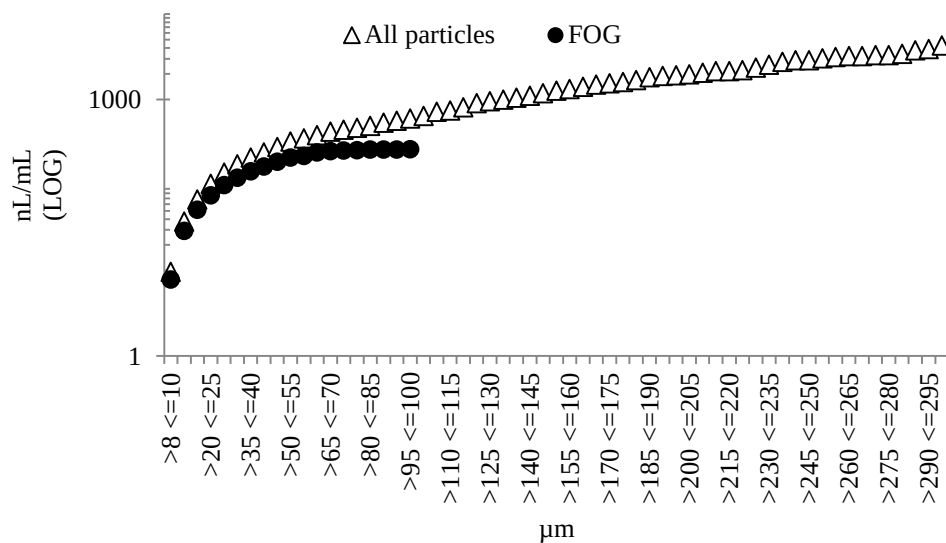


Figure 2-4 Example of a PSD from an environmental FSE sample: Cumulative volume fraction

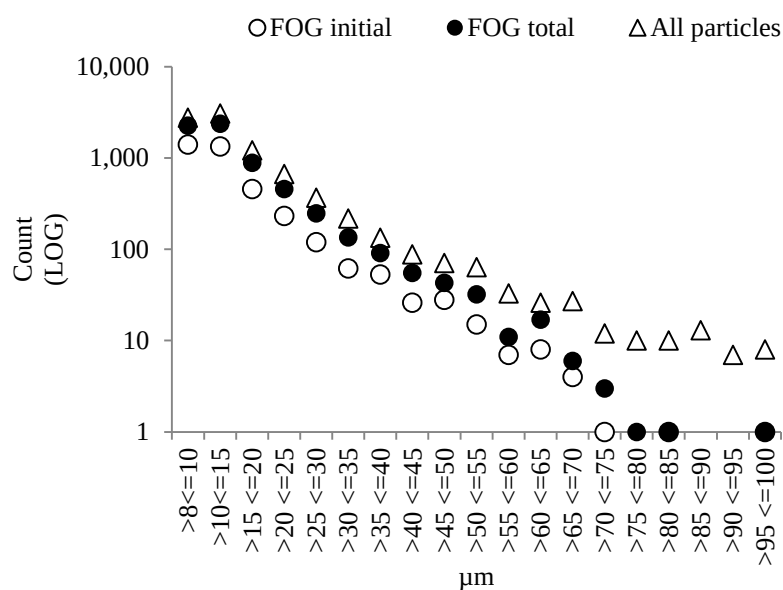


Figure 2-5 Example of a PSD from an environmental FSE sample: Number count

2.4 Conclusions

The application of an optical based sizing instrument is an effective way to measure both the total volume and the size distribution of the FOG in environmental samples. The approach can effectively determine the size distribution of three different fractions within the samples defined as non-FOG debris, FOG-debris mixture and free FOG droplets. The ability to discriminate between these fractions provides fresh insights into the challenges associated with effective FOG separation offering a route to new innovative design and more appropriate testing approaches.

2.5 Acknowledgements

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Chapter 3. Chapter 3 Characterisation of food service establishment wastewater in terms of droplet size distribution

M Fairley, C. Gurd, A. Cermakova, R. Villa, B. Jefferson*

Cranfield University, Bedfordshire, MK43 0AL

Abstract

FOG removal efficiency depends to a large extent on particle and droplet size distributions (PSD), studies of which are very limited with no identified comparisons of FOG source or cuisine type. The present study uses optical microscopy with image processing to determine the relative quantities of FOG and food debris and compare source and cuisine types. Two commercial kitchen facilities were studied where a dishwasher effluent and sink effluent were compared. A study of domestic sink wash system effluent was undertaken comparing cuisine types. No significant differences were identified between cuisine types. Of the commercial facilities, the median range of all particles in the dishwasher spanned 51-135µm, compared to 44 - 151 µm for the commercial sink. When FOG droplets were isolated the sizes ranges dropped to 17-20 and 29-37 µm for the dishwasher and sink respectively. The results show that measurement systems that cannot discriminate food debris will bias the size distribution to much larger sizes. The smaller FOG droplet distribution in the dishwasher negatively impact separation with the sink droplets rising some 2.25 times faster under quiescent conditions. The data provides an effective benchmark against which to test separator performance.

Key words: FOG, separators, grease interceptors, kitchen wastewater, particle size distribution (PSD)

3.1 Introduction

Fats, oils and grease (FOG) enter the sewer network mainly as a by-product of food service establishments (FSEs) and domestic households (Curran, 2015). Inadequate management of such FOGs is implicated as a major cause of sewer blockages with an estimated annual cost of £88 million spent on reactive blockage clearance in the UK alone (Dyson, 2015). Consequently, FSE wastewater requires some form of treatment prior to discharge into the sewer systems. The technologies options vary but group into physical separation and biological additions. The physical systems operate by passive separation driven by the density difference of the FOG with removal strongly affected by the size of the formed droplets.

The majority of existing data on FSE wastewater has focussed on the combined effluent, either before or after any incumbent separator (Chen et al., 2000) and has predominately measured characteristics related to assessment of pH; oil, Hexane extractable material; organics solids and nutrients (Stoll and Gupta, 1995; Nakajima et al., 1999; Lesikar et al 2006., Murthy et al., 2007; Chung and Young, 2013). Typical reported levels of organics are around 1800 mg/L of COD with total suspended solids between 150 and 900 mg/L. FOG concentrations have been shown to be highly variable as illustrated by one study which showed comparison across 88 FSEs where the FOG concentration was below 200 mg/L 32 % of the time, between 200 and 500 mg/L 29% of the time and above 500 mg/L 39% of the time (Garcia and Louch, 1994). Whilst data exists on overall concentrations there remains a genuine paucity of data relating to particle sizes of droplets within FSE wastewaters. Only one study reports particle size in FSE wastewaters and indicated the median size of the distributions were 48-56, 9-123, 23-274 and 31-138 μm across four different FSEs (Barton, 2012). The study used laser diffraction to conduct the measurements and as such sized all components in the wastewater including free FOG droplets, non-FOG debris and combinations of the two.

The current paper addresses this knowledge gap by measuring the size distribution of FOG droplets independently and in conjunction with the other debris from a commercial sink and dishwasher as well as a domestic sink.

3.2 Materials and Methods

Wastewater samples were taken from two source locations. Samples of commercial sink and dishwasher effluent were taken from two operational FSEs on the Cranfield University campus (Figure 3.1). The FSEs prepare and serve hot and cold food with varying menus catering for a wide range of cuisines. Typical kitchen processes involve raw ingredient preparation, boiling, frying, grilling, roasting and production of larger volumes of soups, sauces and bulk dishes such as lasagne and curry. A large part of the business takes place during Monday to Friday, and covers (a person equates to a 'cover') range from 100 to 200 per lunch time for each facility. Agreements on sampling times were made in order to acquire samples during a period of washing, typically 1pm and 3 pm which took place over 4 weeks

in November and December 2016. Eight separate sampling sessions were undertaken during each of which, three 2L samples were taken.



Figure 3-1 Images of sample points. Top left to right, pre-rinse station before dishwasher, sample point shown, typical appearance of waste water from dishwasher. Bottom left to right, pot wash sink with typical appearance of wastewater obtained from sink.

For the domestic kitchen, the washing of utensils for 4 meals was undertaken with a typical small domestic washing system. Some control was exercised on the wash water makeup. For each episode a total of 3 L of water comprising 2 L of boiling water and 1 L of tap dispensed cold water together with 3 mL of washing up liquid was used. Nalgene bottles were used to acquire a gross sample from which approximately 200 mL was filtered through 300 μ m mesh into a beaker.

FOG droplet distributions in kitchen wastewater may be considered dynamic in that larger droplets migrate toward a continuous oil phase, this can be clearly seen in the bottom right image of Figure 3-1. To quantify this effect samples were analysed for free and emulsified FOG content according to the modified Gerber Method ((Gurd et al, 2017) see Appendix 6) as well as COD which was measured according to standard methods. Samples were then inverted gently 5 times to ensure the droplets were mixed before sub surface aliquots were acquired. This was undertaken to avoid free oil during the droplet size measurements. The size distribution and count of the free droplets and the combined droplet particle systems was measured in triplicate by a portable Flowcam automated particle analysis instrument (Meritics, Dunstable, UK) utilising the method developed in chapter 2. Aliquot sizes were 5 mL for the commercial samples and 1 mL for the domestic samples reflecting anticipated particle loads and were measured in triplicate.

Discrimination of the FOG only droplets was achieved through applications of an image processing filter based on a criteria of a circle fit (CF) greater than 0.9, a transparency of less than 0.14 and edge gradient (EG) above 100 (Table 3.1). Diameter was measured on the basis of the mean feret diameter measured across 5° interval calibrated to a known scale. The resulting particle size distributions ranged between 12.7 μm and 272 μm . Data from the triplicate samples was then combined to maximise total FOG count across the distribution.

Table 3-1 Filter types and properties employed

Report type	Property	Effect
1. All data	All data	none
2. Circle fit filter (CF)	≥ 0.9 (0-1 value)	High circle fit reduces non-spherical particle acquisition thereby improving capture of candidate FOG droplets, but at the expense of also removing overlapping spheres.
3. Transparency filter	≤ 0.14 (0 – 1 value)	Some food particles are spherical, oil droplets exhibit low overall transparency, whilst food particles can appear transparent.
4. Edge Gradient (EG)	≥ 100 (0-255 value)	Removes out of focus images, improves size precision

3.3 Results and discussion

3.3.1 Concentration

The COD, aggregated across the eight samples, was 2810 ± 1393 and 1714 ± 113 mg/L for the sink and dishwasher respectively (Table 3.2). Comparison of the previously reported characterisation data reveals a wide range in possible COD levels with typical levels reported between 500-3000 mg/L with some specific cases as high as 20900 mg/L (Barton, 2012). The data is generally collected from the combined wastewater, just prior to a separator/discharge and covers a wide range of cuisines and cooking styles. Direct measurement of the FOG content through the adjusted Gerber method (Gurd et al, 2017) revealed significant differences in the makeup of the FOG. The sink source contained much greater concentrations of free oil, ranging from 83 to 1569 mg/L compared to 0 to 73 mg/L for the dish washer. Greater similarity was observed in terms of emulsified oil with mean concentrations, across the eight samples, of 309 and 291 mg/L for the sink and dishwasher respectively (Table 3.2). Consequently, the ratio of emulsified to free oil varied between 79-

100% for the dishwasher compared to 23-66% for the sink. For comparison, a previous study containing 660 samples found that 32% was below 200 mg/L, 29% ranged between 200 -500 mg/L, 21% ranged between 500 -1000 mg/L and 18% of the FSE was above 1000 mg/L (Garcia and Louch, 1994). The greater difference in the amount of free FOG in the sink is most likely a consequence of pre-rinsing wash ware before the final dishwasher stage. Pre-rinsing into a sink is a standard practice used to conserve the washing water in the dishwasher itself where many commercial models operate through multiple washes before water exchange. Importantly, none of the previous studies have reported sizing data apart from one study that used laser diffraction to measure the particle size distribution from four different FSEs (Barton, 2012). The measurement approach means that the recorded data included both FOG and non-FOG debris with median sizes of 48-56, 9-123, 23-274 and 31-138 μm .

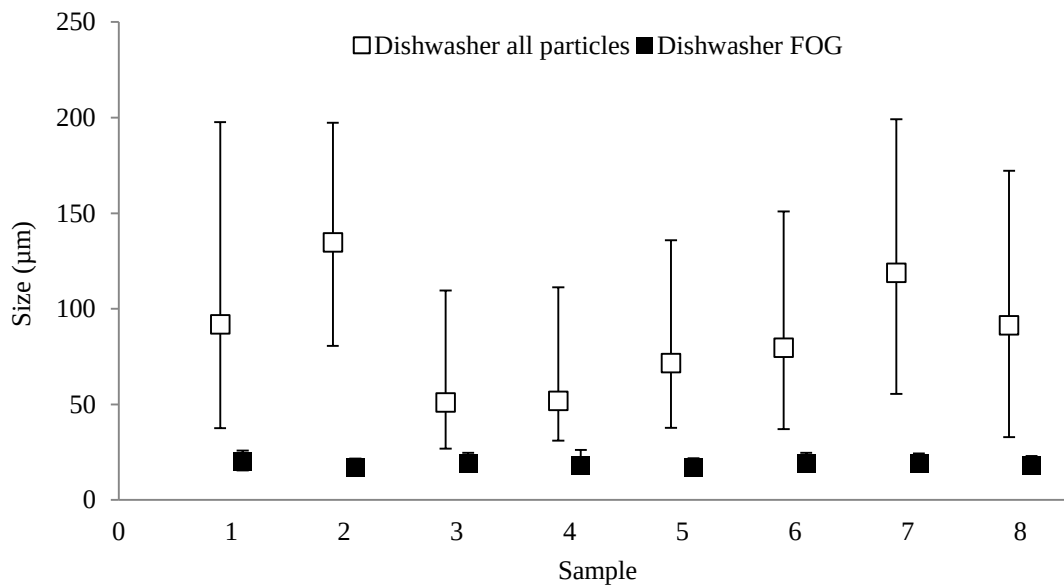
Table 3-2 Summary of FOG characterisation

Sample	Free FOG (mg/L)		Emulsified FOG (mg/L)		COD (mg/L)
	Mean	Range	Mean	Range	
Sink	570	83-1569	309	124-538	2810 $\pm$ 1393
Dishwasher	22	0-44	291	199-432	1714 $\pm$ 113

3.3.2 Particle and droplet size characterisation

Comparison across the eight samples revealed a variation in the median size of all particles within the samples of between 51 and 135 μm for the dishwasher and between 44 and 151 μm for the sink (Figure 3.2). Much greater consistency was observed with respect to the FOG droplet analysis with the median droplet size varying between 17 and 20 μm for the dishwasher and 29 to 37 μm for the sink. Aggregated across all eight samples the median size of the particles were substantially larger than that for the FOG droplets. To illustrate, in the case of the sink, the median particle size was 93 $\pm$ 37 μm for all particles compared to 27 $\pm$ 5 μm for just the FOG droplets. This confirms that measurement approaches that include all particles in the systems will bias the size distribution to much larger sizes. Accordingly, techniques such as laser diffraction are inappropriate if accurate measurement of the FOG

droplets is required. In the case of the dishwasher samples, the median size decreased from $86 \pm 30 \mu\text{m}$ when considering all particles, to $18 \pm 1 \mu\text{m}$ for just the FOG droplets. The smaller sizes in the case of the dishwasher samples reflect the higher energy and chemical inputs of such systems. Further, the difference in size will be reflected in the ease of separation with the larger sink droplets rising under quiescent conditions at a rate 2.25 times faster than the smaller droplets.



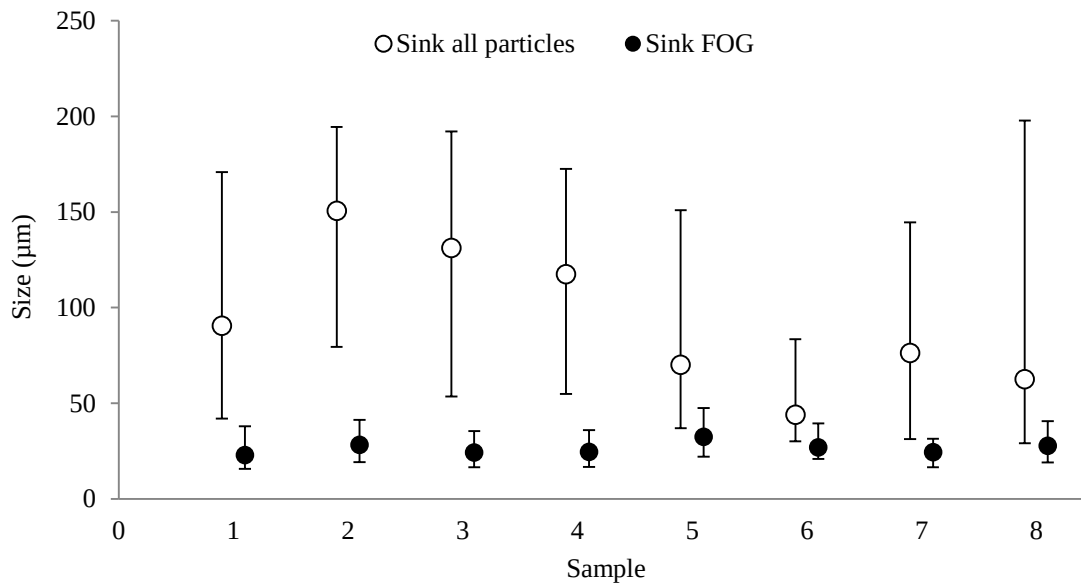
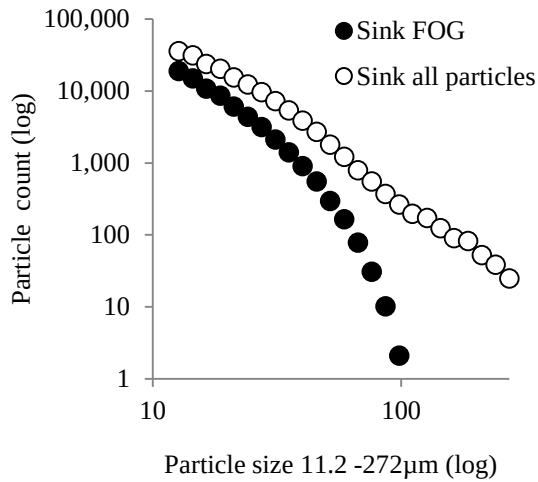


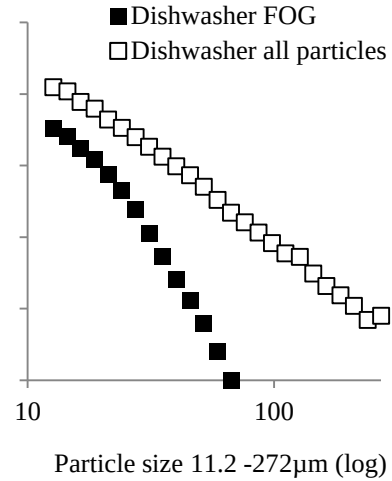
Figure 3-2 Comparison of the summary data from the eight separate samples from each source. Interquartile range by volume shown.

Analysis of the size distributions of the systems by number count revealed a power law decline of count as a function of size for the total particle systems in both the sink and dishwasher samples (Figure 3.3). To illustrate, in the case of the sink, the number count decreased from 35961 particles at a size of 12.7 μm to 25 particles at a size of 272 μm (Figure 3.3a). In comparison, the dishwasher effluent contained 12525 particles at 12.7 μm dropping to 8 particles at a size of 272 μm . Importantly, the data shows that non-FOG debris occurs across the entire size range with the sink again being shown to be the more heavily contaminated with 2.86 times the particles at a size of 12.7 μm and 3.1 times more particles at the maximum size of 272 μm . The FOG droplet counts were substantially lower than the total systems with counts of 18984 and 3298 droplets at a size of 12.7 μm for the sink and dishwasher respectively. This equates to a number ratio of droplets to all particles of 53% and 26 % for the sink and dishwasher respectively. Further, the maximum size of FOG droplet was 98 μm in the case of the sink and 67 μm for the dishwasher with respective counts of 2 and 1 droplets. The FOG count data of individual samples was a minimum of 3559 droplets for the Dishwasher and 42125 droplets in the case of the sink. These levels exceed the suggested 500 minimum counts required to define a meaningful distribution (O'Rourke and MacLoughlin, 2004). However, a count in excess of 90 is recommended at the average

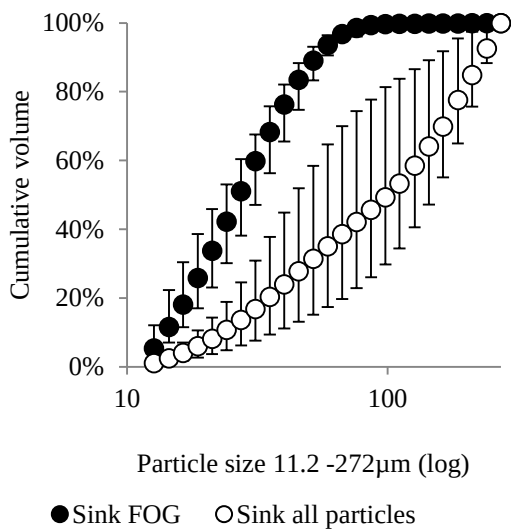
droplet size in order to generate a 95% confidence interval (Gallimore et al., 2011). Count data from all eight samples met these criteria.



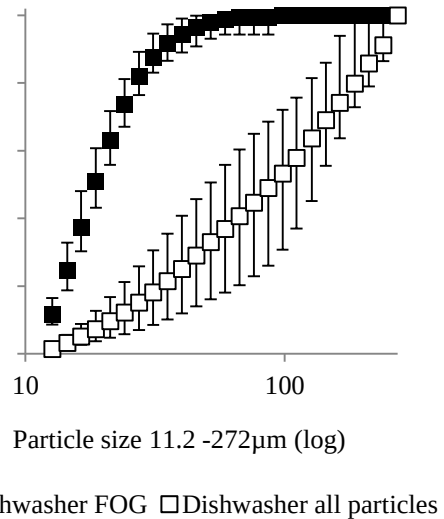
(a) Number count, sink



(b) Number count, dishwasher



(c) Cumulative volume, sink



(d) Cumulative volume, dishwasher

Figure 3-2 Size distributions of the sink and dishwasher samples in terms of number count and cumulative volume – bars show range per bin increment

The impact of the difference in size distribution was more apparent with respect to the cumulative volume (Figure 3.3 c,d). For instance, at the maximum size of the FOG droplets, and hence 100% of the cumulative volume, the respective volume fraction for the total systems was 40.6% and 49.3 % for the dishwasher and sink respectively. Whereas, at the median size of the FOG droplets, the equivalent volume of the whole systems was 13.6% for the sink and 7.3 % for the dishwasher. The variation in the cumulative volume across the eight samples was far greater in terms of all particles compared to the FOG droplets. In the case of the latter, the maximum span of 30-58% occurred across size intervals 14.5-16.4 μm for the dishwasher with a span of 30-53% occurring across size intervals 21.1-24.1 μm for the sink. Notably, none of the samples identified FOG droplets close to the 150 μm cut prescribed by the American Petroleum Institute for separating oil droplets (Chu, 2000; López-Vasquez and Fall, 2004). In total, only 32 droplets from the dishwasher and 2306 droplets from the sink were identified to be above 51.8 μm .

3.3.3 Cuisine type

The number count of the whole particle systems decreased from 2472 at 14.5 μm to 3 at 127 μm and remained around that level up to the maximum measured size of 272 μm (Figure 3.4a). In comparison, the FOG only droplets decreased from a number count of 1154 at 14.5 μm to 1 at 98.1 μm , the maximum size observed. The ratio of counts at 14.5 μm equates to the FOG droplets representing 47% of the total whereas at 76 μm the FOG droplets accounted for only 13% reflecting the increasing dominance of the non-FOG debris in the larger size fractions. The cumulative volume distributions for the four cuisine types were statistically similar at an α value of 0.05 based on a Kruskal-Wallis non-parametric test utilising the Chi-square distribution with 3 degrees of freedom (Figure 3.4b). The maximum variation in the cumulative volume distribution was observed between the baked cod and chicken curry meals and occurred at sizes of 24 and 27.2 μm with a difference in volume fraction of 18% with the chicken curry generating the smaller droplets.

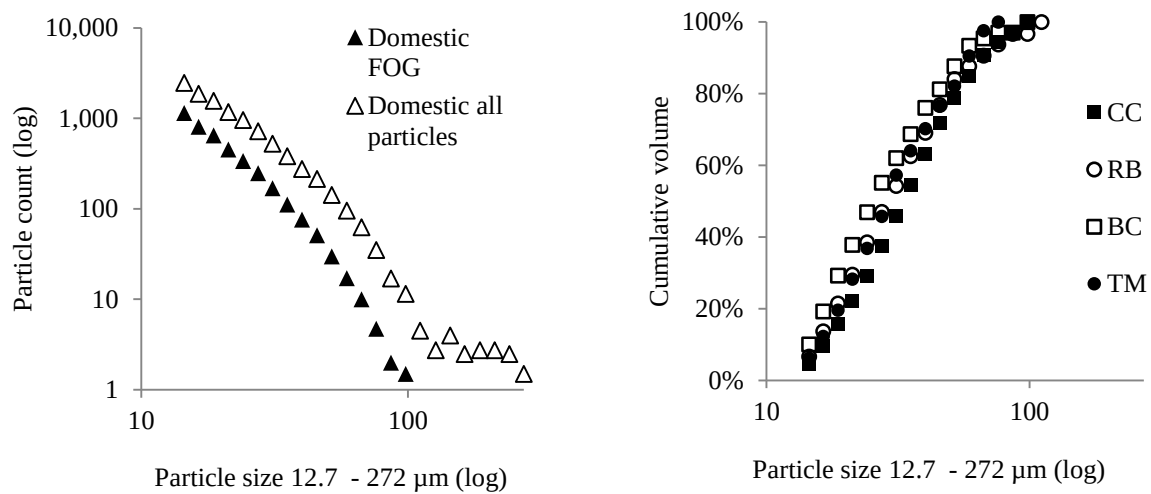


Figure 3-3: size distribution of the domestic sink samples based on four cuisine types: CC = chicken curry; RB = roast beef; BC = baked cod; TM = turkey mozzarella (n=5)

3.3.4 Overall comparison

Comparison between the three sources revealed greater similarity between the commercial sink and the domestic sink both of which generated larger droplets than from the dishwasher (Table 3.3). This confirms the hypothesis that the greater agitation and surfactant levels in the dishwasher result in small droplets. For instance, analysis of the descriptive statistics of the two commercial sources revealed significant difference in regards to the 90th percentile for the whole particle systems and the 50th and 90th percentiles for the FOG only droplets, based on a non-parametric Mann-Whitney U test at $\alpha = 0.05$. Overall the order of droplet size was the dishwasher, commercial sink then domestic sink illustrated by the cumulative volume percentage at a size of 27.4 μm which was 81.8%, 51.1% and 37.5% respectively. The impact of these differences is seen in regards to the terminal rise velocity that occurs under quiescent conditions according to Stokes' law. For instance, at the c80 percentile for each system the respective terminal rise velocities would be 0.172 cm/min for the dishwasher (81.8%ile), 0.476 cm/min for the commercial sink (83.4 %ile) and 0.794 cm/min for the domestic (85%ile) (Table 3.3). The corresponding quiescent period required to rise 30 cm would be 174 minutes, 63 minutes and 38 minutes respectively demonstrating the more challenging nature of removal imparted by the smaller droplets formed in dishwashers. Previous batch

separation data of oil droplets supports this with removal after 10 minutes of 43%, 78% and 98% for droplets of sunflower oil with median sizes of 32 μm , 44 μm and 61 μm respectively (Barton, 2012). A similar set of batch experiments have been reported with respect to separation of droplets formed from automotive repair oil (s.g. 0.92) (López-Vasquez and Fall, 2004). The droplets had a larger mean particle diameter size of $73 \pm 3.9 \mu\text{m}$ with 69% volume $< 150 \mu\text{m}$ and 39% volume $< 50 \mu\text{m}$ at an overall concentration of 2.7 mL/L. The removal efficiency decreased from 2500 mg/L to 1000 mg/L within the first 5 minutes reaching 250 mg/L after 1 hour. For comparison, a previous study on the impact of droplet size on the removal in continuous flow separators used a 4% v/v corn oil solution with 81% of the droplets above 150 μm (Aziz et al., 2011). The reported efficiency was 78% at a hydraulic retention time of 20 minutes which increased to 90 % when the hydraulic retention time was extended to 1 hour. In a similar study testing passive flow based interceptors reported removal efficiencies of 8% for droplet sizes of $143 \pm 41 \mu\text{m}$ at a flow of 0.62 L/s rising to 81% at droplets sizes of $501 \pm 111 \mu\text{m}$ at a flow rate of 0.31 L/s (Gallimore et al., 2011). The tested flow rates equated to hydraulic retention times (HRT) of 30 s and 1 minute respectively and demonstrate that effective removal of droplets can occur in short residence times if large enough.

Table 3-3 Summary of FOG droplet distributions in the three systems

Size (μm)	Mass* (mg/ droplet)	No/L req ^d for 100 mg/L	Rise velocity* (cm/min)	Sink		Dishwasher		Domestic	
				Cum (%)	Dist (%)	Cum (%)	Dist (%)	Cum (%)	Dist (%)
12.7	0.00099	100252	0.04	0.5	0.5	11.5	11.5	-	-
16.4	0.00214	46556	0.06	18.1	17.6	37.4	25.9	11.6	11.6
21.2	0.00463	21553	0.10	33.8	15.7	63.0	25.6	25.7	14.1
27.4	0.01001	9983	0.17	51.1	17.3	81.8	18.8	41.8	16.1
35.3	0.02142	4669	0.28	68.3	17.2	91.6	9.8	58.2	16.4
45.6	0.04617	2166	0.47	83.4	15.1	96.5	4.9	74.1	15.9
58.9	0.09950	1005	0.79	93.6	10.2	98.7	2.2	86.8	12.7
76.0	0.21376	468	1.32	98.5	4.9	99.4	0.7	95.1	8.3
98.1	0.45973	218	2.20	99.7	1.2	100	0.6	99.4	4.3

*s.g. 0.93, $m = 1000 \text{ kg/m.s}$

3.4 Conclusions

The majority of particles in FSE wastewater have been identified as non-FOG debris. Analysis of the FOG only component revealed median droplet sizes of $27 \pm 5 \mu\text{m}$ for sinks and $18 \pm 1 \mu\text{m}$ for dishwashers with maximum observed droplet sizes of $98 \mu\text{m}$ and $67 \mu\text{m}$ respectively. Whereas when all particles are sized the median diameter increased to $93 \pm 37 \mu\text{m}$ for sinks and $86 \pm 30 \mu\text{m}$ for dishwashers. This confirms the bias that is generated by utilising non-discriminating particle sizing techniques and further illustrates the impact of source type on the size of the formed droplets. The data provides an effective benchmark when considering testing of separators and the impact of ensuring appropriately sized droplets are utilised.

3.5 Acknowledgements

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Chapter 4. Measurement of the dynamic flow profile of discharges from food service establishments

M Fairley, R. Villa, B. Jefferson*

Cranfield University, Bedfordshire, MK43 0AL

Abstract

The current study uses a non-invasive ultrasonic flow sensor to record flow in a real FSE over a 14 day period at 4 second intervals. The resulting data allowed calculation of episode volume as well as flow rate. The results indicate the significance of the sporadic nature of the flow with the majority of the total volume discharged through a separator occurring in small packets of flow which are less than 10% of the maximum flow observed. Such events are interspersed by periods of no-flow providing significant periods of near quiescent conditions. Overall the work indicates that future design and testing should focus on the intermittent and small nature of the flow profile. Further, the work brings into question the relevance of the current testing procedure which utilises trials at the maximum design flow of the separator.

Keywords: Food service establishment, flow rate, BS EN 1825, gravity separators, pseudo-batch-separator

4.1 Introduction

Wastewater is generated from a range of operations in food service establishments (FSEs) such as pre-wash rinsing of wares, dishwashers, combination ovens, pot washing, wok ranges and extraction filters as well as general cleaning such as floor washing. The wastewater from some of these operations contain high concentrations of fats, oils and greases (FOG) that need to be removed prior to discharge into the sewer to minimise problems related to clogging. For instance, in the USA it is reported that 40 – 50% of all sanitary sewer overflows are caused by FOG related blockages (Ducoste et al., 2008). One of the major solutions utilised is the inclusion of passive gravity separators that remove the FOG through gravitational displacement. Accordingly, the flow rate profile entering the device is critical. Current selection and testing practice is based on continuous flow with standard testing conducted at the maximum design flow of the specified unit covering a range from 2 to 25 L/s (BS EN 1825, 2004). Many devices on the market do not claim to meet this standard and

are made intentionally smaller to satisfy the spatial limitations in many FSEs. Such devices may be passive or electro-mechanically active, but all operate with substantially lower hydraulic retention times (HRT) making the need to understand hydraulic loading profiles even more pertinent.

Reported flows in FSEs are generally described in terms of the overall discharge volumes. For instance, restaurant wastewater discharge in Beijing is reported to contribute 3% of the total sewer discharge with typical values of 15 – 20 m³/d per FSE with a maximum reported rate of > 80 m³/d in larger facilities (Li et al., 2011). Similarly, reported flow rates from restaurants in Hong Kong were typically 10 – 30 m³/day (Chan, 2010). An equivalent study of 28 restaurants in Texas reported a mean flow of 68 L/day/seat with a standard deviation of 39 L/day/seat based on difference in meter readings from the supply and so represented all flows into the restaurant (Lesiker et al., 2006). Importantly, it is posited that wastewater flow in commercial kitchens is sporadic, depending on washing times, business operational factors as well as connected equipment – commonly dishwashers, rinse and wash sinks. To date, there is a paucity of research exploring the dynamic pattern of wastewater flow rates and associated volumes from commercial kitchens. Of the few available studies, Aziz et al., (2012) confirmed flow to be sporadic and subject to large temporal variation with the 90th percentile rate equating to just 33% of the maximum flow in 75% of the cases examined. Furthermore, 90 – 95% of rates were below 0.63 L/s⁻¹. The study covered 24 facilities over a 24 hour period and the resolution was limited to 15 minute measurement intervals (Ducoste. J.J. pers. Comms., November 2016). Importantly, no study to date has considered the impact of the wide range of volume fluxes that occur in FSEs and intervening quiescent periods that ensue through a given period of operation. The importance of this is that the separators may effectively operate in a batch mode with separation occurring during the quiescent / low flow periods and the flow events displacing cleaned water from within the separator's stored volume.

The current paper aims to further investigate the dynamics of flow in FSEs to establish a basis for understanding the impact of temporal variance in flow rate and volume discharged in consideration of new separator design and performance testing. To do this the study recorded the flow data from a real FSE over a 14 day period using a non-invasive ultrasonic flow sensor with a 4 second interval between data points.

4.2 Materials and Methods

Flow was measured with an ultrasonic non-invasive flow monitor – Flowpulse, linked to a handheld data logger and power source (Pulsar Process Measurement Limited, United Kingdom). The sensor works by measuring refracted ultrasound from particles and bubbles in the flow with a specified preferred nominal particulate load expressed as 200 ppm of particles greater than 100 μm (equivalent of hard water). The manufacturers stated accuracy is $\pm 5\%$, with a range of velocity spanning 0.3 to 4 m/s^{-1} . The data signal is analysed using Flowpulse's Refracted Spread Spectrum Analysis (RSSA) digital signal processing platform to derive flow information. Establishing the coefficient factor used to transform the raw data into site specific flow information was undertaken by reference to flows measured off-site on an induction flow meter for flow rate.

Obtaining flow data in FSEs is problematic in that measurement of flow typically assumes the pipe is full. However, the potential sporadic and variable nature of flows in kitchens together with the variety of different plumbing configurations (including any separator) and pipe sizes prevents universal assumption of such conditions. Equally, effective measurement in real FSEs is only possible if minimal disruption to service is provided and as such non-intrusive measurement technology is required. A site was selected on the basis of its relevance to FOG mitigation and the willingness of the FSE to accommodate installation, some calibration work and retrieval of equipment. The site was located on a relatively new large out of town shopping park and would be exposed to traffic frequenting such facilities with the FSE delivering 200 covers per day during the week and 500 covers per day at the weekend. The FSE is a full service fast food restaurant which is open between 9:00 AM – 8:00 PM during the week as well as 9:00AM-7:00PM and 11:00AM-4:00PM on Saturday and Sunday respectively. The washing operations within the FSE were a spray sink, dishwasher, mop sink and handwashing basin.

4.2.1 Calibration of the flow meter

The flow meter was calibrated utilising pipe gradients based on a single discharge stack with full bore branch discharge pipe; defined as a type 3 system in the Standard BS EN 12056-2 (2000) and identified as the most commonly used (Griggs. J; Price. N. pers. comms., June 2016). Minimum gradient information is supplied in the Standard and is given as 1.8 – 2.2%

for less than DN 100 and 0.9% on DN 100. Separate trials were conducted to establish the relationship between head and flow rate in 40 and 50 mm pipes connected to a conventional sink. Maximum flows of 0.84 L/s and 2.05 L/s were obtained at a head of 350 mm (Further detail can be found in Supplementary Information Appendix 7.)

The Flowpulse was calibrated against a magnetic induction flow meter used to recirculate wastewater through a grease separator unit connected to a 40 mm pipe, the pipe connection size of the separator. The pipe gradient was altered by raising one end of the pipe and the flow rate measured at 4 target flow rates of 0.2, 0.4, 0.6 and 0.8 L/s⁻¹. The sensor was positioned according to manufacturer's instructions, sensor midway on a 560 mm long pipe of 40 mm internal diameter



Figure 4-1 Volume calibration set up based on free draining 40 mm trapped outlet at 6% gradient

A standard domestic sink was modified to enable a 40mm trapped plumbing system to be drained repeatedly with known volumes of a wastewater proxy (Figure 4.1). The outlet pipe was set at a gradient of 6%. Measured volumes of water were decanted into a bucket and the tests for each volume increment repeated 10 times. Maximum flow rate and calculated volume were reported together with standard deviation from which the coefficient of variation was calculated. Equivalent trials were conducted at the FSE site as flow rates are inevitably site specific due to often complex plumbing and attached devices which may attenuate and alter flows, this method potentially offered the most realistic method of calibration. The meter was installed on pipework after the separator and a connected sink was discharged under varying fill levels equating to 32 and 38 litres for a battery of 3 tests at each volume. A section of plumbing pipework was removed and replaced with fresh pipe to which

the sensor was attached with acoustic coupling enhanced by silicone grease application. The fresh pipe was mandated by the sensor instructions which required that the pipe be clean as one of the parameters of meter set up is pipe internal diameter.

4.2.2 Data analysis

Volume per flow episode was calculated from reported time and flow rate data. An episode is defined as a period of flow with a beginning and end identified by zero flow. Identification and episode designation was achieved through use of the *if* function in Excel to label signals as flow or no flow (an illustration is provided in Appendix 8). Pivot table analysis was then used to quantify episode information, for example, totalling the time or volume of each episode or quantifying flow rate (min, av, max, standard deviation). Analysis is then possible over the set of flow episodes or subsequent quiescent periods.

4.3 Results and Discussion

4.3.1 Flow rate and volume calibration

Calibration of the Flowpulse sensor reading against flow rates from a magnetic induction flowmeter revealed a linear relationship across the flow rates tested (Figure 4.2). The correction factor is the ratio of the magnetic induction meter to the Flowpulse sensor for an individual point or the gradient across the data for an overall factor. Individual ratios varied between 0.42 and 0.58 with an overall correction factor of 0.46 with an estimated error of 10.3%. An increase in the level of variation between different pipe gradients was observed at lower flow rates with individual ratios ranging between 0.42-0.58 at 0.23 L/s compared to 0.44-0.47 at a flow rate of 0.8 L/s. Similarly, the extremes of gradients tested, 0-10%, also generated more variation than the other gradients. However, most actual pipe systems are expected to fall within the 2.5-7.5 % gradient range where the sensor response was most consistent.

The ability to use the Flowpulse sensor to estimate volume discharges was then assessed in a laboratory sink trial (Figure 4.1) by discharging known volumes of water through the system to establish if the cumulative data could be accurately used to establish total discharge. The volume estimate was generated by adjusting the sensor signal based on an average correction factor identified over the course of the experiment. The estimated discharge volume was marginally higher than the actual volume across the test range but was not statistically

significantly different. To illustrate, actual volume discharges of 1.5, 6 and 12 L generated estimated volume discharges of 1.32 ± 0.27 L, 6.29 ± 0.37 L and 12.31 ± 0.57 L respectively (Figure 4.3). Overall the sensor could effectively measure the discharged volume across the range with statistical significance as identified through a two sample T-test ($P < 0.01$) coupled with an F-test to determine variance equality: Variance as a percentage of the mean of the recorded flow rates ranged between 0.02 and 0.11%. The limit of detection of the volume estimate was 1.5 L as the flow rate through the sink at the volume was below the detection threshold of the instrument.

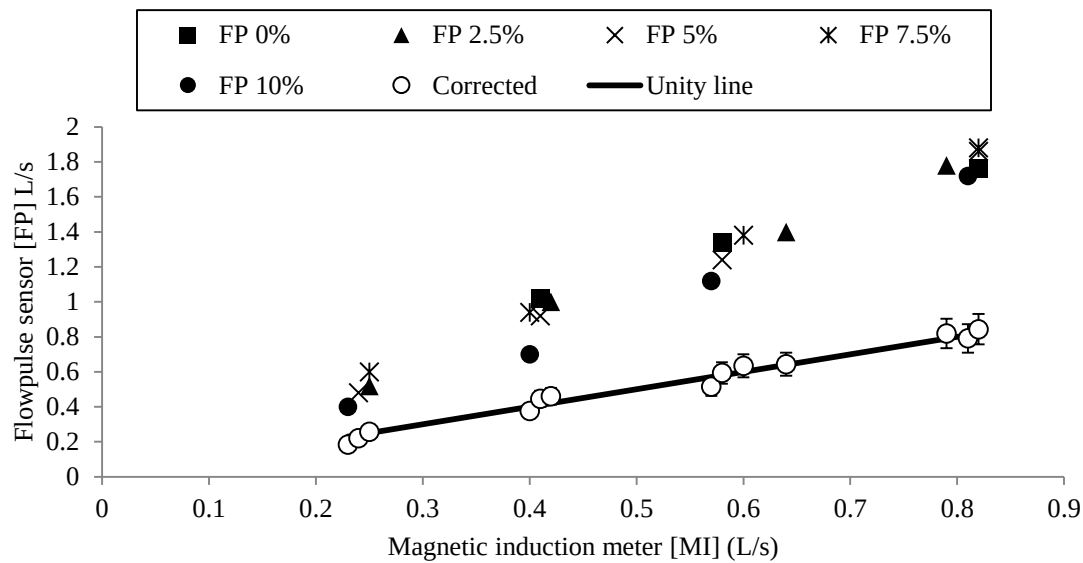


Figure 4-2 Calibration of Flowpulse sensor against magnetic induction meter for a 40 mm pipe at different gradients as denoted in the legend. Corrected values show application of a single correction coefficient, error bars show coefficient of variation (n=4)

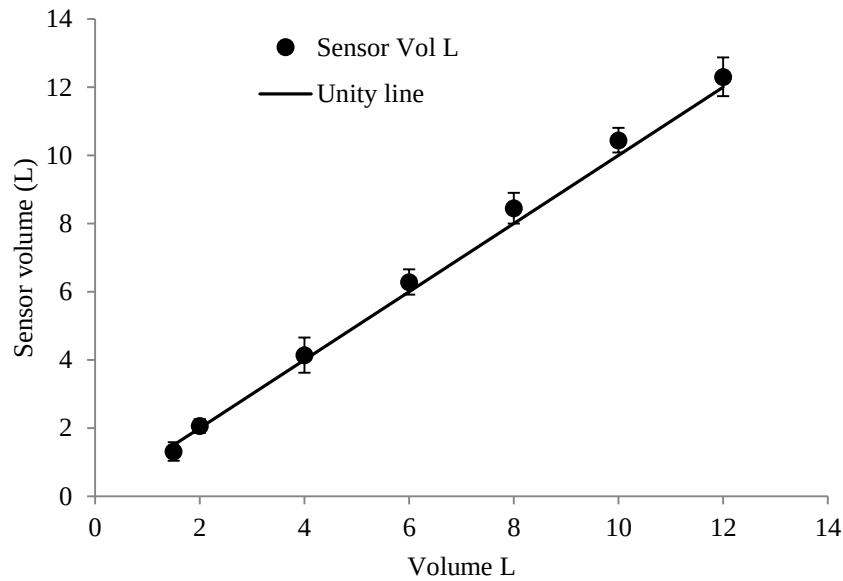


Figure 4-3 Sensor volume vs known volume for 1.5, 2, 4, 6, 8, 10 and 12 L discharge volumes. Error bars are $\pm$ sample standard deviation. (n=10).

The final set of calibrating trials involved on-site tests where known volumes of water were discharged through a sink to the separator and the sensor signal recorded to calibrate the response to the site conditions and the specific pipe layout. The duration of the 32 L discharge events was between 69 and 73 seconds compared to between 81 and 86 seconds for the 38 L discharge events (Figure 4.4). A similar signal pattern was observed for each event as expected with a rapid increase in the signal response in the first 20 seconds of the discharge followed by a more gradual decline. The associated maximum signal response adjusted flow rate for the lower volume events was between 0.81-0.97 L/s compared to 0.82-0.9 L/s for the larger volume events. A slight difference in the first batch was observed in terms of an increase in total duration of 4 seconds and the highest recorded peak flow which was 0.09 L/s higher than the second event (10%) attributed to first flush impacts and not expected to influence subsequent analysis as the trials were conducted over 14 days and captured all events.

The uncorrected volume estimate from the signal response was 53.2 L, 46.7 L and 42.6 L for the three repeat trials with the 32 L discharge batch equating to correction factors of 0.60,

0.69 and 0.75 respectively. More consistency was observed in the second set of trials with the larger batch volume generating associated correction factors of 0.69, 0.68 and 0.72. Overall the average calibration factor was assessed to be 0.69 with a relative error of 7.3%.

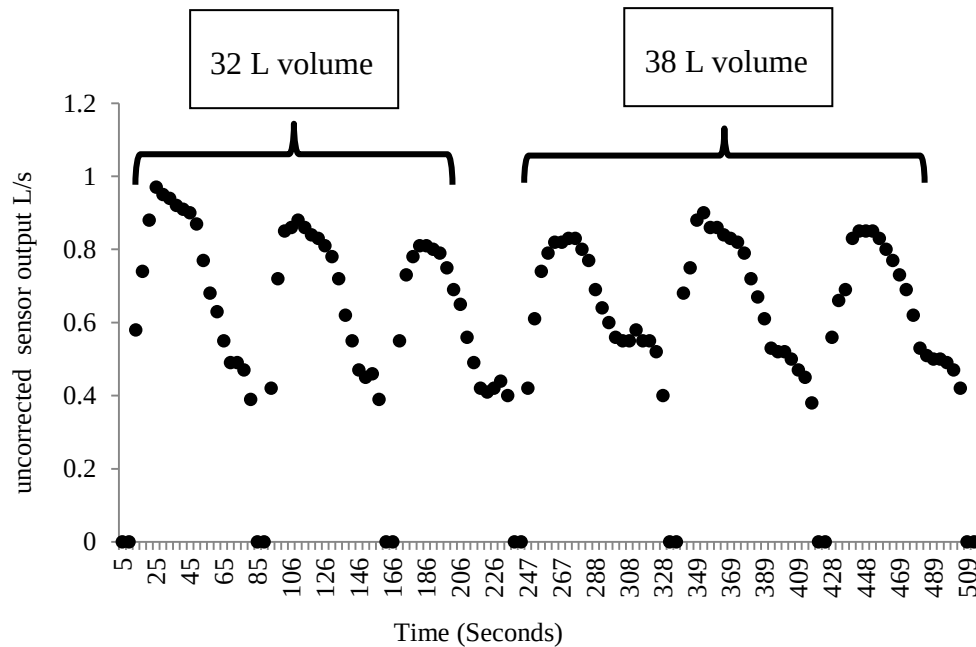


Figure 4-4 Example sensor response from the on-site calibration. First three events were actual discharges of 32 L and the final three events were actual discharges of 38 L.

4.3.2 On site flow measurement

Comparison of the daily discharge profiles revealed no consistent pattern across the fourteen days (Figure 4.5). Overall the split of flow and no-flow events across the fourteen days was 838 flow and 839 no-flow events. Interestingly, a number of events exceeded the suggested design flow for a 40 mm pipe systems of 0.75 L/s (BS EN 12056, 2000) as well as the nominal limit for a sink of 0.84 L/s. The elevated flow rates are attributed to multiple devices discharging simultaneously into the system such as the rinse sink via the separator and dishwasher, mop and handwash sink directly to the pipe. In total, seven events of the 838 exceeded 1.5 L/s of which four events occurred between 22:05 and 22:41 pm, indicating close of day cleaning activities that may have utilised the mop drain. Flow rate data greater than 0.84 L/s was excluded from subsequent analysis due to the limits on the sensor

calibration. Assuming a consistent calibration, the excluded data represented 6.9% of the total volume discharged and 2% of the time that flow was measured.

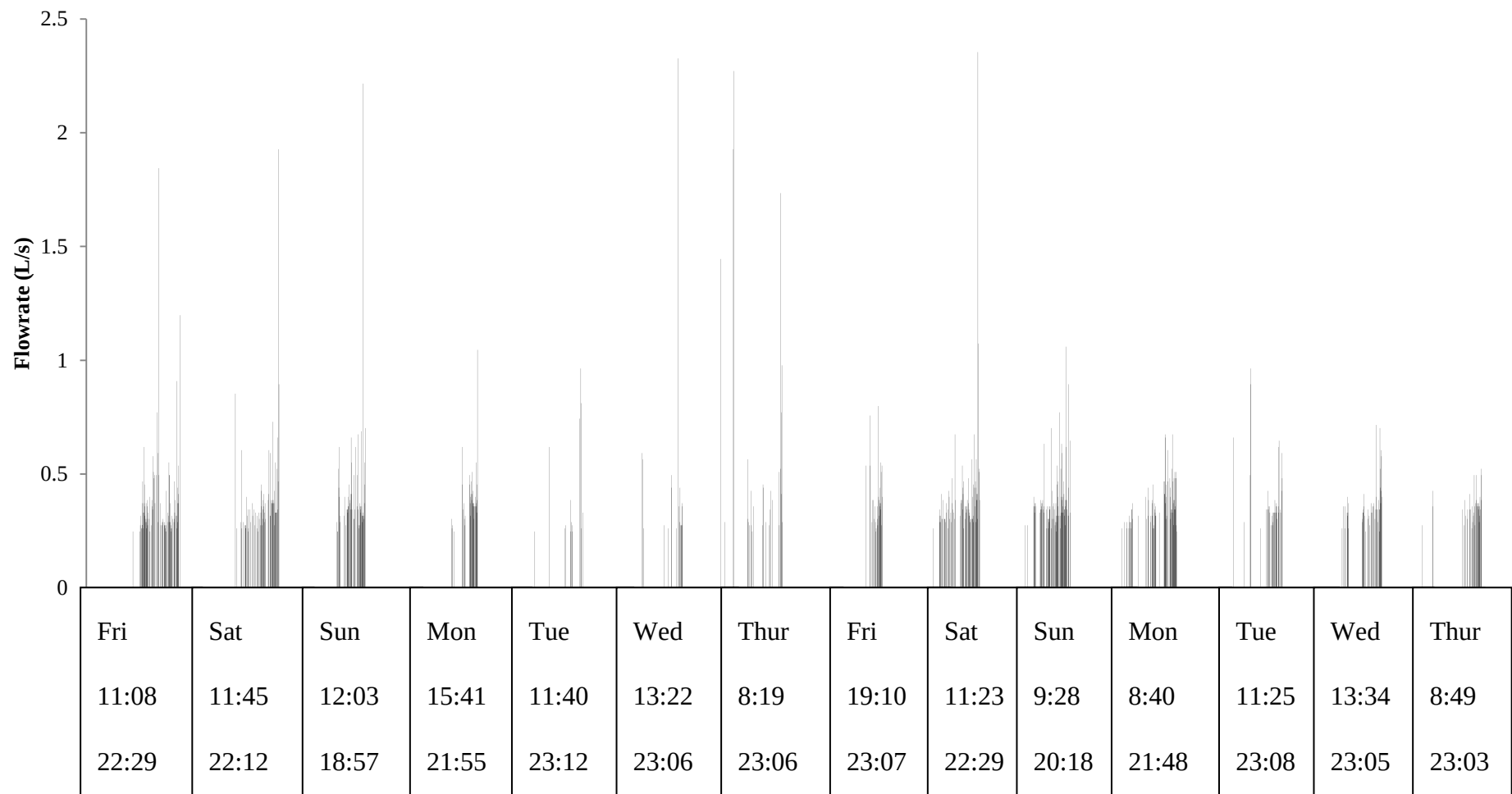


Figure 4-5 Fourteen-day analysis overview with corresponding first and last flow data time indicated.

Overall analysis of the sub 0.84 L/s flows indicated that the small FSE discharged an average of 400 L/d over a period of 18 minutes containing a broad range of flow rates and discharge volume events. Aggregating data over the fourteen days revealed the range of total discharge on an hourly basis (Figure 4.6). The volume of an individual event was fairly constant across the day with the exception of the final hour. For instance, the median hourly volume discharged ranged from 2 to 5 L with an interquartile range of 1.2 to 11 L discharges per event for all but the final hour of the day. In the final hour, the close of day cleaning occurs and this increased the median discharge to 42.7 L with an interquartile range of 18.5 to 55.5 L. Consequently, during the day the majority of the wastewater entering the separator comes in small packets that are significantly less than the stored water volume within the tank. Additionally, peak discharge events between 3.8 and 131 L occurred during most hours of the day which will displace a much greater percentage of the stored water in the separator and hence pose the maximum risk to high concentration FOG discharges.

Whilst the size of individual discharge events across the day remained fairly similar there is a different pattern in terms of the number of events with an overall increase as the day proceeds. The maximum number of individual events occurred between 18:00 and 23:00 and ranged between 76 and 131 events per hour over the 14 days equating to between 5.4 to 9.4 events per hour within a day (Figure 4.7). Accordingly, the majority of the total discharge occurs between those five hours representing 58.9% of the total volume discharged.

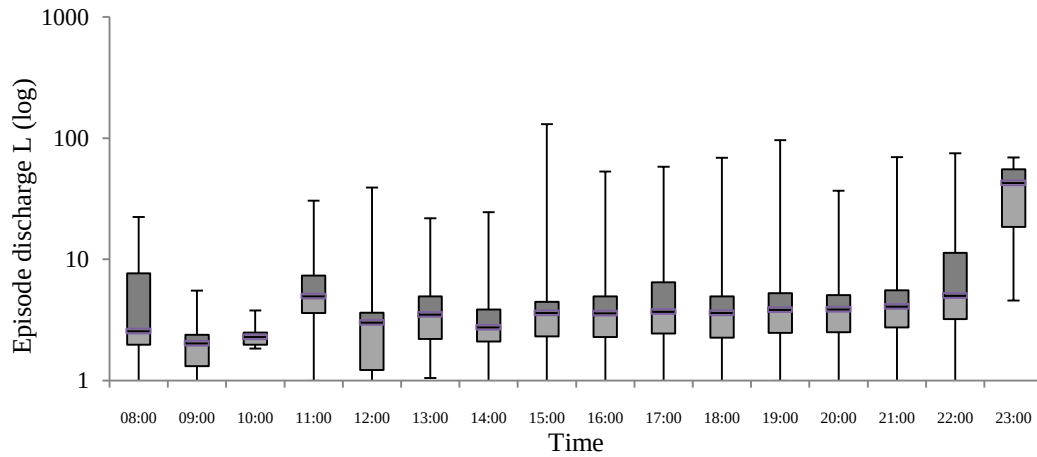


Figure 4-6 Hourly volume discharges over 14 day period – Episode discharge. Horizontal bar = median, Box = interquartile range, tails = range

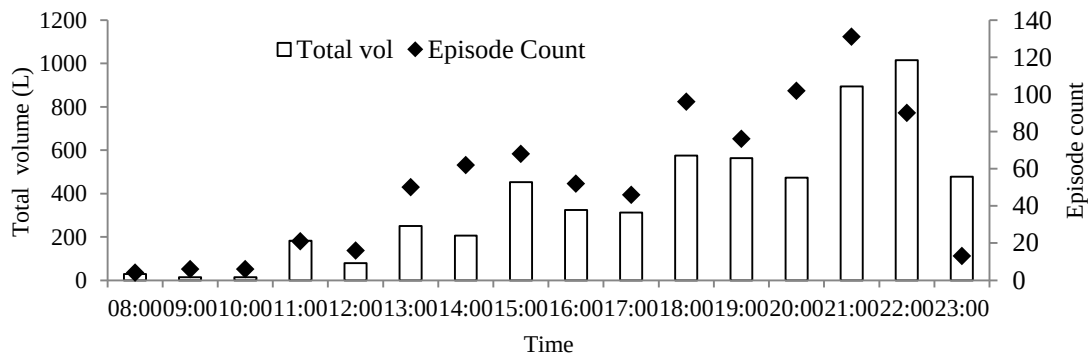


Figure 4-7 Hourly volume discharges over the 14 day trial – total volume discharged and event

4.3.2.1 Flow rate distribution

Further analysis of the data provides insights into the distribution of flow rates the separator will experience (Figure 4.8). Based on the truncated data set, the 90th percentile flow rate was 0.51 L/s which is 60% of the maximum flow included (0.84 L/s). Extending the upper flow limit to 1.5 L/s has no significant impact on the 90th percentile flow rate which becomes 0.52 L/s but this is then 36% of the maximum flow. The later analysis agrees with a previous study of 24 FSEs with a single 24 hour sampling campaign (Aziz et al., 2012). Further, the previous study found that 90-95% of flow events were below 0.63 L/s also consistent with findings here. The context of the

data is provided by comparison to the test standard BS EN1825 (2004) where the device is tested for a minimum of 4 volume exchanges at the maximum flow rate for which the device is expected to demonstrate a prescribed level of efficiency. Notably BS EN 1825 is premised on a preferred range of 2 to 25 L/s⁻¹. The maximum flow rate experienced in the 14 day period was 2.2 L/s compared to 2.83 L/s reported elsewhere (Aziz et al., 2012). Further high flow events, 1.45-2.2 L/s were observed to account for only 2 % of the time flow occurred (c22 seconds per day) and provided 6.9% of the total volume discharged. Consequently, the current test method does not appropriately mirror actual flow patterns in FSEs and is likely to provide limited insight into actual removal.

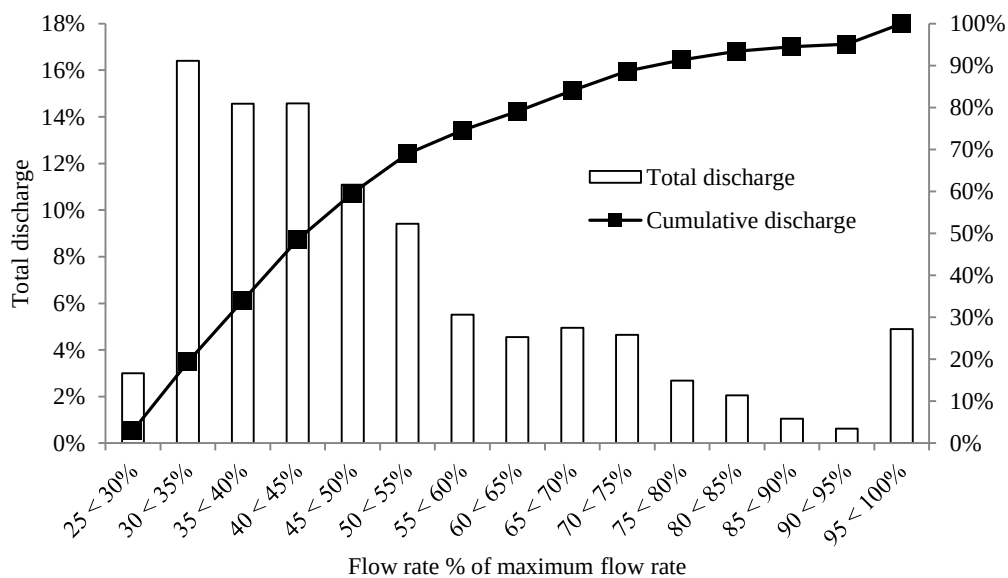


Figure 4-8 Total discharge vs flow rate. Flow rate interval expressed as a percentage of maximum episode flow rate (0.84 L/s⁻¹). The increase in total discharge in the 95 – 100% bin is a consequence of assigning a single maximum of 0.84 L/s⁻¹ to the time periods where flow exceeded the imposed limit

4.3.2.2 Sporadic flow analysis

Across the trial only 2 episodes occurred that combined relatively high rates and large total volumes with all other high rate discharges containing less the 60% of the

maximum volume of an individual discharge event. In fact the majority of events discharged volumes less than stored in the separator with no-flow periods in between discharge events. Consequently, it is posited that the separators may operate predominately as a batch devices with the majority of the removal occurring during combinations of low flow, low volume events and quiescent periods. Support is provided through previous studies measuring batch separation rates of FOG as a function of droplet size and density (Barton 2012). For instance, 80% removal of the total FOG was observed in 120 seconds for 66 μm droplets whereas 44 μm and 32 μm droplets were removed by 70 and 40 % within 600 seconds. Similarly, López-Vasquez & Fall (2004) showed that under quiescent conditions removal efficiencies of 80% were observed after 10 minutes and 85% after 20 minutes and then rising only 1.5% for each successive 10 minute step. Importantly significant removal can occur in relatively short quiescent periods.

No-flow events accounted for the vast majority of the day (23 hours, 42 minutes). Analysis of the no-flow periods reveals that 60 % of the no flow periods lasted less than 300 seconds with 80% occurring for less than 10 minutes (600 seconds) (Figure 4.9). However, the no-flow condition was triggered by the lower limit of the flow sensor, c 0.2 L/s, such that the condition reflects combinations of no flow and low flow. Whilst the majority of no flow events were short in duration, 20% of such events exceeded 600 seconds such that a significant period of operation occurs when effective separation can occur. Further, the analysis suggests that during operational hours consideration of these shorter periods of quiescence is also of importance for product design optimisation. However, the combination of the low flow and relatively low volume contributions mean that near quiescent condition are likely to prevail. The data presented suggests a useful guide is packages of 5 minutes of quiescent / low flow conditions punctuated by small packages of flow.

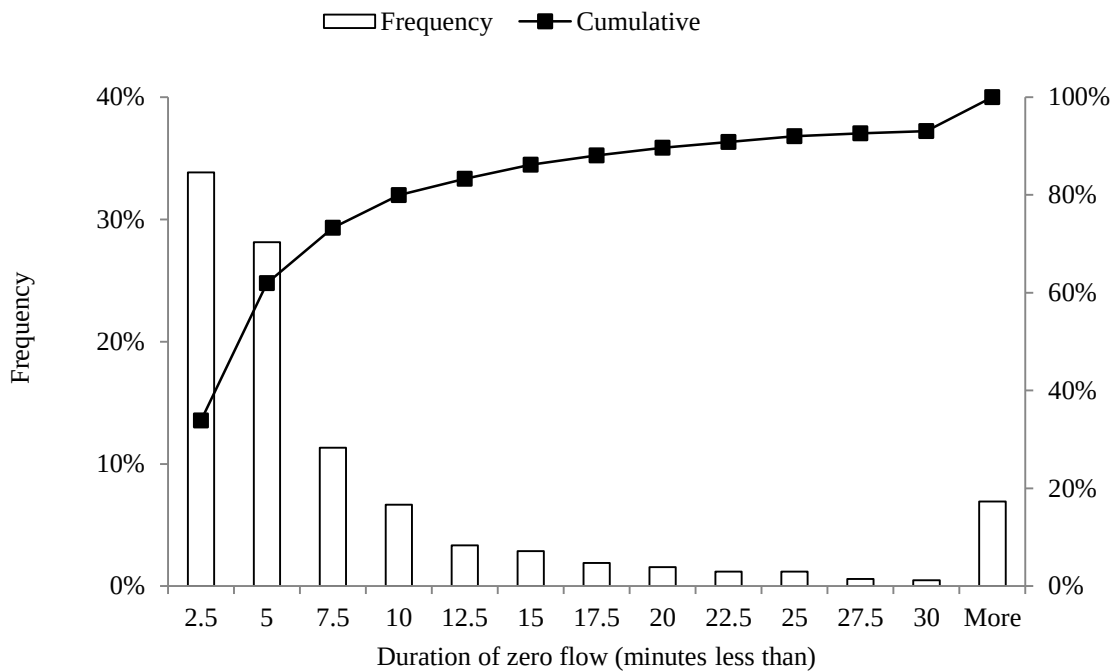


Figure 4-9 No flow frequency and duration

The impact of quiescent periods is related to the volume of discharge that occurs as a function of the volume of the separator. The data was analysed with respect to a 150 L separator and demonstrated that nearly half (49.4%) of the flow episodes contained less than 10% of the volume of the separator (Figure 4.10). Importantly, the majority of volume displaced from the separator is delivered in relatively small packets with 50% of the total discharge delivered in volume packages of less than 15.5 L. This may be accommodated in the size of the third chamber in a design such that the discharged volume will have resided in the separator for a prolonged period. Further, no event occurred that matched the volume of the separator such that complete displacement of the water volume never occurred. Overall the analysis supported the hypothesis towards visualisation of the system as a pseudo batch separator.

It is suggested that future design innovation and testing should focus on the intermittent nature of the flow events in FSEs to better reflect actual practice. To illustrate, a sub EN 1825-1 separator with a working volume of 150 L would provide an average effective

HRT of 45 minutes based on the majority of events containing less than 15.5L and an average 5 minute quiescent period between events. This exceeds the notional target of 30 minutes and enables occasional packages of 62 L to be discharged without significant negative impact. Such volumes cover 85% of the entire discharge to sewer with no event representing a complete volume exchange of the separator. The situation would be further improved if the FOG concentration of the different events were also known so that the system could be sized to ensure effective management of the key loads and not worry about high flow, low FOG events.

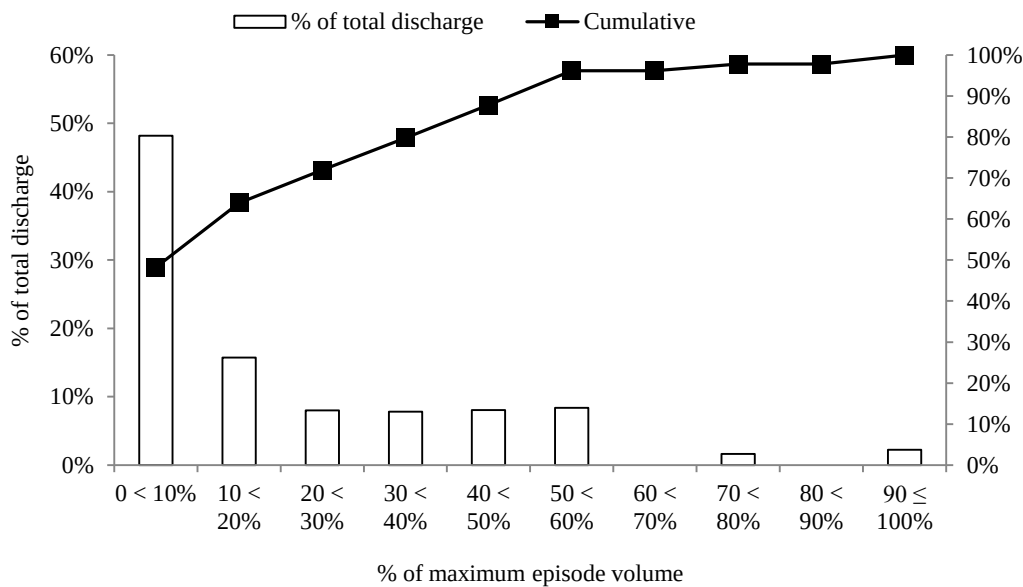


Figure 4-10 Total discharge per episode: volume interval expressed as a percentage of maximum episode volume (131 L)

4.4 Conclusions

Discharge flows in food service establishments are characterised by sporadic events containing relatively small packets of wastewater interspersed with periods of no flow. The majority of discharge events that occur will constitute less than 10% of the maximum flow discharged. Overall the findings suggest that future design and testing should consider the systems in terms of a pseudo batch basis rather than as a continuous

flow separator. Importantly, the work brings into question the appropriateness of the current standard testing procedure which operates only at the maximum design flowrate of the separator being tested.

4.5 Acknowledgements

The authors thank ACO Building Drainage for provision of the flow monitor, and their assistance in fabricating test equipment. We are especially grateful to Geof Elvyhart of Goodflo Ltd UK, who provided introduction to 3 prospective commercial FSE sites, and installed the required new plumbing system in order that the measurement could take place.

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Chapter 5. Understanding the impact of retained oil on the efficacy of FOG separation in a continuous flow passive gravity separator.

M. Fairley, R. Villa, B. Jefferson*

Cranfield University, Bedfordshire, MK43 0AL

Abstract

Performance assessment of the FOG separator and its sub types has no internationally accepted methodology. Arguably the most prevalent types of separator are smaller separators which are not acknowledged in current Euronorm standards. This study uses a recirculating system design and droplet image analysis to determine impact of flow rate and captured oil thickness on oil re-entrainment and assesses oil separation and capture using an influent comprised of a distribution of poly-disperse oil droplets consistent with the sizes observed in real FSEs. Oil re-entrainment was shown to onset rapidly for higher flow rates once a large level of static oil had been reached. Oil separation / droplet capture was shown to follow a second order kinetic analogue. The resulting straight line slope can be taken as removal efficiency and shows greater sensitivity to initial oil concentration than captured oil thickness level.

Keywords: FOG, capture, separator, re-entrainment, droplets, BS EN 1825,

5.1 Introduction

The removal of fats, oils and greases (FOGs) from commercial food service establishment (FSE) wastewater is a critical component in the effective management of sewer catchments as FOG has been implicated in at least 50% of all sewer blockages in the UK (Williams et al., 2012) and 60% in Hong Kong (Chan, 2010). Most of the FOG mitigation technologies available in the marketplace employ gravitational displacement of immiscible oils in the wastewater. The types of separator encompass devices where captured FOG remains in the unit, awaiting at some point, removal, by a variety of methods including automated non-intrusive processes, through to simple but ‘invasive’ removal. The latter appeals, not least, because of inherent simplicity and potentially low capital outlay. A further major category incorporates both passive and electro mechanically active devices: here the FOG is deposited in an external container

implying more immediate consideration of maintenance (if the necessary procedures are in place).

Separators range in volumetric size from small $\sim 50\text{L}$ through to thousands of litres. The European normal minimum size is 380L (Nominal size 'NS1' BS EN 1825 - 2004) which has a preferred flow rate range of NS2 to NS25 (where NS denotes test flow rate in L/s^{-1}). Currently there are no internationally accepted methods to quantify performance, and arguably the market dominating small separator sub-category eludes qualification completely. Where applied, performance measurement invariably consists of assessing removal efficiency over a specified time for a specific flow rate maximum with a new separator which importantly does not contain previously captured oil. However, removal efficiency will depend to a large extent on influent character with better removal expected for readily separable oil fractions compared to stabilised emulsions. As such, testing with readily separable oil fractions can lead to seemingly high efficiency benchmarks for example 98.4% for the Euronorm (Forty, 2004). Real world performance is likely to be far less, with influents comprising oils over a range of droplet sizes, their stability influenced by surfactant presence as well as variable, possibly turbulent flow conditions (see chapter 4). In addition, retained FOGs provide a potential re-entrainment route during periods of high flow. However, current testing procedures do not consider FOG droplet size or the potential for re-entrainment within their assessment.

In contrast, in the adjacent field of oil separation, consideration of emulsions is considered key to successful separator design, though it is noted that such studies are limited (Grimes, 2012). Effective separation requires the droplet to reach the continuous phase (Jaworski and Meng., 2009) leading to the significance of learning from Stokes' law that it is more difficult to remove smaller droplets (Jaworski and Dyakowski., 2005). Measurement or specification of performance in oil related devices typically entails specification of droplet 'cut size' for example the $150\mu\text{m}$ target of the API criteria (Chu, 2000), or assessment of hydraulic retention time which is often undertaken with some conservative chemical tracer (Crittenden et al., 2012). Emulsion evolution however is normally concerned with coalescence and measurement of continuous phase growth (Grimes et al., 2012) or droplet diameter variation over time

(Pierrard et al., 2007) but has also usefully being considered analogous to chemical kinetics (Qi et al., 2013) with respect to their study of flotation.

Overall it is posited that a more robust test of performance should challenge devices with droplet size distributions that might evade capture in less proficient designs or become re-entrained at some level of separator inundation with sediment and FOG. Accordingly, the current study aims to investigate the impact of retained oil layers and flow rate on re-entrainment and removal of emulsified oil. To achieve this a separator was employed within a closed recirculation loop that enabled study of the effect of oil level depth and flow rate on re-entrainment and oil capture performance as measured by the kinetics of oil droplet total volume whilst also measuring droplet size and volume.

5.2 Materials and Methods

The experiments were performed in a specifically developed test separator rig operated in recirculation mode and comprised of a separator, pump and flow measurement (Figures 5.1 and 5.2). A standard 3 compartment design was used comprising an inlet with a baffle plate that would act as a flow breaker and facilitate oil droplet breakup. The second compartment formed the oil separation zone and the final compartment was partitioned using a further baffle plate before feeding to a water oil reservoir required in order to maintain head and feed to the progressive cavity pump. The separator was fabricated in semi-transparent PVC to enable LED backlighting and easy measurement of retained free oil level.

Water was taken from a local supply and a single brand vegetable oil used in all cases. Oil was added either manually for re-entrainment experiments, or via a peristaltic pump for capture experiments. Oil and droplet PSD was quantified by use of the Flowcam digital imaging system (Chapter 2). Where intended, oil droplet formation was effected by turbulence and shear primarily in the water / oil reservoir, connected pipework and by impact with the inlet baffle. The Flowcam facilitated assessment of overall droplet volume and size distribution and it was found unnecessary to specify an alternate droplet creation method at the flow rate used (0.75 L/s^{-1}).

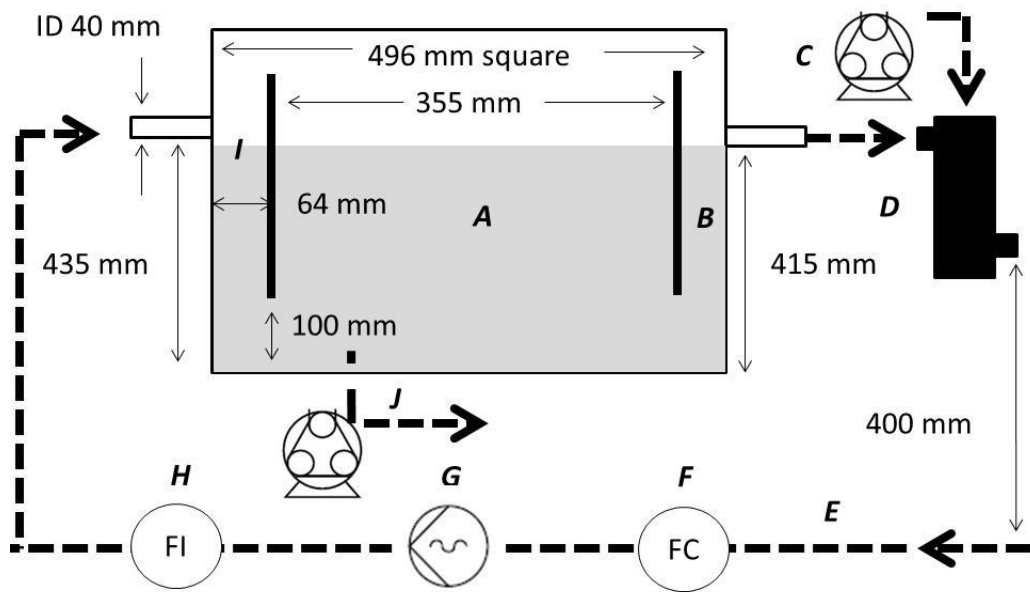


Figure 5-1 Schematic of the separator test rig. (A)Transparent oil separator capacity 98.4 L, **(B)** Sampling points 3 horizontal – 10cm apart, at 3 depths 10, 15 and 20cm below surface, after exit baffle plate, **(C)** Peristaltic pump for oil injection, **(D)** Oil / water reservoir, oil injection point, **(E)** Flexible connecting pipework, **(F)** Flow control system 0.2 – 0.8 L/s (ACO Industries k.s Příbyslav Czech Republic), **(G)** Progressive cavity pump type NEMO by NETZSCH Pumpen & Systeme GmbH, **(H)** Induction flow meter was a FLONET FN 20XX.1 by ELIS PLZEŇ a. s., **(I)** Baffle plate – incoming flow breaker. **(J)** Peristaltic pump for oil / water removal

The experiment was separated into two sections. In the first, *re-entrainment*, varying depths of oil (Table 5.1) were carefully placed into the oil separation zone without introducing any oil below the baffle plates. Following each addition, 3 flow rates were employed: ~0.25, 0.5, 0.75 L/s to establish the level of re-entrainment. In each case the flow was allowed a period of stabilisation then samples 3 samples were taken (approx. 6 mL) from the distributed sampling point. In the second set of experiments, *capture*, the feed water contained emulsified droplets of oil and the experiments repeated at the highest flow rate ~ 0.75 L/s. The design of this experiment generated increasing thicknesses of oil (Table 5-2) enabling its effect on *capture* to be evaluated.

Table 5-1 experimental oil layer thicknesses tested: *re-entrainment*

Oil layer thickness (mm)	140	198	252	310	340
Oil volume (L)	25	35	45	55	60

Table 5-2 experimental oil layer: *capture*

Centre zone oil thickness (mm)	127	152	175	203	220
Total (L)	25	30	34	39	41



Figure 5-2 Images of apparatus. Top left - apparatus showing separator, connecting pipework, pump, flow meter, and flow control. Top right – oil water reservoir / injection point. Bottom left - transparent separator illuminated by LED with oil layer in oil separation zone. Bottom right – sampling apparatus support and 3mm PE pipe (sampling position would be to the left of the baffle plate)

The droplets were formed by adding oil at a rate of 5 L/h with a peristaltic pump (Series 600, Watson Marlow, Falmouth UK) into the reservoir (C and D on Figure 5.1). The total water volume was kept constant by removing an equivalent volume from the base of the separator with another peristaltic pump (J on Figure 5.1). As it is expected that

removal of both water and oil takes place as a partial emulsion exists, the absolute oil volume was estimated after each trial by reference to the separated layer thickness in all compartments.

Following oil introduction, the oil supply was turned off and the separator was run at full flow for 5 minutes before sampling commenced. In both trials, sampling was undertaken from the 3rd compartment where 3 lengths of 3mm ID PE pipe were configured in a horizontally and vertically distributed arrangement. The sample could be withdrawn via a pipettor from a consistent sub-surface location avoiding contamination by any separated and floating oils. These were combined and this combined sample was analysed for oil droplet volume by the Flowcam set to capture high circle fit (CF) droplets (CF>0.9). The analysis was repeated 4 times for each combined sample. A period of quiescence of at least 30 minutes was allowed after the highest flow rate before additional oil was added and the process repeated. Typically 8 or more time sequential samples were taken in any period for a total of 5 analyses.

5.3 Results and Discussion

5.3.1 Re-entrainment

No re-entrainment was observed at any flow rate until an oil thickness of 140 mm was added. This equate to a height above the bottom of the baffle plate of ~ 165mm, 27% of the design storage capacity and represents a guide to the level of FOG that can be stored within a separator without any risk of re-entrainment. Below this level, insignificant counts could be detected with the total count across the first four oil depths equally 100 droplets. The level of re-entrainment increased with both oil depth and flow rate (Figure 5.3). To illustrate, at a flow rate of 0.75 l/s, the measured FOG volume fraction increased by almost two orders of magnitude from 8×10^{-7} mL/mL with an oil depth of 140 mm to 4.5×10^{-5} mL/mL with an oil depth of 340 mm. The latter represents the static oil layer being 6 mm from the bottom of the baffle. However, during flow the oil layer rises slightly so the effective oil layer distance to the bottom of the baffle was closer to ~ 175 mm. Greater re-entrainment was observed at higher flow rates as illustrated at the largest static oil depth of 340 mm where the FOG volume fraction was 1.3×10^{-5} , 1.5×10^{-5} and 4.5×10^{-5} mL/mL at flow rates of 0.25 L/s, 0.5 L/s and 0.75

L/s respectively. Overall statistical analysis of the data revealed the results to be significant with the exception of depths 2 and 4 with regard to difference between flow rate. The tests were based on a non-parametric Kruskal-Wallis test utilising a H distribution for the different oil levels and the Chi Squared distribution for the different flow rates.

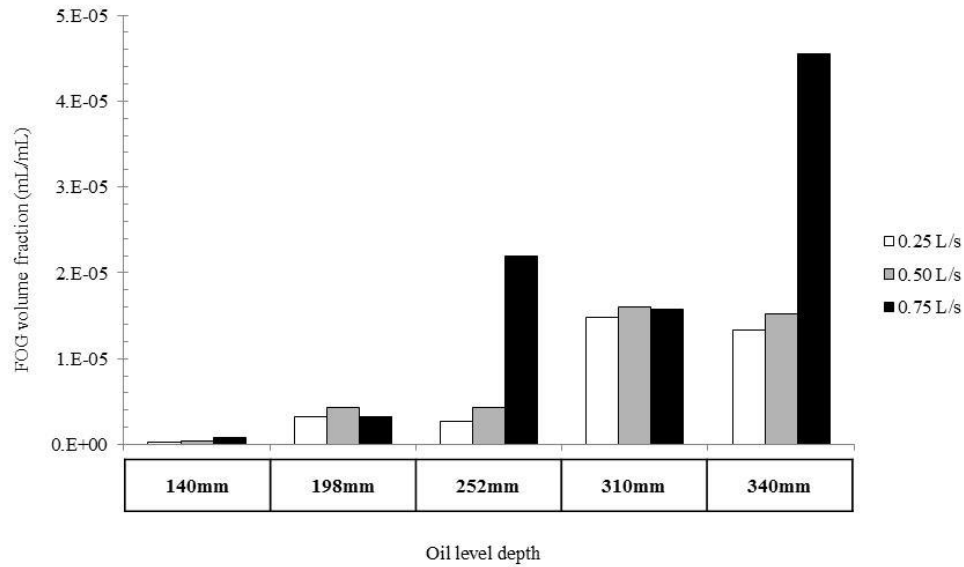


Figure 5-3 FOG volume fraction of re-entrained oil against static oil layer depth and flowrate (n=4)

Overall, the proximity of the O/W interface to flow turbulence affects the quantity of re-entrainment. In part, some of the re-entrained FOG at the lower flow rates may have been a consequence of previous re-entrainment generating the so called creaming layer; Jeelani et al., (2005) use this term with reference to droplet dispersion phase separation to distinguish between the densely packed zone where droplet proximity cause droplets to deform, and the zone where droplets are spaced further apart, with potentially greater susceptibility to re-entrainment. Previous studies have also shown the significance of the densely packed layer, also called the rag layer (Khatri et al., 2011), which can comprise mechanical barriers that inhibit separation (Dickinson et al., 1988). In the

present study what was likely to be a biofilm layer was present after a few days that had to be broken down (Figure 5.4). To test impact of creaming, post the 198 mm static oil layer tests, a quiescent period of 20 hours was employed before the next set. No significant difference was observed indicating that creaming was not likely to be influencing the results. Accordingly, the results indicate the importance of hydraulic drag on re-entrainment and the formation of droplets. Across all re-entrainment data, the median droplet sizes ranged between 19.89 and 34.96 μm . The droplet size increased at higher flow rates as demonstrated by median droplet sizes of 19.89, 19.9 and 24.79 μm for flow rates of 0.25, 0.5 and 0.75 L/s with a static oil layer of 340 mm. Previous work with CFD has demonstrated that the entering flow protrudes into the baffled area (Aziz et al., 2011) up into the separator volume thus provides a pathway for re-entrainment. For instance, simulations of a separator operating at a 20 minute hydraulic retention time revealed elevated local velocities half the maximum rate extended 50% up the baffle height.

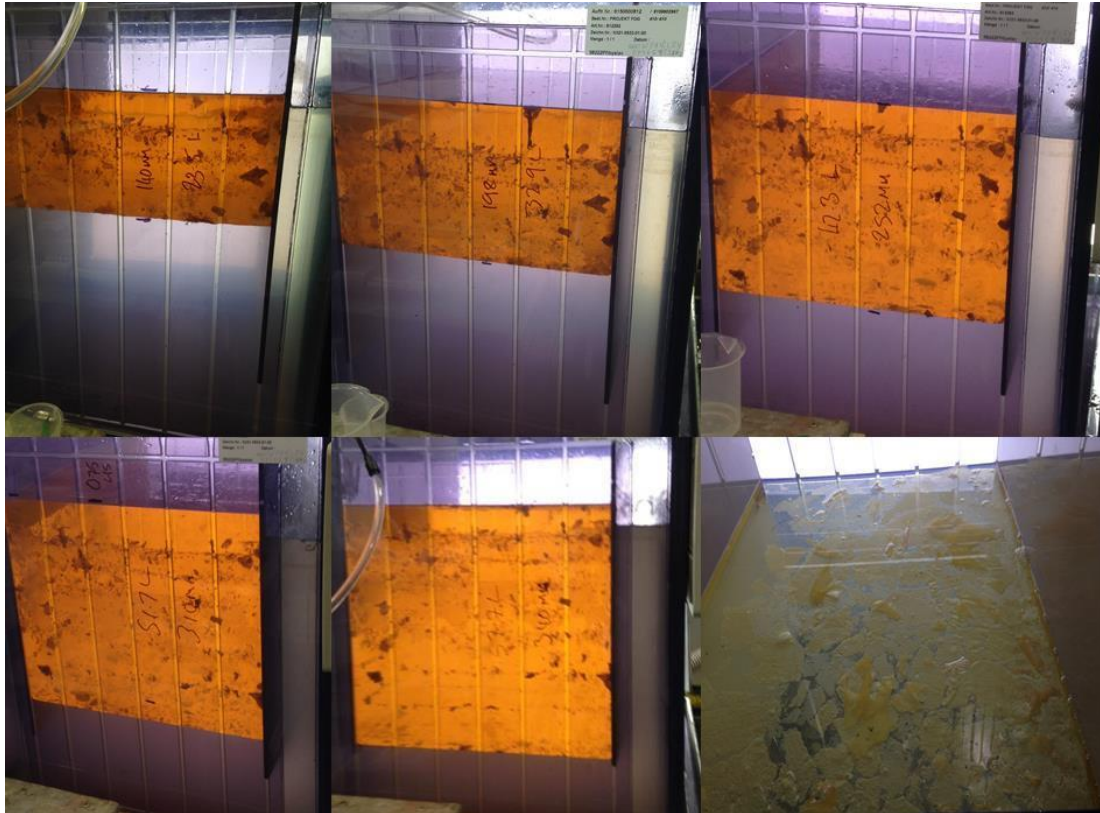


Figure 5-4 Retention experiment oil levels 1-5 corresponding to oil thicknesses left to right of 140, 198, 252, 310 and 340mm. Bottom right hand image illustrates biofilm build up at oil water interface.

5.3.2 Capture

As with the retention experiments, capture performance was evaluated under different oil loads, this time injected at the outlet recirculation point in order to cause droplet break up. The residual oil volume fraction was seen to decrease rapidly over the initial period and then remain stable (Figure 5.5). To illustrate, in the case of the experiment with a static oil layer of 84 mm and a flow rate of 0.75 L/s, the FOG volume fraction decreased from an initial concentration of 7.6×10^{-5} mL/mL to 4.27×10^{-5} mL/mL within 8 minutes before further reducing to 1.8×10^{-5} mL/mL for the remaining 4 hours and 40 minutes (Figure 5.5). This can be considered a steady state level from the given droplet size distribution which had a median size of 21.8 μm at the start and decreased to a median size of 20.96 μm once the stabilised level has been established. The effective removal can then be considered as either the initial drop from 7.63 to 4.27 mL/mL (45%) or the level once the system stabilises (~76%). Similar patterns have

been observed in other systems such as flotation with an inability to remove very small particles (Qi et al., 2013; Rajak et al., 2015) and oil separations (Kang et al., 2012).

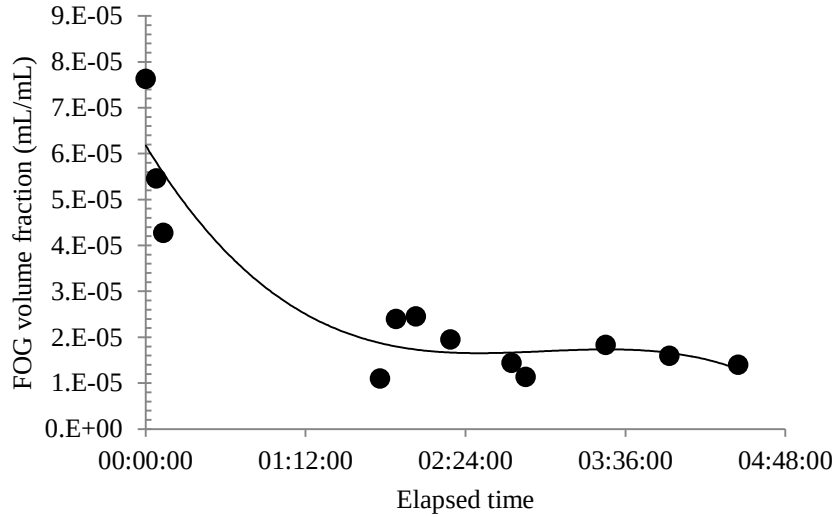


Figure 5-5 Total oil volume of droplets (15 – 105 μm) as a function of elapsed time with an initial oil volume fraction of 7.6×10^{-5} mL/mL, a static oil layer depth of 84 mm and a flow rate of 0.75 L/s.

In total five experimental periods were separated by at least a day but often considerably longer. The flow rate was 0.75 L/s and the static oil layer ranged between 127 mm and 220 mm (Table 5-2). Droplet size analysis revealed a maximum observed size of 105 μm although data beyond 55 μm was scarce and so excluded in subsequent analysis. Analysis utilising droplets sizes up to 55 μm effectively reflects measured droplet sizes in real FSEs (Chapter 3). To illustrate, median droplet sizes in commercial sinks were between 29 and 37 μm with a maximum recorded size of 98 μm . Furthermore the initial FOG volume fraction utilised here are also similar to those measured in real FSEs. For instance, in the case of a commercial sink the maximum FOG volume fraction measured was 1.15×10^{-4} mL/mL compared to 1.24×10^{-4} mL/mL at T0 in test A. Overall the full range of FOG volume fractions measured in the sink were measured at various points during the trials here indicating that the current tests will provide similar or more onerous levels of FOG to real examples.

Table 5-2 Capture test oil load volume and thickness, and PSD determined oil droplet volume 15 - 55µm. * 'm' in the rectilinear equation form $y = b+mx$

Test	A	B	C	D	E
Centre zone oil thickness (mm)	127	152	175	203	220
Total (L)	25	30	34	39	41
C_0 (mL _{oil} /mL _{water})	1.24×10^{-4}	3.58×10^{-4}	2.31×10^{-4}	3.5×10^{-4}	2.48×10^{-4}
Removal (%)	81	86.7	73.2	82.4	77.7
Median size (µm)	23.69	25.73	23.52	24.19	23.3
K (mL/mL/min)*	9.85^{-7}	2.63^{-6}	1.2^{-6}	2.31^{-6}	1.14^{-6}

The FOG volume fraction decreased in all experiments demonstrating droplet migration from the flow field to the central compartment (Figure 5.6). To illustrate, in the case of the smallest static oil layer, experiment A, the FOG volume fraction decreased from 12.4×10^{-5} to 2.4×10^{-5} mL/mL during the 140 minutes experiment, representing a removal efficiency of 81%. To compare, at the largest initial static oil layer of 220 mm, the FOG volume fraction decreased from 24.8×10^{-5} to 5.5×10^{-5} mL/mL, a removal efficiency of 77.7% indicating that the static oil layer has minimal impact on the removal efficiency. The residual median droplet size was 18, 16.6, 17.4, 16.4 and 16.37 µm for static oil layers of 127, 152, 175, 203 and 220 mm respectively. This confirms the grade efficiency cut of the separator with the residual oil constituting the smaller droplet sizes. For instance, in the case of experiment A, the ratio of small to larger droplets was 21% (15-20µm) to 6% (50-55µm) at the start of the experiments transforming to 35% to 3% respectively at the end (Figure 5.7). Importantly the data demonstrates effective removal across all droplet sizes measured during the test. To illustrate, removal levels of 61%, 71% and 76% were observed at sizes of >15-20 µm,

25-30 μm and 40-45 μm respectively demonstrating the grade efficiency of the separator.

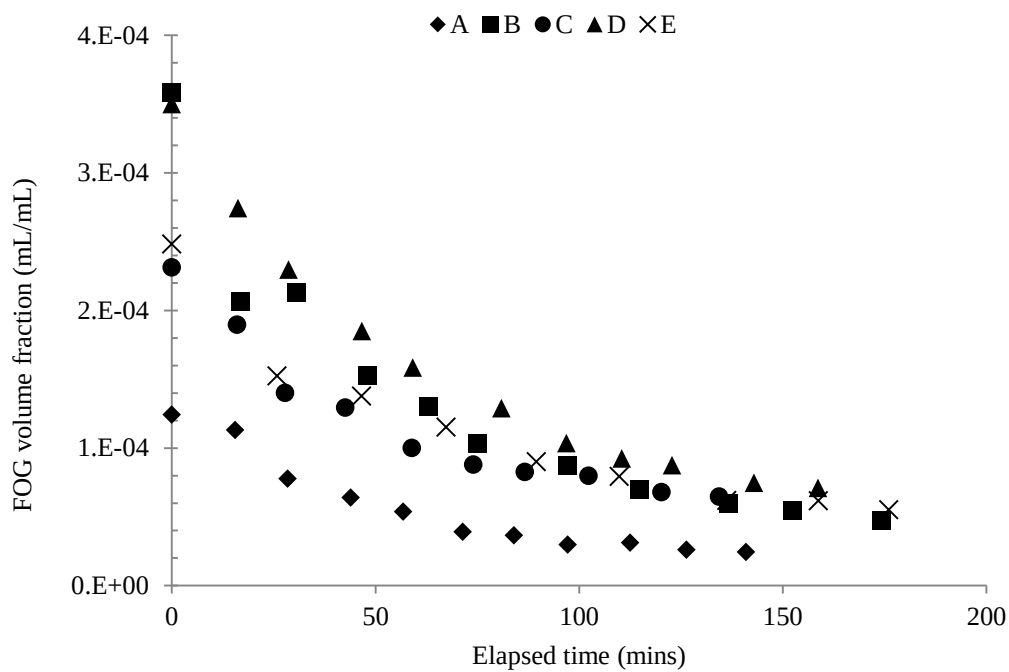


Figure 5-6 Total oil droplet volume change over time for 5 initial concentrations and oil layer thicknesses in central compartment

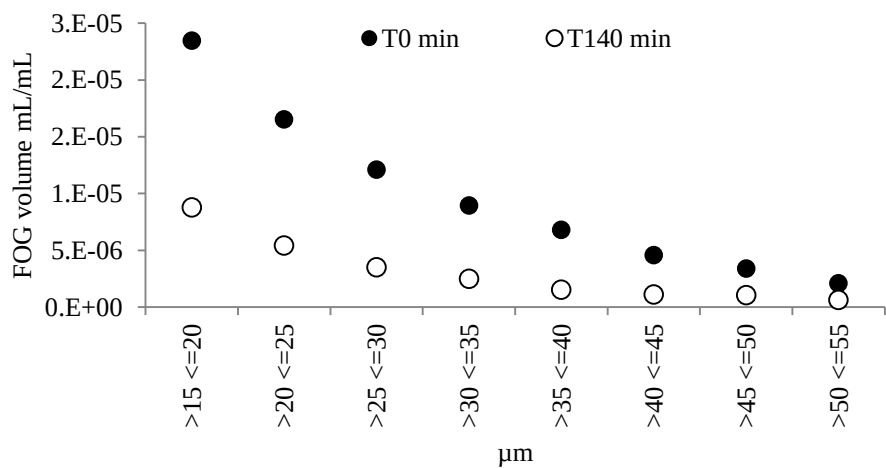


Figure 5-7 Total FOG volume change over time of test (140 minutes) for droplet size range 15-55 μm for test sequence A

The data was fit to a kinetic model and was best represented by a second order expression. Subsequent analysis of the kinetic constants revealed values of $9.85 \cdot 10^{-7}$; $2.63 \cdot 10^{-6}$; $1.2 \cdot 10^{-6}$; $2.31 \cdot 10^{-6}$; $1.14 \cdot 10^{-6}$ mL/mL/min for initial static oil layers of 127, 152, 175, 203 and 220 mm respectively (Table 5.3). Statistical analysis of the kinetic curves was undertaken to determine the equality of the regression coefficients in respect of both slope and elevation, a multiple sample analysis of covariance was undertaken (Zar 1999). The resulting F statistic is used to test the null hypothesis: $H_0: \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5$ with regard to slope and is employed in this case with β_1 and then β_1 and β_2 removed from the analysis sequentially.

The resulting statistics are reported in Table 5.4 and show that slopes c,d, and e cannot be treated as different, whereas slopes a and b are shown to be not equal to c,d and e. The corresponding elevation test informs that there are differences within the combinations analysed implying that initial concentration is a more influential factor than oil level – within the restricted range analysed at least.

Table 5-3 Covariance analysis for equality of slope and elevation. (DFp = pooled degrees of freedom. DFc = common degrees of freedom)

Test: slope	F α 0.05 (1) k	F α 0.05 (1) DFp	F stat	F crit	H ₀ :	H _A :
H ₀ : $\beta_1=\beta_2=\beta_3=\beta_4=\beta_5$	4	42	137.31	2.61	reject	accept
H ₀ : $\beta_2=\beta_3=\beta_4=\beta_5$	3	33	18.54	2.92	reject	accept
H ₀ : $\beta_3=\beta_4=\beta_5$	2	24	2.33	3.4	accept	
Test: elevation	F0.05 (1) k	F0.05 (1) DFc	F stat	F crit	H ₀ :	H _A :
H ₀ : $\beta_1=\beta_2=\beta_3=\beta_4=\beta_5$	4	46	42.51	2.58	reject	accept
H ₀ : $\beta_2=\beta_3=\beta_4=\beta_5$	3	36	22.26	2.87	reject	accept
H ₀ : $\beta_3=\beta_4=\beta_5$	2	26	84.46	3.37	reject	accept

5.4 Conclusion

The set of experiments undertaken can be considered as preliminary evidence of the potential to use such a recirculating test rig to determine separator performance. Retention of captured oil was shown to be influenced by oil level thickness and flow rate, and should be considered as part of an overall test specification. In terms of oil droplet removal the systems fits well to a second order kinetic analogue, and is related to initial concentration more so than oil thickness. As such the experiment appears to offer a robust method to establish removal efficiency of an influent whose characteristic makeup reflects the challenges that separators face with regard to the partial emulsion load in real applications.

5.5 Acknowledgements

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Chapter 6. Overall discussion

6.1 Overview

The challenge that FOG presents is a global phenomenon – a consequence of increasing population, urbanisation, economic growth and climate change. Aged sewer infrastructure capacity is reduced by FOG discharged from daily cooking activities with numerous food service establishments typically concentrating in and around areas of high population and economic activity. The food service industry consists of a range of facility sizes, some very large serving thousands of meals daily, but it also has numerous small to medium sized outlets often with consequent spatial challenges in the hub of the operation – the kitchen and its associated service areas. Accordingly, FOG mitigation devices must physically fit into spaces available, be accessible for hygienic maintenance but still provide measurable removal efficiency. The UK industry response to these market needs has promoted evolution of the simplistic gravity separator into 3 major sub-types. However, only one of these sub-types is designed and tested to a recognised Standard: the incumbent Euronorm – EN 1825. This Standard has a minimum preferred size, related to its flow capacity, of 2 L/s, with a corresponding working volume of $\sim 0.75\text{m}^3$. Other sub-types serve lower flow rates and are typically much smaller, overcoming a key hurdle in adoption, but have no agreed test method in the UK.

The EN 1825 Euronorm is also contentious due to its use of a 0.85 g/cm^3 light fuel oil test media – marine diesel – introduced at a rate of 5 mL / L. The diesel test media is trickled into the influent feed system in such a way that the extent of its mixing with water, in that the oil becomes a dispersed phase consisting of varied droplet sizes, is negligible. This is further evidenced by the 98.4% removal target, again suggesting that small droplet formation is insignificant – the oil quantity readily separates out - even under full flow conditions with a product that passes the test. Performance is evaluated over a 5 minute period of a products intended maximum design flow. This follows a 15 minute (or 4 x volume exchange) running in period at full flow with test media which will deposit 15 of 15.2 L of diesel in the separation compartment of its 760L overall volume if target efficiency is met (assuming 2 L/s test flow). The resident oil load at

start of the test proper is therefore 2%, No account is made of the effect of sediment build up in the test.

The product size selection processes assumes continuous flow of kitchen wastewater albeit at fractions of a flow source actual flow rate. Temperature, oil density and emulsion extent effects are incorporated by additional product size multipliers in that the nominal or test flow rate is multiplied by specified coefficients to arrive at a larger nominal size.

Extending the application and adoption of FOG mitigation devices requires that an appropriate test regime is designed; one that is representative of the loads experienced during operation. The absence of such guidance serves as a barrier, limiting take-up in the food service industry. This leads to the key question of removal of what? What are the relevant characteristics of the wastewater and under what conditions must removal take place?

This thesis posits that product design, testing and application should be informed by waste water characterisation and flow dynamics, whilst performance evaluation should further accommodate separator status – a defined level of fill of both FOG and sediment.

6.2 Wastewater character

Kitchen wastewater is subject to a variety of influences that affect FOG droplet distribution formation. Chief among these are factors common to washing processes and include the use of detergents, mechanical agitation and high water temperatures. Such factors are applicable in two common FOG sources – the wash or rinse sink and the dishwasher. Fundamental to FOG separation is the notion of droplet size: large droplets separate to a form or join a continuous oil phase faster than smaller droplets. As droplet size decreases physical separation takes longer until eventually a size is reached that provides a relatively stable emulsion. Determining the size range of FOG droplets in wastewater has received little attention. Furthermore no attempts have been made to quantify FOG state at point of discharge with respect to the wastewaters free oil (continuous phase) content and the quantity of dispersed phase droplets. The character of separating droplets is complicated in real wastewaters by the presence of food

particles that also reside on items to be washed. Prior efforts to determine wastewater particle size distributions have used methods that cannot discriminate between food particles that may sink and FOG droplets that float. The FOG removal efficiency of a product will be directly related to the extent of the dispersed FOG phase and droplet sizes therein. The remaining food debris particles then pose the issue of sediment build up in the separating device.

This study differentiated between food particles and FOG droplets by use of high speed digital imaging and processing. The overall wastewater character was further discerned by evaluating free oil on the surface and sub-surface oil in droplet form that may still separate. Comparisons were made of two key sources – a sink and a dishwasher, and also between cuisine types with regard to droplet size distribution. Samples exhibited far greater particulate or food debris loads compared to oil or FOG droplet loads. As such any sinking debris consumes working volume of the separator and its effects should be accommodated in any performance test evaluation. The study revealed no discernible differences in the FOG droplet size distributions created by different cuisines. However the impact of key FOG sources in the kitchen was readily apparent. The sink wash facility was shown to contain effluent with a majority proportion (65%) of free oil or already separated FOG. This compared to a 7% free oil component in the dishwasher wastewater. This was most likely a consequence of the pre-rinse operation which is common in commercial kitchens. Though the sink waste water is subject to some disturbance when draining, it is likely that the free oil remains readily separable, making control at, or near source a key tactic in FOG mitigation strategy.

The sink and dishwasher contained nearly the same quantities of FOG in the more challenging sub-surface FOG load in its dispersed state. However, the particle size distribution of each was shown to be different with the sink droplet FOG load more amenable to separation than that exhibited in dishwasher waste water with a corresponding rise rate some 2.25 x faster at the median volume particle size. Importantly, knowledge of the size distributions presents an opportunity to challenge separator testing with an appropriate influent FOG state – an appropriately challenging test might use a droplet distribution centred on the sink median size of $27\pm 5\mu\text{m}$.

FOG droplet separation probability is further affected by wastewater flow: separators are dynamic systems in that they receive and discharge wastewater of varying quantities and at varying rates. As such, any removal efficiency is a product of droplet size and their associated rise time, as well as flow rate and volume discharged per drainage event. It follows that removal performance at maximum flow rate will be lower than removal at a smaller flow or period of quiescence. It is therefore imperative to understand the flow dynamics experienced in typical applications.

6.3 Flow dynamics

FOG can only separate if it has sufficient rise time to reach the continuous phase or area of the separator where it is un-interrupted in its passage by convective or turbulent flow forces. The best case is a period of long quiescence; shorter periods may also be useful. Then lower flow rates will be more advantageous than higher rates – the dominant flow rate is clearly of interest. Of significant importance is the notion of discharge volume; if the discharge volume is less than the separator working volume, then a *pseudo batch separation* mode ensues where the separation efficiency is more akin to a physically larger product with greater hydraulic retention time operated in continuous flow mode.

Study of the dynamic flow profile from a small FSE operating in the eat-in, fast food environment revealed that overall flow is sporadic and dominated by relatively low flow events that discharge manageable packets of wastewater to the receiving sewer system (less than the likely working volume of a separator). Over the 14 days measurement period a separator would be exposed to an average operating period of 18 minutes per day in this facility. The corresponding periods of quiescence are regularly punctuated but are considered to allow for on average 5 minutes of low disturbance separation, although separation will be more efficient in the 20% of events that lasted in excess of 10 minutes.

Flow rate maxima are relatively rare. Of the 838 flow events, the 90th % event resulted in a rate of 0.5 L/s, or 60% of the maximum rate experienced of 0.84 L/s, far below the minimum suggested test flow in EN 1825. A flow rate of half of the maximum flow explains 62% of the discharge volume to the sewer. The significance of sub maximum flows suggests that the maximum rate test approach of the Euronorm Standard coupled

with the far higher absolute flow rates might be considered overly conservative in considering flows from these ubiquitous smaller establishments.

These results suggest that appropriate tests might comprise of flow rates that are representative of the actual profiles experienced in practice and that FOG removal performance be evaluated against a range of flow rates weighted according to their probability of occurrence. FOG removal efficiency – per flow rate is then arrived at as a summation of the individual test results. In such a case the lower flow rates would figure predominantly in the test regime, and it would be expected that FOG removal performance can be shown to be higher at a lower flow rate than at any maximum flow rate. Maximum and near maximum design flow rates must still be tested at least to prove that no detrimental re-entrainment occurs at these higher flow rates. Knowledge of performance at different flow rates and at maximum will inform product choices where some notion exists of the likely wastewater flow regime. The flow regime will be a consequence of kitchen operation practices which may possibly be varied to reduce peak loads.

Furthermore in the case measured here, approximately 50% of the total discharge to sewer is in volume packets of less than 15.5 L. The nett effect is that the separator experiences longer hydraulic retention times than is the case under a continuous flow regime. Accordingly greater separation of more challenging droplet sizes might be expected under such conditions which are best thought of as *pseudo batch operation*.

Overall designing a separator to operate in pseudo batch mode and testing with a range of flow rates from a fraction of, up to maximum should lead to validation of smaller separators whose dimensions are more appropriate to the smaller FSE.

6.4 FOG capture, re-entrainment and performance evaluation.

Testing removal efficiency through EN 1825 is a costly process: for a small 2 L / s design (760 L working volume) the test process would require over 3.6m³ of test influent that has to be treated further before drainage as it contains diesel fuel. More importantly, any product innovation process may require multiple tests of a unit being developed to evaluate performance. The test itself is a pass /fail test with a corresponding pass level rather than a method of evaluating incremental improvement.

The test infrastructure including the infrared spectroscopic or gas chromatographic measurement methods are also likely to be a barrier for many companies who might wish to develop separators and improve designs.

This study used a simple recirculating plant to study the effects of flow rate, oil concentration and central compartment oil thickness on oil re-entrainment and oil capture. As such, the total water used approximated to just over separator volume ~ 100 L. Multiple experiments did not necessitate drainage at any point in the experimental programme. The study further incorporated analysis of oil volumes by use of the high speed imaging system. In this case, the task of quantifying oil droplet distributions and overall volume was considerably easier due to the lack of food debris – in essence the system comprised water and a vegetable oil distributed into droplets via shear processes in the recirculation system.

Re-entrainment was found to be a function of captured oil thickness and flow rate. Re-entrainment occurred at a thickness of 140mm which equated to ~25% of the working volume – far in excess of the 2% volume introduced during the EN 1825 running in period. In practice, the FOG level will be a function of maintenance and may well exceed the anticipated level. At the point of fill demonstrated in these experiments, the separator becomes a FOG source rather than a mitigation device. The results indicate that high flow rates in particular initiate re-entrainment events. Even though the majority of flow rates in practice were found to be around 50% of maximum, maximum and more frequent near-maximum rates do occur and may serve to re-entrain if duration exceeds working volume. As such, fully qualifying the effects of re-entrainment will provide evidence to further enforce sufficient maintenance intervals to remove collected FOGs. Notably, sediment deposition is also likely to affect re-entrainment dynamics but was not tested here.

Capture performance was qualified by study of the total oil volume per water volume and its associated droplet distribution in a sample at sequential times over a period of operation of the recirculating separator. The study was complicated by the variance of both influent oil concentration and central compartment captured oil thickness at the same time, however clear indicators of removal efficiency were illustrated.

Analysis of droplets can be confined to a range of sizes that were representative of droplet distribution sizes in real wastewater – in this case a range over 15 -55 μm was studied. Representative influent concentrations were also replicable during the experiment period. Importantly, particle counts per bin size of the distribution examined ensured statistical validity levels can be ascribed. Time sequential samples invariably revealed lower overall quantities of oil and further illustrated the preferential separation of larger droplets over smaller droplets. Capture effects were determined at 15 minute intervals – it is thought this time might be further shortened. The resultant removal or capture curve can be represented as a 2nd order kinetic analogue by the simple process of taking the reciprocal on the measured concentration. The five experiments provided very strong data fits to the linear regression line and the rectilinear equation format $y = m + bx$ is provided through conventional spreadsheet analysis tools. Here m can be taken as the initial concentration, x as time, and b as the removal constant. The removal constant for a given concentration then serves as an expression of separator efficiency. A product designer might choose to modify a separator design and can easily quantify the outcome using such a system: a steeper regression line indicates improved capture performance; a shallower line indicates less oil is being captured; more of the droplets are bypassing any internal baffles or other arrangement.

Although further work is required to explore the system in respect of differing oil concentrations, captured oil load, sediment load, flow rate and time increments necessary to form a justified picture of removal efficiency it is possible to provide a benchmark example by testing a current EN 1825 (or other test standardised product) separator. Importantly, the test is wholly based around droplet size distributions that were thought to be too small for a separator to remove, yet are now known to be relevant. Accordingly, such a test is likely to provide information on a separator's performance when challenged by an influent with characteristics similar to real wastewaters.

6.5 Implications

The main experimental work in this project has quantified and further characterised the nature of real kitchen wastewater with respect to easily separable and more challenging,

partly emulsified FOG components. It has illustrated the importance of food debris, and has distinguished between these wastewater components using a novel application of high speed digital imaging. Understanding the droplet size distributions of oils in wastewater provides a benchmark on which to test separator performance. Quantifying the fractions already separated and still separating highlights the impact of targeted source control – an ideal mitigation device should service wash and rinse sinks.

Separation efficiency is a function of flow rate and volume, and is related further to the internal fill levels of the separator. In practice, smaller than *working volume* discharge events dominate in the market relevant FSEs studied. Ultimately this provides for more efficient separation and in itself may help inform kitchen operational procedures. Performance in the field will depend on dominant flow rates, and it has been shown that the half maximum flow rate describes over 60% of the total discharge volume. Consequently, declaring separator performance against a range of flow rates provides a more insightful picture and should allow some fine tuning of choice if for example it is likely that continuous flow at high rates are dominant.

A simple recirculating separator rig enabled assessment of performance with oil volumes and distribution sizes enumerated by high speed imaging. Oil re-entrainment from the captured compartment was found to onset rapidly once a critical fill level was reached and indicates the importance of FOG and possibly sediment removal – otherwise a separator may become a FOG source. FOG capture was evaluated by quantifying the volumes of FOG droplets present over a period of operation with time sequential sampling. The droplet sizes studied were typical of FOG found in real wastewaters. The resulting linear regression slope can be taken as a FOG removal constant and may provide a readily accessible way to quantify performance during product development. As a test per-se it can be readily quantified by assessing the performance of a current Standard meeting system. Such a test would evaluate separator performance over a range of flow rates utilizing an influent with challenging but relevant characteristics.

FOG is already problematic in many areas globally. Mitigating its affect requires a more thorough understanding of the nature of the problem in order to define appropriate test procedures for products and guide their application.

Chapter 7. Conclusions and Future Work

7.1 Conclusions

The overall findings of this research confirm the hypothesis that the current testing procedure for passive gravity separators does not appropriately reflect the characteristics of FOG in FSEs and the removal mechanisms that operate. The specific conclusions in relation to the original objectives that lead to this overall conclusion are:

7.1.1 Objective 1: To develop a method for selectively sizing FOG droplets in FSE wastewater (Chapter 2, Paper 1).

- Selective sizing of FOG droplets in FSE wastewater is possible through the use of optical microscopy coupled to image processing.
- The particle system is dominated by non-FOG debris such that non-discriminating sizing techniques will only determine the size of the combined systems which will be biased towards the larger non-FOG debris.
- The proposed technique is capable of determination three fractions: separating FOG, non-FOG debris and combined components. Through further processing the sizing approach can be used to estimate total sub-surface FOG load in the sample.

7.1.2 Objective 2: To determine the size of FOG droplets and other debris in FSE wastewater from different source types (Chapter 3, Paper 2).

- The size of FOG droplets in FSE is dependent on the source of the wastewater with representative median droplet sizes between 18 ± 1 and 27 ± 5 μm
- The higher level of agitation, temperature and surfactant addition in dishwashers or combination ovens with cleaning facilities leads to smaller droplets being formed. The median size was 18 ± 1 μm with a maximum size of 67 μm . Whereas

the sink generate droplets with a median size of $27 \pm 5 \mu\text{m}$ and a maximum size of $98 \mu\text{m}$

- The non-FOG debris was substantially larger with median particle sizes of $86 \pm 30 \mu\text{m}$ for the dishwasher and $93 \pm 37 \mu\text{m}$. The maximum size of the FOG droplet in each case equated to between 40-49% of the total particle volume.
- There was no statistically significant differences in FOG PSD and volume between 4 cuisine types prepared in a domestic environment

7.1.3 Objective 3: To determine the dynamics of flow in FSEs to establish a basis for understanding the impact of temporal variance in flow rate and volume discharged (Chapter 4, Paper 3)

- Discharge flow patterns in the FSE studied were sporadic and characterised by small batch volumes interspersed with periods of no flow.
- The majority of discharge events that occurred constituted less than 10% of the volume of a 155 L separator
- Flow rate maximums are rare; the 90th percentile rate $\sim 0.5 \text{ L/s}^{-1}$ was 60% of the truncated maximum. Flow rates higher than the truncated cut-off point of 0.84 L/s^{-1} accounted for just $\sim 7\%$ of the volume discharged to sewer
- Overall the separator is better visualised as a *pseudo batch separator* rather than a continuous flow separator

7.1.4 Objective 4: To understand the impact of oil layer thickness on the potential for re-entrainment of previously captured FOG and the capture of new droplets.

- Retaining FOG within the separator generates a potential re-entrainment pathway when the FOG layer is only 33% down the height of the baffle plate
- Retaining FOG layers within separators was not observed to influence capture of new droplets.
- Effective removal of droplets is observed across all droplet sizes studied (15-105 μm) with removal rate increasing as droplet size increases.

- The combination of microscopy and image processing when used for water and oil droplet only evaluation, such as in product development or testing, the droplet size distribution and volumetric information can be used to determine removal efficiency

7.2 Summary

Consideration of the above conclusions confirms that current testing approaches will not adequately reflect the critical characteristics and removal mechanisms by which passive gravity separators work. A more appropriate basis for testing needs to include:

- (1) A defined specific droplet size distribution and specific gravity. Evidence from the current study suggests that needs to be across the 10 to 100 μm range with median sizes in the 20-40 μm range (Figure 6.1)
- (2) The use of an oil with a specific gravity between 0.9-0.94 is required. Specifically, the use of diesel oil specific gravity 0.85 (BS EN 1825 2004) is a poor surrogate and the selected oil needs to be effectively dispersed into droplets to avoid free oil which will be too easily removed.
- (3) The separator test should occur through a series of flow events based on the percentage volume of the separator. Weightings should be applied to the aggregated results in accordance with the probability of those flow rates occurring.
- (4) The separator should be preloaded with a defined level of oil to reflect the captured layer.
- (5) Small droplet removal can be practically assessed by the recirculation method in order to establish a grade efficacy of the unit with respect to the flow rate examined
- (6) Performance should be based on the removal of droplets across the whole size range and converted into a final concentration.

Revisiting Figure 1.4, the batch separation effect is highlighted by new droplets d_4 and d_5 . Droplet d_4 , is smaller than d_3 and cannot successfully be captured under maximum

convective flow. However, when operating as a batch separator (which is the majority of the time), such a droplet might successfully migrate to the separation zone. Its inclusion in the test regime is then important as this smaller droplet will be more influenced by turbulent conditions in the separation zone leading to re-entrainment. Droplet d_5 represents the smallest droplet and evades removal under quiescent conditions.

It is proposed that the test influent media has a median PSD value that represents d_4 , and in the case of a minimum baffle height of 100mm, droplets $\sim 27\mu\text{m}$ as identified as the median sink size in this study, will be challenged to migrate successfully. Measurement of escaped oil is then the sum of the volumes of d_2 through d_5 .

As separators are shown to operate under pseudo batch conditions, an approximation of this effect is gained by considering removal performance at flow rates lower than the designed maximum flow rate. The probability weighted and aggregate outcome then provide a realistic determination of performance.

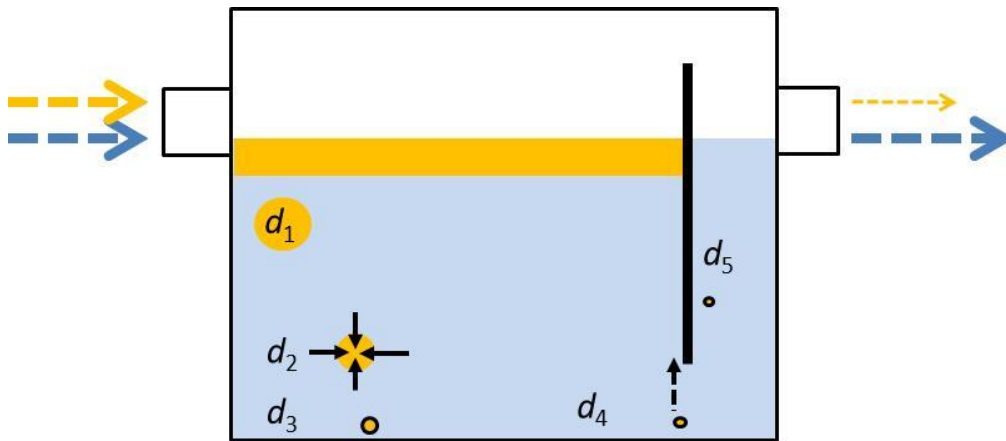


Figure 7-1 simple separator based on Figure 1.4 with droplets d_4 and d_5

7.3 Future work.

- (1) The current study was restricted 2 principal FOG sources in the kitchen. Other pertinent point sources include:

- combination ovens – which may include automated cleaning features
 - extraction filter cleaning,
 - Bulk equipment cleaning (bratt pans, tilting kettles)
 - Such equipment is likely to generate volumetrically diverse amounts of FOG, and as with the sink and dishwasher, the resulting PSD's will affect ultimate treatability.
- (2) The study indicates the comparative rarity of large FOG droplets. Larger droplets will of course exist in real wastewaters and even individual droplet volumes can encompass the volumes of an entire smaller PSD. Automated imaging systems such as the Flowcam might be used in 'on-line' mode where samples are extracted from a flowing network in real time providing opportunity to quantify the PSD of more separable FOG as it is presented to a mitigation device.
- (3) Surfactants, detergents and high temperatures are part of the tools used to clean kitchen wares. Future work should consider their effects on captured FOG re-entrainment and new droplet capture.
- (4) Further work is required to establish the consistency of the recirculating separator methodology as a testing method in its own right. Efforts to shorten the quantification period and establish alternate methods to the Flowcam system used may make the methodology more accessible to those developing separator products.
- (5) Whilst the study concludes that oil layers thickness has little effect on capture, sediment level was not assessed and is likely to be the dominating load in a separator. Sediment loading effect on capture and re entrainment is needed to develop a robust test methodology.

Appendices

Appendix 1 Flowcam overview

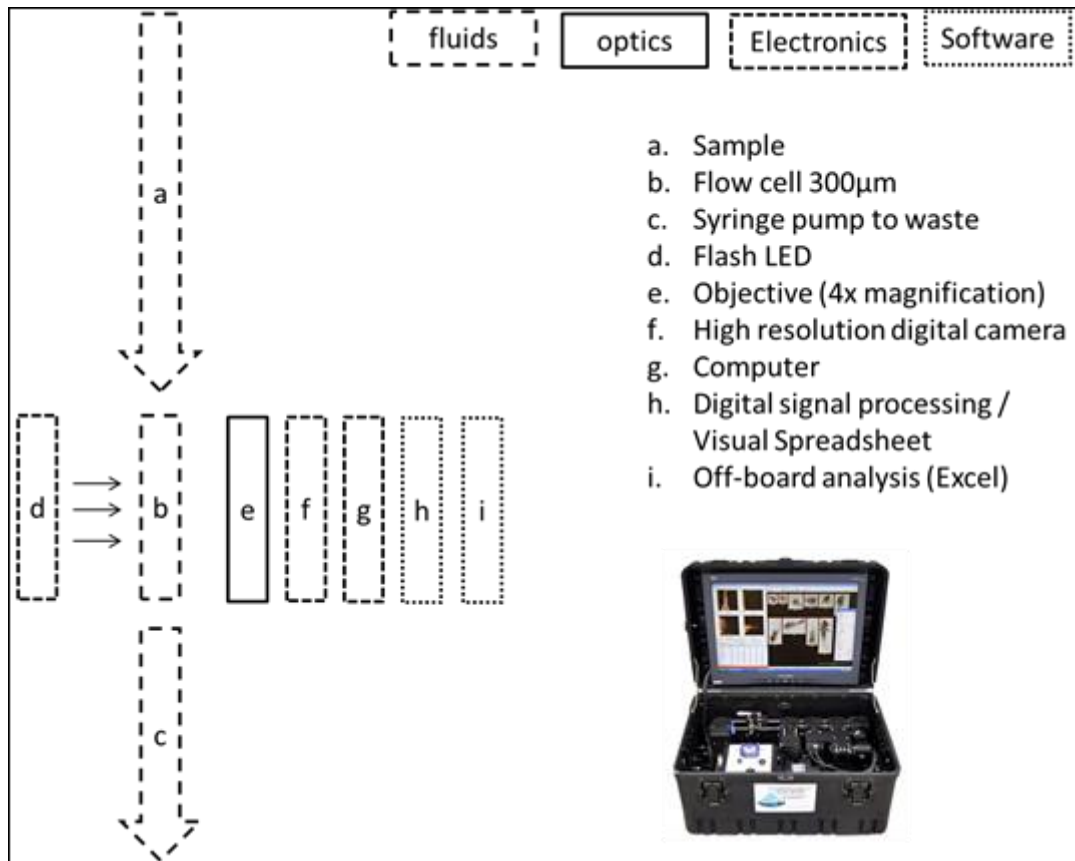


Figure A1 1 Flowcam portable imaging system type - Flowcam VSI – Portable, with external syringe pump (Meritics, Dunstable,UK).

Appendix 2. Flowcam parameter set up

Threshold adjustment.

Threshold values determine at what intensity a particle boundary is defined. In complex wastewater examples of FOG and food debris candidate FOG particles are taken to be highly circular and when in focus will exhibit a dark external annulus with a much brighter centre. In the case of FOG identification, threshold values higher than 24 will maintain FOG identification but at the expense of particles that are lighter. Figure A2-1 below illustrates a candidate FOG globule near centre surrounded by much lighter – sometimes near transparent food debris.



Figure A2-1 Candidate FOG droplet near centre and lighter near transparent food debris.

Too low a threshold value will obscure target size identification by defining the particle boundary to a wider area as in Figure A2-2 below.

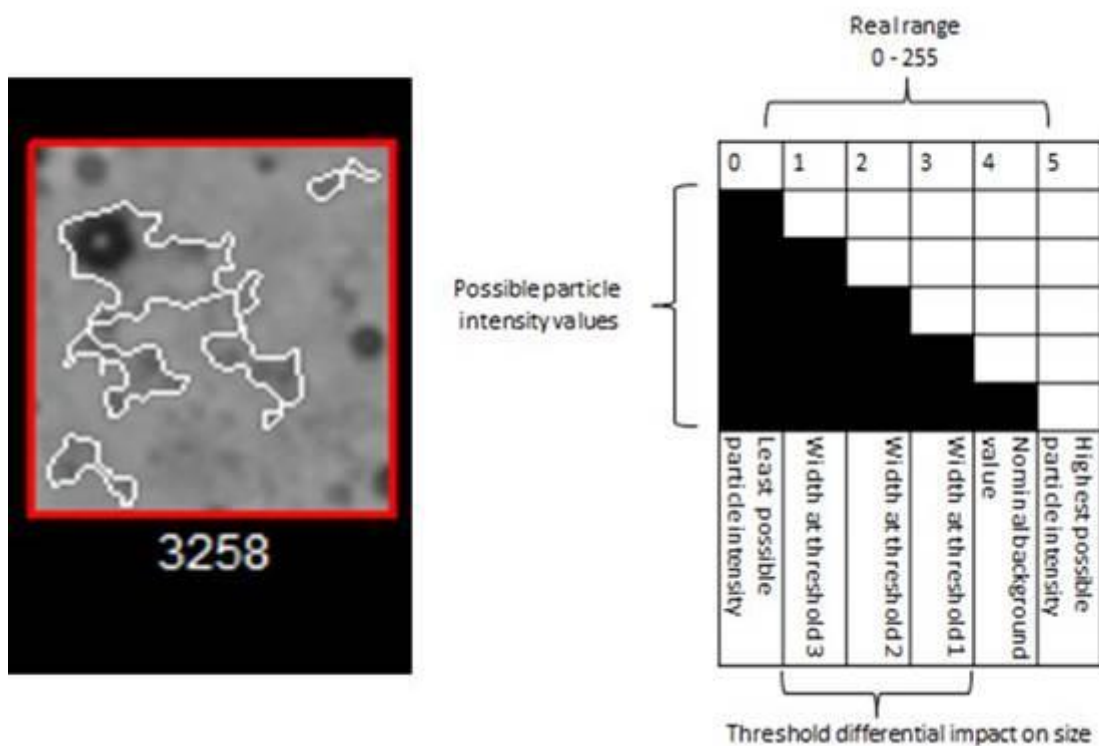


Figure A2-2 Candidate FOG globule captured within a much larger particle definition as defined by threshold. B) Example of thresholding effect on measured size

Threshold effect evaluation.

A microsphere size standard of $50.2 \pm 1 \mu\text{m}$ (CC50-PK) suspended in ultraclean diluent at a concentration of 3000 particles / mL ($\pm 10\%$) (Thermo-Scientific COUNT-CALTM, Meritics, Dunstable, UK) was used to evaluate threshold adjustments by recording raw images and reprocessing under different threshold settings adjusted in the Context screen.

Table A2-1 Effect of different threshold settings on 50 μm test microsphere size

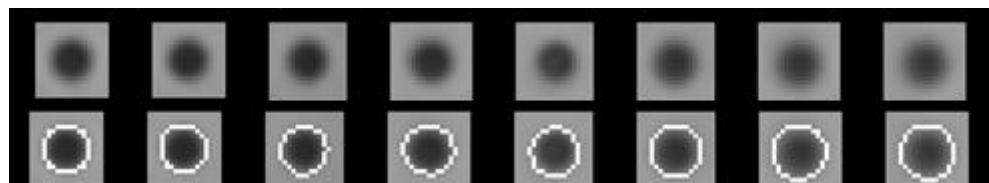
Threshold value	12	16	20	24
Count	187	187	185	185
Average ESD μm	52.29	51.63	51.12	50.62
Standard deviation μm	1.33	1.26	0.91	0.87

Low threshold settings extend the size reported whilst higher settings eradicate target particles. A setting of 18 was found to provide a compromise where capture of much lighter food debris was also required.

Edge gradient

Edge gradient is defined as the average intensity of the pixels making up the outside border of a particle. As a reported parameter it serves as a surrogate for focus which in turn impacts sizing precision.

The effect of different edge gradients is reported in the main text section 2.3.2. Here, it is illustrated by using a microsphere size standard of $10 \pm 0.08 \mu\text{m}$ (CC10-PK) suspended in ultraclean diluent at a concentration of 3000 particles / mL ($\pm 10\%$) (Thermo-Scientific COUNT-CALTM, Meritics, Dunstable, UK). In this case the test is outside of the scope recommended by the manufacturer of the Flowcam, a range of 12 - 300 μm is specified for the 4x objective. This project utilised the 4x objective to a lower limit of 11.2 μm .



Edge Gradient	138	131	118	115	102	97	85	80
ESD (μm)	9.9	9.8	10.2	10.9	10.5	11.2	12.2	12.3

Figure A2 3 Edge gradient variance of 10 μm test microsphere and reported ESD effect. Top row images as captured bottom image row with particle edge trace enabled. 4x objective.

Appendix 3. FOG identification

As identified in Table 2-2, the largest particulates in the sample analysed had visual properties that enabled them to be readily classified as food debris. The combined volume of these 126 particles was over 85% of the particulate volume. These are shown in Figure A3-1. The Figure also indicates the challenges in quantifying food debris – in the case of this sample, near transparent particulates were evident, to fully quantify them lower threshold settings would be required, which may lead to erroneous particle definitions.

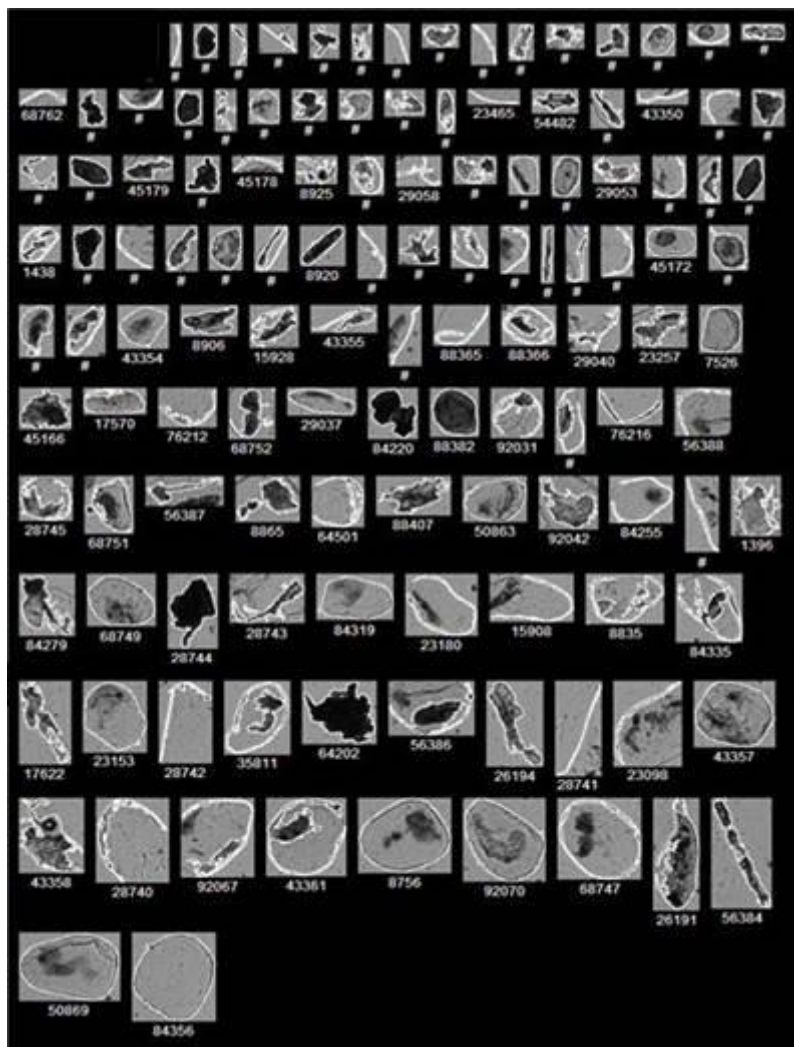


Figure A3-1 largest 126 Particles imaged showing boundary definition by white edge trace ESD range 97 - 299 μ m

Circle Fit to identify FOG

Circle fit was the prime parameter used to evaluate candidate FOG in the size range where candidate FOG droplets were present. Figure A3-2 illustrates the size range where candidate FOG droplets became apparent.

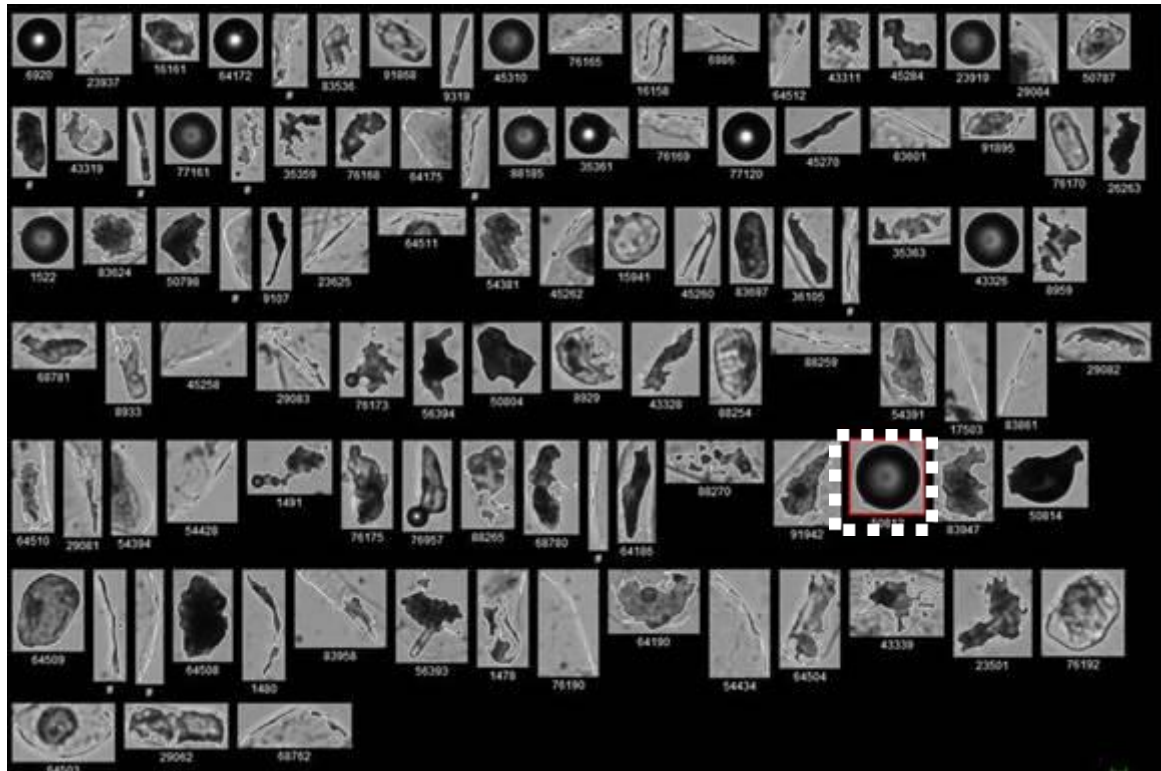


Figure A3-2 Largest candidate FOG droplet indicated by white dashes at 96 μ m. Collage ordered by ESD

High and low circle fit particles are indicated in Figure A3-3 at opposite ends of the scale that has a value range of 0-1.

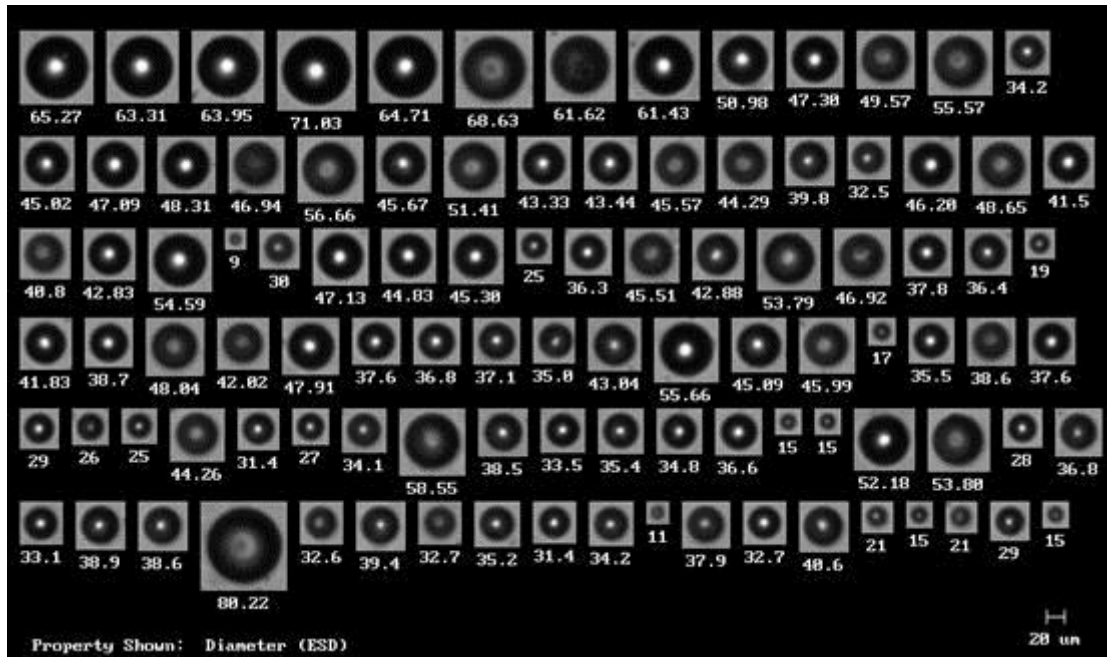
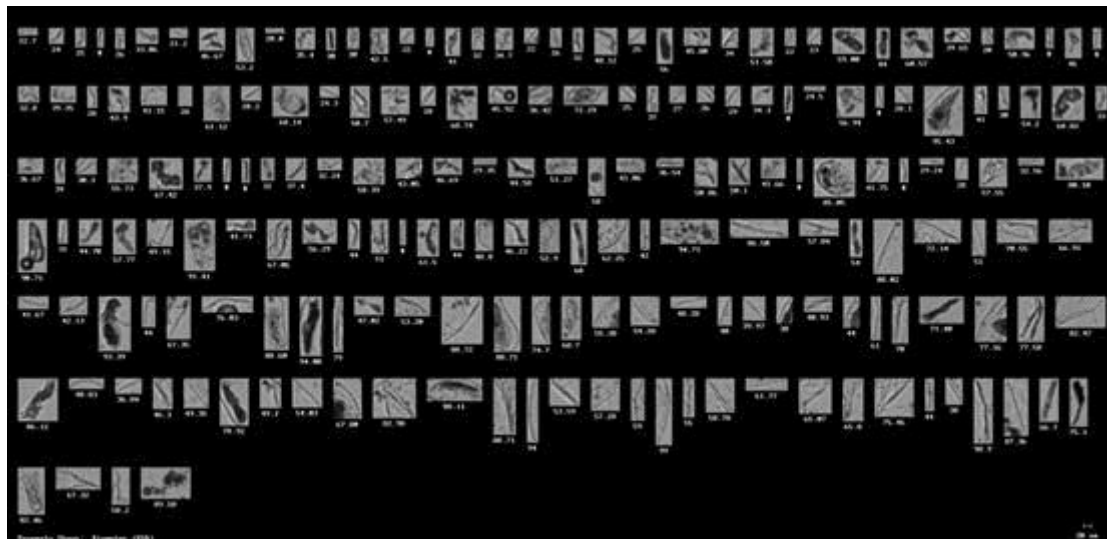


Figure A3-3 Circle fit 0.96 – 0.97 top image collage, 0-0.23 lower image collage.

In order to choose circle fit value, a collage was visually examined over a transition range from 0.88 through 0.92. The full range ordered by Circle Fit is shown in Figure A 3-4 with the 0.9 value identified.

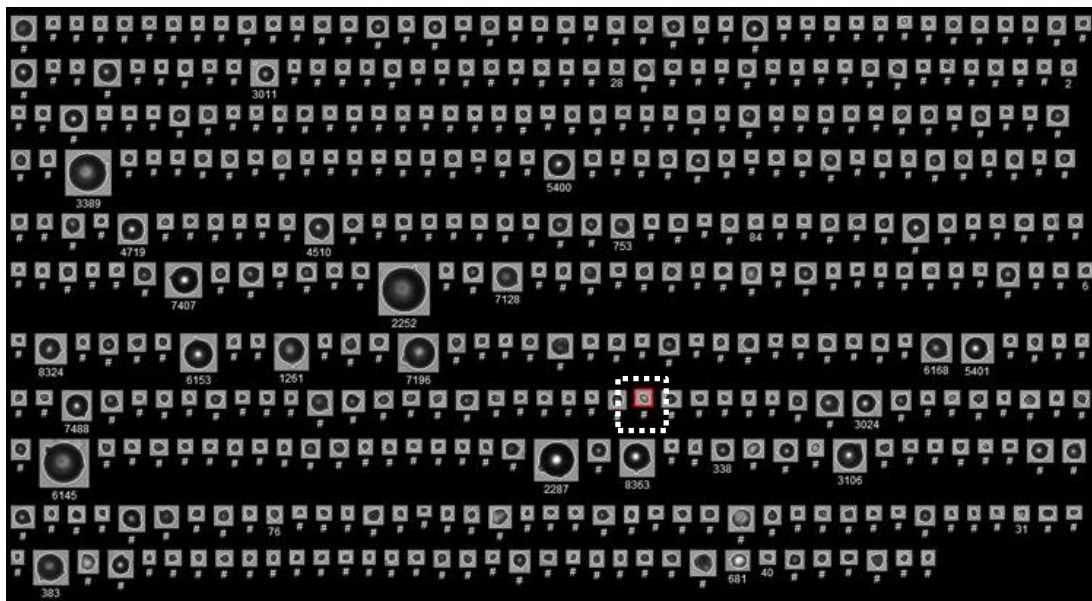


Figure A3-4 Circle Fit range 0.92 to 0.88, 0.9 value indicated with white hatched surround

The extent of successful discrimination of candidate FOG droplets by circle fit alone is demonstrated by Figure A3-5 where 75% of the segment of high circle fit total volume is described by the images shown. Visual inspection would reject one particle indicated by hatched outline.

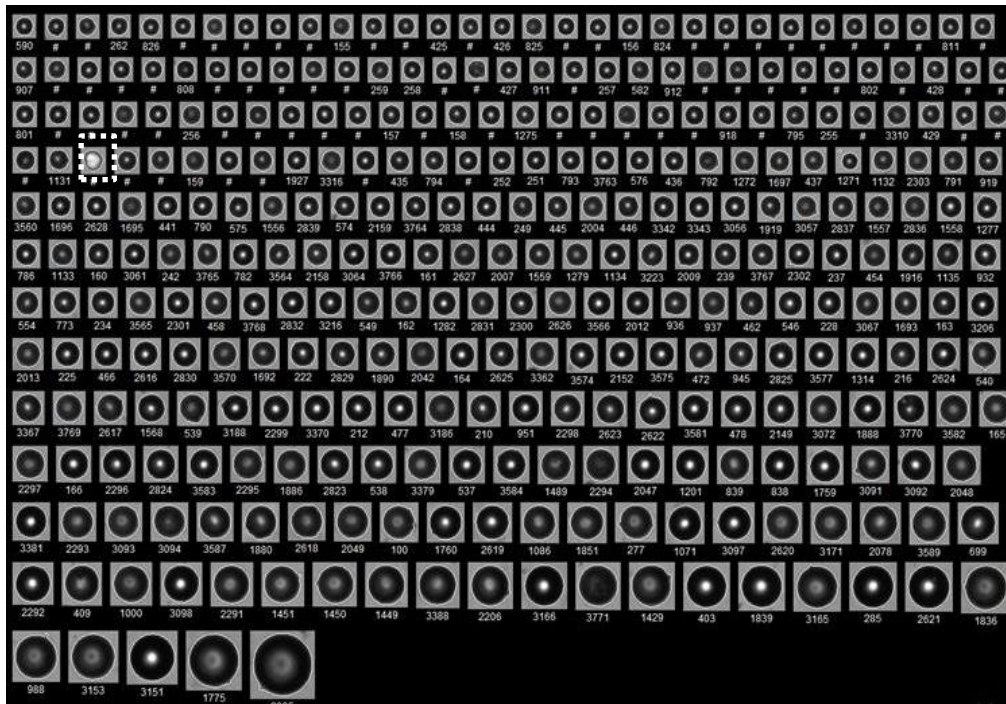


Figure A3-5 Size ordered collage of high Circle Fit droplets (CF>0.9) as reported in row 4 Table 2-2, (easily identified FOG) the range of images shown encompass the 75th percentile volume of this segment

Use of Transparency filters in FOG identification.

The results of the circle fit filter is illustrated in the top image collage in Figure A3-6, here the range of >25 μ m to maximum is presented for a sample. Candidate oil droplets, which comprise of a darker annulus with lighter centre are further qualified by application of the transparency filter – the result is shown in the lower image collage of Figure A3-6. Assessed volumetrically, the CF filter alone provided a 48% error (determined visually on the basis of likelihood of a particle being an oil droplet), the error reduces to 16% for the CFT filter. The impact of the additional transparency filter on particle number was to reduce reported volume by a further 16.4%.

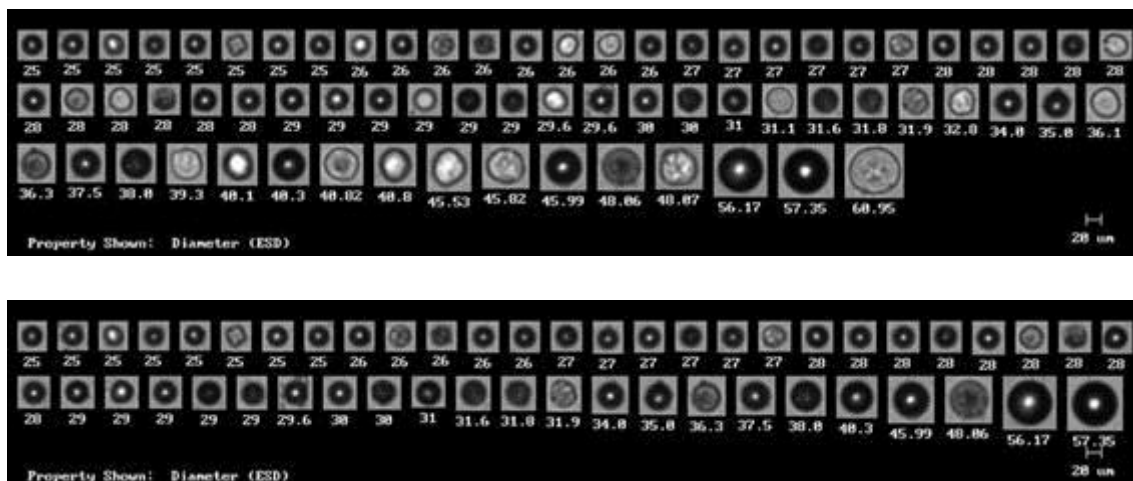


Figure A3-6 Top image illustrates outcome of Circle Fit filter CF>09– collage ordered by increasing ESD . Lower image is circle fit plus Transparency filter

Use of library based filters

The Flowcam facilitates filter construction by reference to a set of particle images saved as a library. In the case of filters constructed for Chapter 2 the library of particles was determined from attributes of candidate FOG droplets that would evade simple Circle Fit and Transparency filters. Table A 3-1 compares 577 FOG particles to 1153 non FOG particles. In each case the difference is visually determined. Particles in both sets are acquired from item 5 Table 2 and thus represent images that comprise of overlapping or otherwise compromised particles that cannot be effectively discriminated as FOG by a simple circle fit filter. Filter parameters are ordered by their score as provided by comparing d90 differences between both subsets, d50 values are provided for information. Grey shade parameters are used in subsequent filter development.

Table A3-1 FOG and non-FOG particle attribute comparison

FOG		non FOG		Comparison		
d50	d90	d50	d90	d90 difference	d50 difference	Summary Stats
26.1	32.8	21.63	27.58	-18.93%	-20.67%	Sigma Intensity
0.78	0.89	0.7	0.85	-4.71%	-11.43%	Circle Fit
0.93	0.98	0.85	0.96	-2.08%	-9.41%	Circularity (Hu)
0.85	0.99	0.82	0.98	-1.02%	-3.66%	Circularity
1	1	1	1	0.00%	0.00%	Geodesic Aspect Ratio
0.73	0.86	0.7	0.86	0.00%	-4.29%	Symmetry
14384	36595	9754	40485	9.61%	-47.47%	Sum Intensity
1.17	1.6	1.22	2.21	27.60%	4.10%	Compactness
0	0.26	0	0.36	27.78%	-	Fibre Curl
0.12	0.21	0.17	0.31	32.26%	29.41%	Transparency
1	2.66	1	4.72	43.64%	0.00%	Elongation

A number of measured attributes do not help discriminate between particles, or are reciprocals of some other reported metric. For example, ESD or other size based metrics cannot help. In selecting potential parameters a further check was made to assess that the measure will not affect total FOG volumetric determination given that any resulting

PSD classification is volumetric in principal. Figure A 3-7 provides an example where the parameter ‘Sum Intensity’ has strong correlation to particulate volume and is therefore not a prime candidate for a filter parameter.

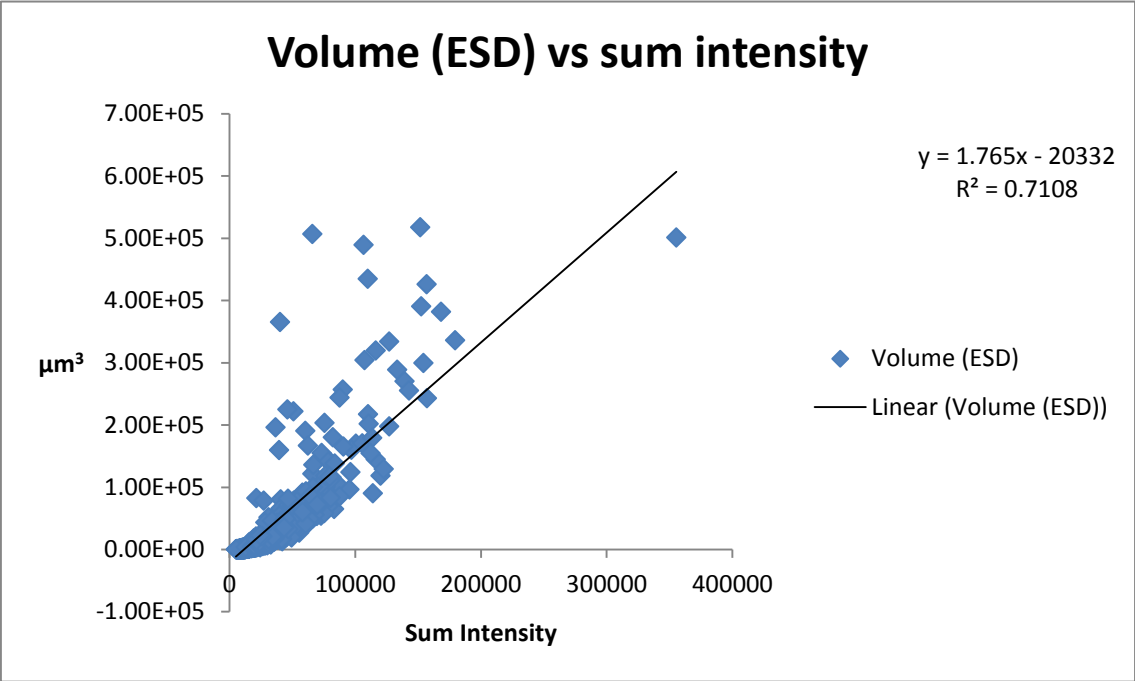


Figure A3-7 Particle volume correlation with Sum Intensity

The coefficient of determination (R^2 values) of the parameters selected are given in Table A3-2 and are based on assessment of the relationships within 2312 number FOG / Food segment with higher Edge Gradient.

Table A3-2 R^2 values for candidate filter parameters vs ESD

R^2	R^2
Sigma Intensity	0.0469
Circle Fit	0.1783
Compactness	0.2224
Fibre Curl	0.0404
Transparency	0.0366
Elongation	0.2182

Library based statistical filter application

Figure A3-8 illustrates the largest candidate FOG particles as reported following filter application. Due to touching or partial occlusion, such particles evade simple Circle Fit Filters

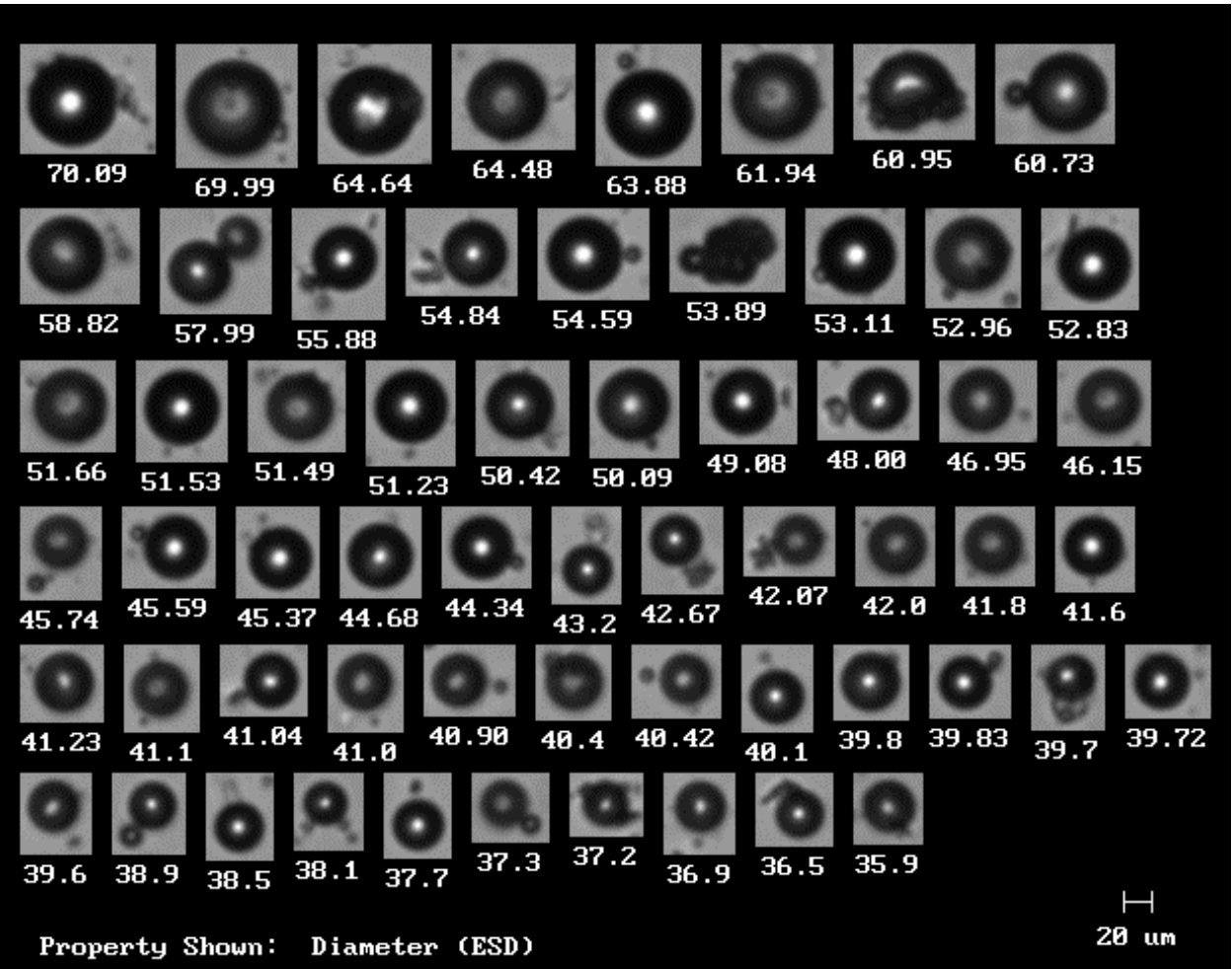


Figure A3-8 Filter application to Table 2 row 5 component - Top 60 by ESD droplets show overlapping or touching FOG droplets.

Appendix 4. Kitchen wastewater particulate analysis method

This method aims to determine the particle size distribution (PSD) of food and candidate FOG droplets in kitchen wastewater. Such wastewater is dynamic in that the components of interest have densities that may be less or greater than water and further separate at velocities depending on particle size, shape and water temperature. Quantification is therefore a function of the wastewater state at point of sampling and may further change during examination. As the intention was to capture a snapshot of the wastewater characteristic at point of entry into a FOG mitigating device – for example at such time that the sink is drained, three tactics were employed:

1. The bulk sample source is agitated to mobilise and disperse particulates

FOG mitigation devices generally sit after the sink foul air trap. The wastewater flow disrupts any settled or separated substances before entry into the separator.

2. Bulk samples are extracted from a sub-surface point above the base of the sink

FOG that is readily separable cannot be quantified by droplet size – droplets have migrated to a continuous oil phase.

3. Sample aliquot size is minimised and was between 1mL and 5mL

Subsequent analysis times are minimised negating the effect of separation during analysis.

Flowcam analysis

Assumption of 4x objective – range 12-300µm flow cell using syringe pump system

Stage one – optimising for sample characteristics

1. Sieve coarse sample through 300µm mesh
2. Stir to prevent separation and settlement
3. Pipette required quantity to flow cell feed (1 – 5mL)

4. Adjust focus manually in 'set up and focus' mode
5. Adjust flash frequency and / or gain to achieve 150 mean intensity

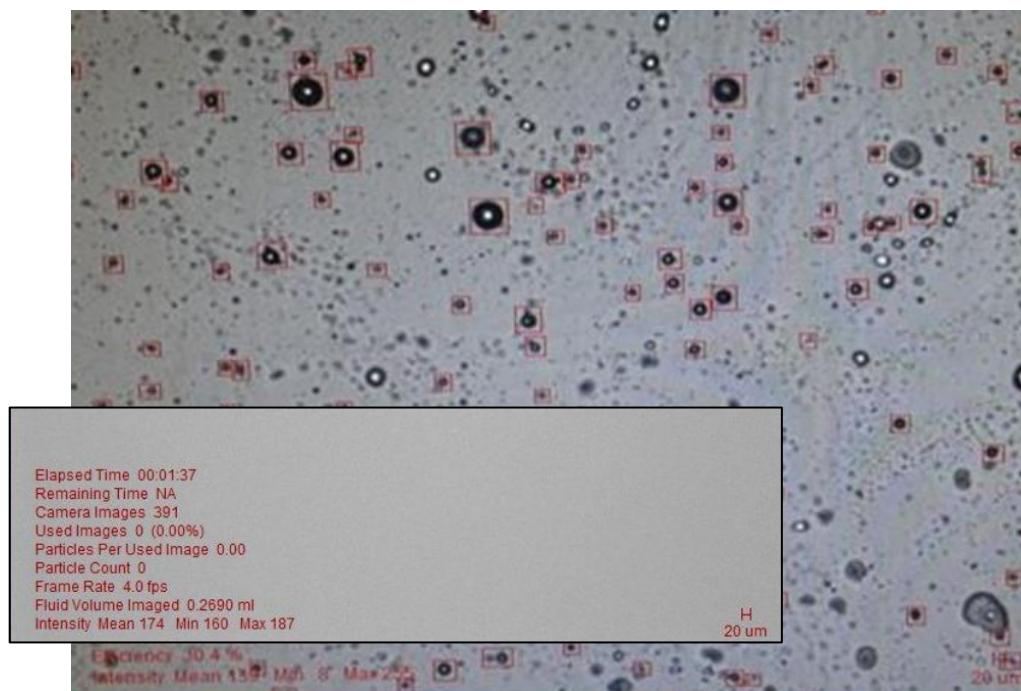


Figure A4-1 Focus window showing particles being imaged. The red box surrounds indicate particle properties meet capture requirements. Inset frame provides example of data displayed including intensity.

6. Adjust flow rate to maximum capture efficiency (provided by the software)
7. Set Context settings to prescriptions in Table 2-1
8. Set capture minimum to 10 μ m
9. Set Context to 'save raw images'
10. Run analysis

11. Consider parameter tuning to suit sample:

- a. A large departure from 'Fluid volume processed' to 'Fluid volume imaged' – in excess of 50%, indicates concentration of particulates is too high. This can be resolved by:
 - i. Adjusting minimum capture size to a larger value. The sample can be reprocessed from the saved raw images
 - ii. Physically altering the concentration and amending the Context settings accordingly

- b. Use *file re-process* mode to observe effects of Context setting changes

File re-process mode facilitates image capture setting optimisation without having to analyse further samples.

Use '*open view*' to observe captured images.

Stage two - Sample analysis.

Once optimised, the context settings should be saved and used for all subsequent analyses. Stages are:

1. Analyse as per optimised stage one
2. Repeat depending on statistical method requirements giving consideration to particle counts per size bin size increment
3. Following every analysis check X or Y axis capture graphic. Particles that become stuck to the flow cell are imaged repeatedly, this can be identified by a spike in the X or Y graphic – the y axis displays frequency. Multiple images of the same particle can be removed manually and the file re-saved under a revised name OR the experiment repeated.
4. Set and deploy filters – filtered data can be saved as a different file name enabling images to be sorted by a number of parameters – e.g ESD or Circle Fit

5. Set export criteria to include desired attributes typically particle ID, ESD, Volume, Edge Gradient, Circle fit. Export to CSV file for subsequent analysis
6. Define spreadsheet histogram parameters and analyse data.

Appendix 5. Domestic wash system overview

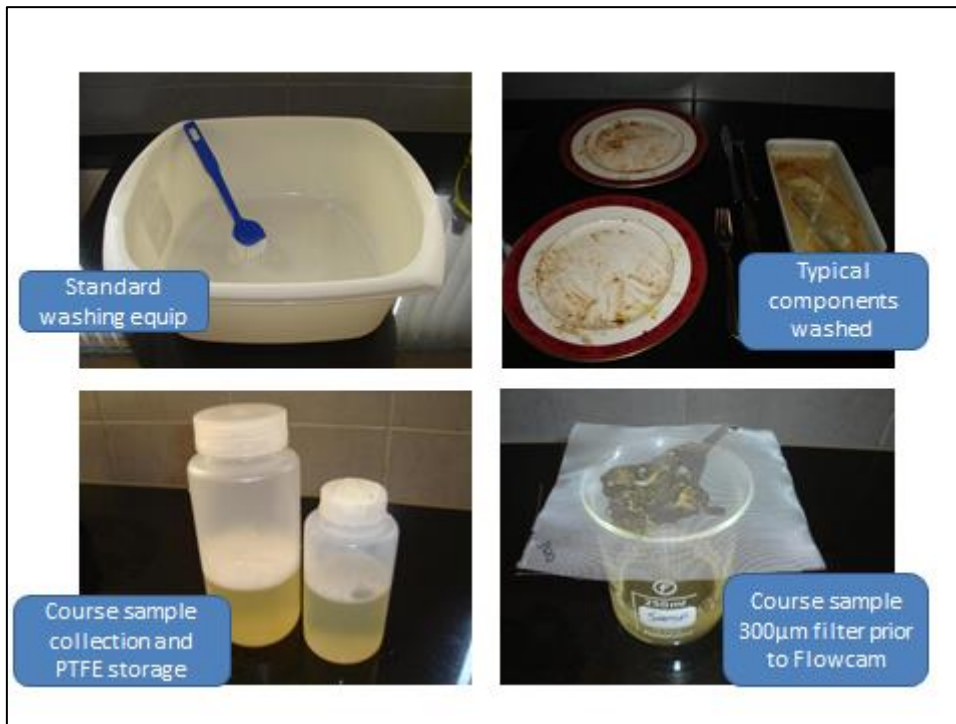


Figure A5-1 components of domestic wash systems used to evaluate cuisine particle size distribution

Appendix 6 Modified Gerber method – brief description

The modified Gerber method is an alternative to standard solvent extraction methods developed to overcome limitations of total oil quantification in kitchen wastewaters where emulsions have formed and are stabilised by surfactants such as protein (Wang and Ducoste, 2012) and detergents (Barton, 2012).

In this case the method was used to assess both free oil – that oil that has separated and has formed a continuous phase on the wastewater surface, and sub-surface oil droplets. As such the method quantifies the total FOG content of a sample and discriminates between readily separable FOG and emulsified fractions.

Triplicate samples of approximately 200mL are heated to 50°C to melt solidified fats. Surface oils are removed by application of an oil-adsorbent material (Serpro Ltd UK) over a 30 minute period. Oil is removed from the material by addition of 40mL of hexane, 20 mL of which is evaporated in order to gravimetrically determine the free oil content. Sodium caseinate (1mL, 10% solution) is added to the remaining sample aqueous phase which adsorbs rapidly to the oil droplets. pH reduction, depending on wastewater composition induces casein stabilised FOG droplets to form precipitate aggregates.

The slurry is washed into a 0-1% butyrometer containing 10 mL of sulphuric acid. Following addition of 1mL isoamyl alcohol the butyrometer is centrifuged in a heated Gerber unit for 10 minutes. FOG is released and separates in a column in the butyrometer tube allowing quantification.

References

- Barton, P. (2012) Enhancing separation of fats, oils and greases (FOGs) from catering establishment wastewater. *Cranfield University PhD thesis*.
- Yang, Y., Ducoste, J. (2012) Challenges in the Measurement of Fats, Oils and Grease (FOG) in Food Service Establishment Waste Streams. *North Carolina AWWA 92nd Annual Conference* November 11-14th, Raleigh, North Carolina.

Appendix 7 Flow to head relationship from a sink

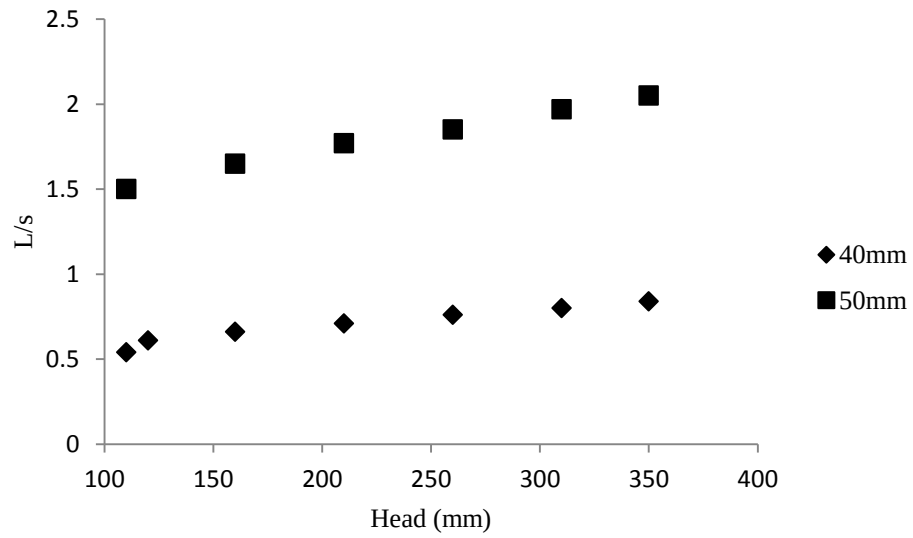


Figure A7-1 Flow rate from a sink for two common pipe diameters 40mm and 50mm.

Appendix 8 Excel processing of flow data

Volume per flow episode is calculated from reported time and flow rate data and requires post processing of CSV generated files in Excel. An episode is defined as a period of flow with a beginning and end identified by zero flow. With a record made at 4 second intervals a large amount of data is generated that requires the identification of an episode of flow or corresponding quiescence. This was undertaken using the spreadsheet method described in Table 4.

Column D identifies a flow data by assigning either 1 for flow or 0 for no flow. Column E designates an episode – be it flow or no flow, this requires 1 to be input to the first cell in E, then the formula as shown. Finally column F determines flow status as it follows that all odd episodes (column E) have zero flow and all even episodes have flow.

Table 2.1 Example data from CSV file with cell formula to determine flow and non-flow episodes

Column A Row number	Column B Time	Column C Flow (l/s ⁻¹)	Column D Flow identification tag	Column E Flow episode number	Column F Flow / non-flow assignment
Formula used:			=IF(C2>0,1,0)	=IF(D3=D2,E2,E2+1)	=ISEVEN(E10166)
2	11:26:19	0	0	9	FALSE
3	11:26:22	0.2929	1	10	TRUE
4	11:26:26	0.3535	1	10	TRUE
5	11:26:55	0	0	11	FALSE

Pivot table analysis is then used to quantify episode information, for example, totalling the time or volume of each episode or quantifying flow rate (min, av, max, standard

deviation). Analysis is then possible over the set of flow episodes or subsequent quiescent periods.