AUTHOR: VIJAYAKUMAR, B.

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Optimisation of Mare’s Tail Coalescer Technology

Bhavani Vijayakumar

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Abstract

The Mare's Tail technology was invented in ERT(Orkney) as a Joint industrial Project to reduce the use of chemicals in the produced water treatment process. The Mare's Tail is a fibrous type of coalescer used in the coalescence of oil droplets that are finely dispersed in the produced water stream with less or no chemicals. This thesis describes the work done under the auspices of the Knowledge Transfer Partnership (KTP) between Opus Plus Ltd and the Robert Gordon University (RGU), which is concerned with optimising the existing Mare's Tail technology.

A number of parameters like surface energy, flow rate, viscosity, density, length of the fibre, porosity, inlet oil droplet size, oil concentration and spool diameter, which affect both the coalescence efficiency and the separation efficiency were identified. These parameters were then grouped together to form an Initial Semi Empirical Model (SEM). From the Initial SEM; SEM1 and SEM2 were developed based on experiments conducted in the bespoke test rig. SEM1 was developed to predict the separation efficiency of a hydrocyclone or Compact Floatation Unit(CFU) downstream to the Mare's Tail Coalescer and SEM2 can be used to predict the coalescence efficiency of the Mare's Tail Coalescer, based on the growth of the oil droplet size. SEM1 was developed and tested using experimental and offshore data while SEM2 was developed and tested only using the experimental data. The results show that the optimum porosity is between 0.54 to 0.51 for a spool diameter from $2''$ to $20''$. It was identified that, as the pack structure increases the coalescence efficiency increases. The optimum velocity was identified as 0.4m/s. It was proved both experimentally and theoretically that increase in inlet oil droplet sizes decreases the coalescence efficiency but increases separation efficiency. At the final stage of the project, even though SEM1 ($R^2 = 0.85$)had higher accuracy level , SEM2 ($R^2 = 0.66$) was selected to be used in the software as it depicts only the performance of the Mare' Tail and not the separation equipment downstream. The method to evaluate the drople size and their respective concentration were identified to calculate the efficiency of the Mare's Tail. In this project the difference between coalescence efficiency and seperation efficiency were distinguished and the method to evaluate them were addressed to the sponsoring company. Even though most of the model was derived from a paper published by (Oyeneyin, Peden, Hosseini, Ren & Bigno 1992) it was then modified to suit the requirements of the Mare's Tail.

Acknowledgments

I would like to thank my supervisory team in RGU, Professor Babs Oyeneyin and Dr. Mamdud Hossain. Especially Professor Babs for supporting me and encouraging me in getting this KTP project done on time and also for helping and motivating me in continuing my studies after a tough time.

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I am great-full to my family members for helping and supporting me during my tough times and understanding my passion for research. I would also like to thank my husband Dr. Thierry Mamer who worked on the development of the Mares Tail software and helped me by supporting all throughout this project.

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Glossary

CFD Computational Fluid Dynamics.

CFU Compact Floatation Unit.

COD Chemical Oxygen Demand.

JIP Joint Industrial Project.

KTP Knowledge Transfer Partnership.

OSPAR Oslo Paris convention.

RGU Robert Gordon University.

SEM Semi Emperical Model.

VDM Visual Display Modeling.

Δ Difference between the normalised outlet droplet size concentration and the inlet droplet size concentration (ppm).

ΔP Differential pressure across the Spool/cartridge (Pa).

γ Surface tension (N/m).

γ^d Forces that act in the dispersive components (N/m).

γ_l Surface tension of the liquid (N/m).

γ_l^d Surface tension of the dispersed part of the liquid (N/m).

γ^p Forces that act in the polar components (N/m).

γ_s Surface tension of the polar solid (N/m).

η Overall efficiency (%).

θ Contact angle (^{o}).

μ_{fluid} Fluid viscosity ((N)/m^2).

ρ_{fluid} Fluid density (kg/m^3).

ρ_{pp} Density of polypropylene (kg/m^3).

ϕ Porosity.

B Pack structure.

C_i Inlet Concentration (ppm by mass).

C_{in} Concentration for the inlet droplet size (microns).

C_o Outlet Concentration (ppm by mass).

C_{on} Concentration for the onlet droplet size (microns).

D_c Cartridge diameter (m).

D_s Spool diameter (m).

F Normalising constant.

L_s Length of the Spool (m).

NC_{on} Normalised outlet droplet size concentration (ppm by mass).

Q Cumulative volume of produced water (m^3).

S Concentration of uncoalesced oil droplets in the outlet.

S_{pp} Specific surface area of the media (m^2).

S_{oil} Specific surface area of the oil droplet (m^2).

W_i Weight of the inlet area.

W_o Weight of the outlet area.

a_n Droplet Size (microns).

b_{in} Inlet Volume percentage.

d_i Inlet oil diameter (microns).

b_{on} Outlet Volume percentage.

q Flow rate (m^3/s).

t Production time (hr).

Chapter 1

Introduction

1.1 Background

Discharge of produced water into the sea poses a hazardous and dangerous threat to the sea environment. Part of Oslo Paris convention (OSPAR) Convention for the Protection of the Marine Environment of the North-East Atlantic regulations is to make sure that regulations are put in place to reduce these impacts on the marine environment. There have been several challenges in the past on production platforms to reduce the level of oil in produced water before the produced water is re-injected or discharged. The oil discharge limit in the produced water was up to 40 mg/l in 1988. The first generation Mare's Tail Coalescer was developed in a Joint Industrial Project (JIP) between Oil companies and ERT (Orkney) to overcome these challenges on production platforms. Even though the Mare's Tail was developed and was in production, the research on the Mare's Tail after the JIP was intermittent. Then ERT(Orkney) now Opus Plus Ltd decided to re-start the research on Mare's Tail to identify its working mechanism and the potential parameters that affects it coalescence in order to improve it performance to aid in Oil recovery. This led to the initiation of the Knowledge Transfer Partnership (KTP) between Opus Plus Ltd and the Robert Gordon University (RGU).

1.2 Project Objectives

This KTP project was started to develop a second generation Mare's Tail, which is optimised to improve coalescence by analysing different factors that are involved in the coalescence. [1]

The project objective involved three important tasks. Each main task was sub divided into sub tasks, which were simplified further to meet the project objectives.

- Better understanding of the operating parameters
  - Coalescence mechanism
  - Factors that influence the coalescence
- Optimise Mare's Tail for improved oil recovery
  - Run experimental trials to record performance at different conditions
  - Develop a mathematical equation to predict the performance
  - Optimise the mathematical equation to improve its accuracy
- Making a robust technology
  - Perform experiments to check the accuracy of the mathematical equation
  - Design the equipment to improve the performance using Computational Fluid Dynamics (CFD)or Visual Display Modeling (VDM)
  - Analyse the results and test the prototype

1.3 Methodology

In order to achieve the main tasks, an initial plan with a work schedule was drawn for all the tasks that were involved in meeting the project objectives. The tasks explained in this section, whose aim is to improve the existing technology, were approached methodically in order to produce the best result within the budget provided.

[1] Coalescence: Coalescence is the process by which two or more droplets merge during contact to form a bigger droplet

1.3.1 Better understanding of the operating parameters

The first objective of the project was to get a better understanding of the operating parameters of the Mare's Tail. Before proceeding with any further improvements in the Mare's Tail coalescer it was necessary to understand the system and the principles behind its working methodology. In order to complete this task, an extensive literature review about coalescence mechanisms was carried out. Although there was a lot of information about woven fibres, there was only little information available about linear fibres similar to the application in Mare's Tail coalescer. Mare's Tail is a linear type coalescer and most of the research conducted to date was concerned with linear fibres which achieved cross flow across the media. Although this information was useful, it did not help to reach any conclusion. Therefore a literature review of the previous research conducted in Opus Plus was carried out to identify the basic parameters that affected the coalescence. The mechanism of coalescence was reviewed by studying about emulsions, their formation and the methods to break the emulsion.

1.3.2 Optimising Mare's Tail for improved oil recovery

In order to optimise the Mare's tail the previous task, Section1.3.1 played a major part, as it gave the understanding of the working principle and results of the previous experiments. Armed with this base information, a number of experiments were designed and conducted to analyse the parameters that affect the coalescence. The results of these experiments and the parameter's levels were recorded. From those parameters that have an influence over the coalescence efficiency, a Semi Emperical Model (SEM) was developed. This equation was further optimised by varying the groupings and carrying out an error reduction process.

1.3.3 Making a robust technology

After obtaining the SEM, experimental tests were carried out to optimise the model further and improve its accuracy. The physical changes of the equipments including fibre structure, fibre material, fibre length, total number of fibres, fibre pattern and inlet and outlet designs were tested. Tests were also carried out in varying the concentration of oil, flow rate, diameter of the spool section and the application of solids. The results from these experiments further optimised the model and helped improve its accuracy.

1.4 Contributions to Knowledge

The work presented in this document made several contributions to knowledge in the field of Produced Water Treatment. The results of previously conducted experiments with Mare's Tail in the offshore platforms were analysed and the datasets were utilised to develop an initial SEM. Two more Semi Empirical Models were also developed, SEM1 and SEM2 which can now be used by the company to generate optimum design parameters for a Mare's Tail installation.

Some of this work has been presented and published in:

> Oyeneyin, M. B.; Glen MacLellan; Bhavani Vijayakumar; Mamdud Hussain; Roy Bichan and Nigel Wier, The Mare's Tail - *The answer to produced water management in deepwater environment?*, SPE Paper No 128609, Aug. 2009

The full paper can be found in Appendix C.

Finally, one of the SEMs developed in this work was implemented into a Mare's Tail Optimisation Software. A unique algorithm for the software was designed as a part of this project. Based on the algorithm the software was developed by a contractor, to be used by the company to automatically generate optimum design parameters for a Mare's Tail installation with respect to the platform conditions. Two types of efficiencies were identified to analyse the coalescer's performance: separation efficiency and coalescence efficiency. Previously, the performance of the coalescer was always based on the performance of the downstream equipment. During this research the method of evaluating the coalescence efficiency was developed for the first time based on the improvement in the volume of bigger droplet size range for a given concentration. This method proves that there is a difference between the coalescence efficiency and separation efficiency.

The effect of parameters like length of the fibre, use of cartridge cage, porosity, wettability of the fibres, strength of the fibres, influence of the temperature on coalescence were identified in this research.

1.5 Structure of this Document

The remainder of this thesis is structured as follows:

- Chapter 2 contains the Literature review. First, the environmental regulations on produced water discharge are discussed, then the factors involved in coalescence of Mare's Tail are described and all efficiency calculation methods considered in this work are explained.

- Chapter 3 explains the development of the SEM. The definitions for coalescence efficiency and separation efficiency are given, all parameters used in the model are explained and descriptions are given for the different models developed in this work.

- Chapter 4 first gives the details of the experiments conducted and then explains the results obtained from both the practical experiments and the analysis of the SEM. This chapter also introduces the Mare's Tail Optimisation Software which was produced as part of this work.

- Chapter 5 finally offers some conclusions and some suggestions for further work.

Chapter 2

Literature Review

Most of the information required for the initial understanding of the Mare's Tail were taken from the Joint Industrial Project that was done in the company (Environmental Resource Ltd 2000), (Opus Plus Ltd 2005). The contents of these reports are omitted from this document due to intellectual property restrictions. To optimise Mare's Tail, more information about the petroleum industry and their discharge rates in the oil fields was necessary. Also, the main parameters involved in the coalescence of Mare's Tail were identified and different methods to determine coalescence efficiency were investigated.

2.1 Mare's Tail Coalescer technology

The Mare's Tail (Ekundayo 2009), (Oyeneyin, McLellan, Vijayakumar & Hussain 2009) is a coalescer device. It was developed by Opus Plus through a joint industry project in 1998. The first generation Mare's Tail Coalescer was developed to overcome the challenges in coalescing smaller oil droplets dispersed in produced water on production platforms and thus, meeting the regulation target set by Government bodies. This technology helped the oil industry clients to improve the quality of produced water, which is being discharged to the sea, by less or no use of de-oiling chemicals. Furthermore it enabled them to meet the challenge of OSPAR (OSPAR 2011a) regulation by reducing the total quantity of oil by 15% (15 ppm)in the produced water discharge and the performance standard of dispersed oil of 30mg/l.

Figure 2.1: The Mare's Tail.

The Mare's Tail (See Figure 2.1) works by coalescing small oil droplets i.e droplets as small as 2 microns, found in produced water, into significantly larger sizes. This enabled the down stream oil water separation equipment to efficiently separate the droplets from the water. The design of Mare's Tail involves a spool and a cartridge, containing a fibrous coalescer element, which is fixed at the end of the spool closest to the inlet. Fluids enter the inlet T section and flow along the spool piece in the same direction as the coalescer media. As the fluids travel along the oleophilic fibres, the oil droplets are attracted to the fibrous media surface and coalesce with other droplets as they migrate towards the outlet. The flow is in-line with the fibrous media, rather than cross flow, (as with more conventional technologies). As a result, solids are passed through the Mare's Tail without clogging the system as opposed to building up within the media.

Figure 2.1 shows a Mare's Tail Coalescer alone and Figure 2.2 shows a Mare's Tail installation in full setup.

2.2 Related work

Coalescence in fibrous bed coalescers were explained in several papers (Li & Gu 2005) (Secerov Sokolovic, Sokolovic & Dokovic 1997) (Secerov Sokolovic, Vulic & Sokolovic 2007)

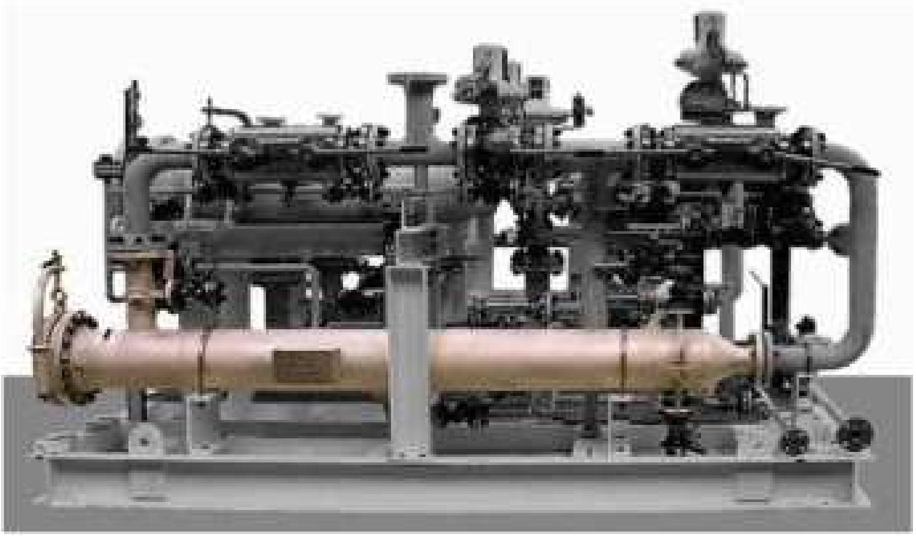

Figure 2.2: Mare's Tail in full setup

(Sokolovic, Govedarica & Sokolovic 2010) (Painmanakul, Kongkangwarn & Chawaloesphonsiya 2009). Sokolovic, Govedarica and Sokolovi (2010) explained the effect of the coalescer geometry on steady-state bed coalescence where as Sokolovic,Vulic and Sokolovic (2007) investigated the effect of bed length in coalescence with Polyurethane fibres. Shah, Langdon and Wasan (1977)and Ji (2009) demonstrated the effect of coating fibre materials. Hong, Fane and Burford (2003) and Hong, Fane and Burford (2002) conducted experiments with Teflon membrane to enhance the size of the oil droplets. Hong, Fane and Burford (2003) conducted experiments in operating conditions such as transmembrane pressure, membrane orientation, and emulsion concentration. Their results proved that the membrane pore size is a major influential parameter in the coalescence of the oil droplets. Hong, Fane and Burford (2002) conducted experiments with cross flow filtration cell and the coalescence performance improved with low cross flow velocities. Kulkarni, Patel and Chase (2012) explain the importance of wettability of the fiber media and state that " By varying the fiber composition and thickness of hydrophilic and hydrophobic layers in the media, filter media with different wetting properties can be prepared". Painmanakul, Kongkangwarn and Chawaloesphonsiya (2009) studied the effects of bed types, bed height, liquid flow rate and stage coalescer (step-bed) on the treatment efficiencies in term of

Chemical Oxygen Demand (COD) values, where the Chemical Oxygen Demand (COD) level was analysed using the closed flux method.

2.3 Environmental Regulations

One of the most critical issues associated with the high cost and poor production performance in the oil industry is early water and sand production. During the earlier stage of the oil well, the amount of oil in the petroleum fluid is high when compared to that of the water. Over time the oil content in the petroleum fluid decreases and the water content increases. This phenomenon is called as water production and the same happens with sand as well. Continuous water production is also a common phenomenon with mature or depleted reservoirs. Therefore companies are constantly looking for new ways to improve performance. Keeping production costs to a minimum while keeping production targets high, requires an effective management of the produced water either by re-injection of fluids into the reservoir, or by discharge to the environment (Rigzone 2011). The challenge is in meeting the strict operational requirements and environmental disposal regulations set by OSPAR, which define the level of oil in water before re-injection or discharge.

> OSPARis the mechanism by which fifteen Governments of the western coasts and catchments of Europe, together with the European Community, cooperate to protect the marine environment of the North-East Atlantic. It started in 1972 with the Oslo Convention against dumping. It was broadened to cover land-based sources and the offshore industry by the Paris Convention of 1974. These two conventions were unified, up-dated and extended by the 1992 OSPAR Convention. The new annex on biodiversity and ecosystems was adopted in 1998 to cover non-polluting human activities that can adversely affect the sea (OSPAR 2011a).

The Convention for the Protection of the marine Environment of the North-East Atlantic (the OSPAR Convention) was open for signature at the Ministerial Meeting of the Oslo and Paris Commissions in Paris on 22 September 1992. It was adopted together with a

Final declaration and an Action Plan (OSPAR 2011b). The concentration of dispersed oil in Produced water [1] has been immensely reduced over the years. In 2007, the OSPAR regulations demanded less than 30 mg/l of dispersed oil, which was a 15% reduction compared to regulations in 2000 (OSPAR 2010). Though the value of 30 mg/l is still valid, OSPAR regulations on produced water are expected get more stringent (OSPAR 2010). There is a potential for future OSPAR regulation to demand a level of 10 mg/l or lower (Ekundayo 2009). In the United Kingdom, for instance, environmental legislation is becoming increasingly strict as the *Convention for the Protection of the Marine Environment* is even further reducing the total amount of allowed discharge of oil. There have been several challenges in the past on production platforms to reduce the level of oil in produced water before it is re-injected or discharged.

2.4 Factors involved in Coalescence of Mare's Tail

There are many factors that are relevant to determining the coalescence efficiency of a the Mare's Tail. According to Chris Rulison (Chris Rulison 2009), London Dispersion effect, Dipolar effect, Cohesive Attraction, Capillary Force, Drag, Gravity and Kinetic Energy have a strong influence on the coalescence while the size of the droplets, Oswald Ripening and lack of Brownian Motion have only little or no influence (Rulison 1999), (Rulison 1996). Furthermore, solids, viscosity of fluid, flow rate of fluid, temperature and interfacial surface tension between the fluid and the Mare's Tail media, which are parameters related to the oilfield, affect the coalescence efficiency (Oyeneyin et al. 1992).

Before setting up a model, there is a need to investigate all the individual factors that affect the coalescence in fibres. Several papers were referred for the determination of the parameters individually. Each of these is explained in the following sections.

[1] Produced water is a term used to describe water produced from a well bore that is not a treatment fluid. The characteristics of produced water vary and use of the term often implies an inexact or unknown composition (Schlumberger oil field glossary 2011).

2.4.1 Affinity of oil droplets towards the medium

Oil droplets get attracted towards the media due to the forces acting between them. These forces are caused by the presence of polar and dispersive components in the fluid and in the media. The forces that act in the polar components γ^p consists of dipolar interaction, hydrogen bonds, Lewis acid-base interactions and charge transfer interaction (Rendtel 2002). The forces that act in the dispersive components γ^d consists of London dispersion force and Van der Waals interaction (Chris Rulison 2009). Therefore the total surface tension γ of a substance is given by

$$\gamma = \gamma^p + \gamma^d \tag{2.1}$$

a. Hydrogen Bond

Hydrogen Bond is a form of association between an electronegative atom and a hydrogen atom attached to a second, relatively electronegative atom. It is best considered as an electrostatic interaction, heightened by the small size of hydrogen, which permits proximity of the interacting dipoles or charges. Both electronegative atoms are usually (but not necessarily) from the first row of the Periodic Table, i.e. N, O or F. Hydrogen bonds may be inter-molecular or intramolecular. With a few exceptions, usually involving fluorine, the associated energies are less than 20-25kJ/mol (5-6kcal/mol) (McNaught & Wilkinson 1997).

b. Lewis acid-base interactions

Lewis acid-base interactions are a molecular entity (and the corresponding chemical species) that is an electron-pair acceptor and therefore able to react with a Lewis base to form a Lewis adduct, by sharing the electron pair furnished by the Lewis base (McNaught & Wilkinson 1997).

2.4.2 Forces helping coalescence

a. London dispersion Effect

The intermolecular attraction force in non polar components which has an uneven charge distribution within the molecule as shown in Figure 2.3 is know as the London dispersion Effect(Purdue University Lecture paper 2010), (London 1937), (Hettema 2000),

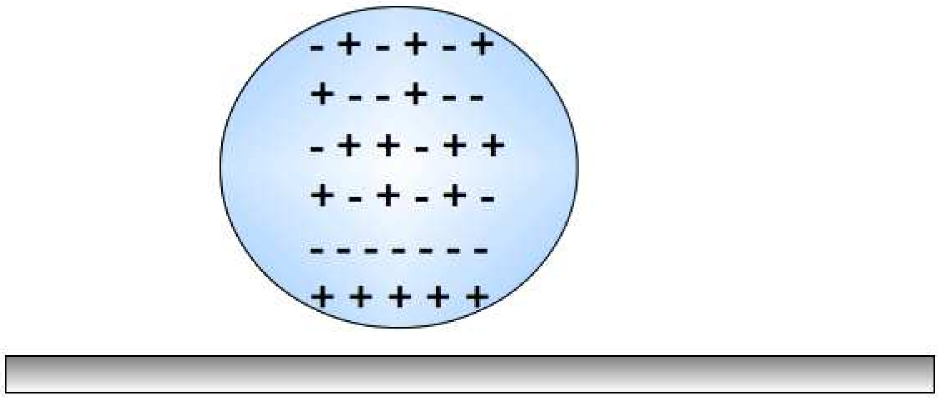

Figure 2.3: London dispersion effect.

b. Dipolar effect

Dipolar interaction is an intermolecular or intra-molecular interaction between molecules or groups having a permanent electric dipole moment. The strength of the interaction depends on the distance and relative orientation of the dipoles. The term applies also to intra-molecular interactions between bonds having permanent dipole moments (McNaught & Wilkinson 1997). Dipole-dipole forces have strengths that range from 5 kJ to 20 kJ per mole. They are much weaker than ionic or covalent bonds and have a significant effect only when the molecules involved are close together (touching or almost touching) (purdue.edu 2011). The uneven distribution of charged particles can lead to the dipolar effect (change in the shape of the molecule due to the presence of an external electric field) when it comes into close proximity with the Mare's Tail media. This then leads to the initial attraction of the droplets to the Mare's Tail media as in Figure 2.4.

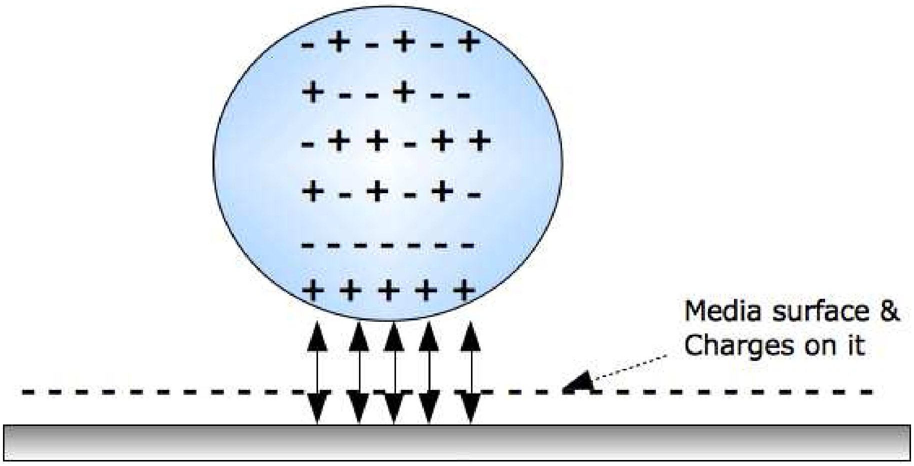

Figure 2.4: Dipolar effect.

c. Cohesive attraction

The initial step of coalescence is followed by cohesive attraction, which is intermolecular attraction between like molecules (Birdi 2003) (See Figure 2.5). Cohesive attraction can then lead to week boundary layer conditions which merge oil droplets together. The size of an oil droplet plays a vital role in coalescence due to cohesion. If the size of the oil droplet is bigger the charge distribution will be higher, and the there will be less or no zeta potential (voltage difference between the inner and the outer layer of the droplet) and week boundary layer condition.

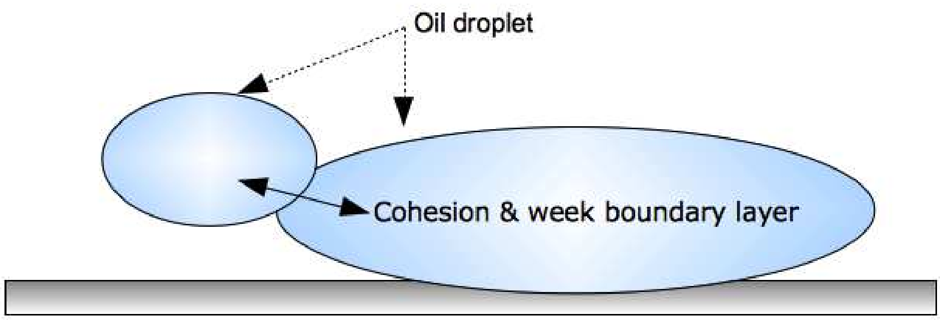

Figure 2.5: Cohesive attraction between like substances.

Further coalescence is promoted by capillary force, which is the ability of a substance to draw another substance into it (Pashley & Karaman 2004b), and the surface tension properties of the Mare's Tail media. These are forces that occur due to the surface energy of the media towards the oil droplets, which makes the oil droplets coat the media surface.

d. Drag, Gravity and Kinetic Energy

Drag, gravity and kinetic energy (Pashley & Karaman 2004a) of the oil droplet entering the Mare's Tail system act on the big droplets (droplets that have already coated the media) and break their boundary layer to form a bigger droplet as shown in Figure 2.6. Gravity helps in increasing the residence time of the droplet, and the drag and kinetic energy helps the droplet to collide with media surface.

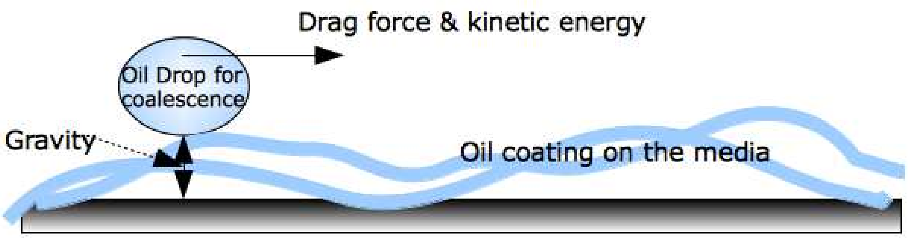

Figure 2.6: Different forces acting on the oil to help in coalescence.

2.4.3 Forces opposing coalescence

a. Smaller size of the droplet

If the size of the droplet is smaller than 2 microns, then the Mare's Tail will not be able to coalesce. The reason is, these smaller oil droplets escapes without coalescing due their charge density being stronger than their size when compared to charge density of bigger oil droplets. (Deng, Bai, Chen, Yu, Jiang & Zhou 2002)

b. Ostwald ripening process

When droplets collide with each other, they may result in forming a smaller droplet and a bigger droplet. When these droplets collide with two other different droplets the smaller droplet may become much smaller whereas the bigger droplet become more bigger as shown in Figure 2.7. This is referred to as Ostwald ripening process (Birdi 2003).

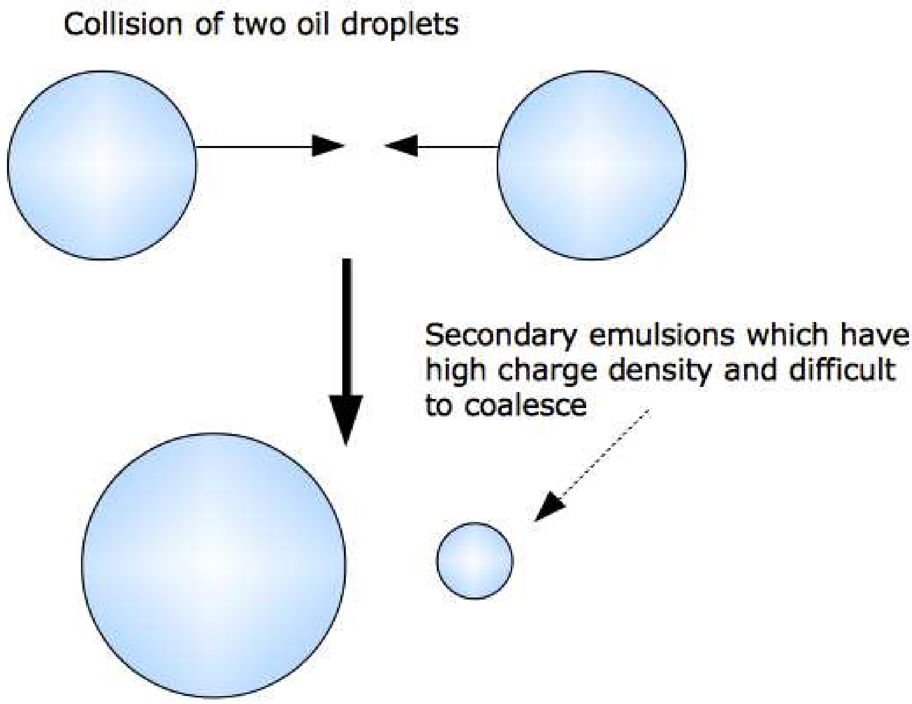

Figure 2.7: Ostwald ripening process.

c. Lack of Brownian motion

The random movement of microscopic particles suspended in a liquid or gas, caused by collisions between these particles and the molecules of the liquid or gas is referred to as Brownian Motion. Despite the fine solid particles and secondary emulsions that carry a high amount of kinetic energy in them, the oil droplets escape from being in contact with the media. The Oil droplets lack Brownian motion as they mostly tend to flow along the direction of the produced water. This prevents coalescing due to the flow that flushes these oil droplets to the outlet (Hetsroni 1982), as shown in Figure 2.8.

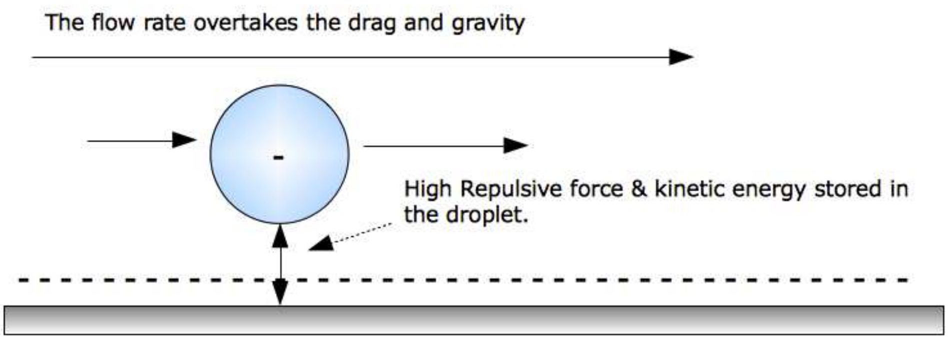

Figure 2.8: Brownian motion.

2.4.4 Presence of solids

The presence of solids will improve coalescence by forming a surface for the oil droplets to coat, which will decrease the coalescence time. However, this will also cause droplet stabilisation, as some water soluble surface-active agents (surfactants/ detergents) and fine solid mineral particles are often adsorbed (surface attraction/coating e.g. painting a wall) onto the oil droplets, which makes it difficult to de-emulsify the emulsions any further (Hetsroni 1982).

2.4.5 Viscosity of the fluid

The lower the viscosity of the continuous phase (water), the more rapid film drainage (e.g. oil droplet surfaces breaking) and the shorter the coalescence time (Oyeneyin et al. 1992).

2.4.6 Temperature

An increase in temperature causes a decrease in coalescence time (Oyeneyin et al. 1992).

2.4.7 Fluid flow Rate

An optimal fluid flow rate generally improves coalescence. However, even if the flow rate is optimal, a too high oil droplet concentration will cause the smaller oil droplets to not coalesce on the media. This is because the small oil droplets get flushed away by the fluid without leaving them time to coalesce. Therefore, a too high oil droplet concentration will decrease the overall coalescence efficiency for Mare's Tail. (Hong, Fane & Burford 2002) demonstrates that there is an improvement in coalescence performance during intermittent operation at low crossflow velocities.

2.4.8 Contact angle and Inter-facial surface tension

The angle between the media and the fluid at the point of contact is referred to as the contact angle θ, as shown in the Figure 2.9. This angle depends on the wettability of the media with the fluid, which in turn, depends on the interface between them. The smaller the contact angle, the better the wettability.

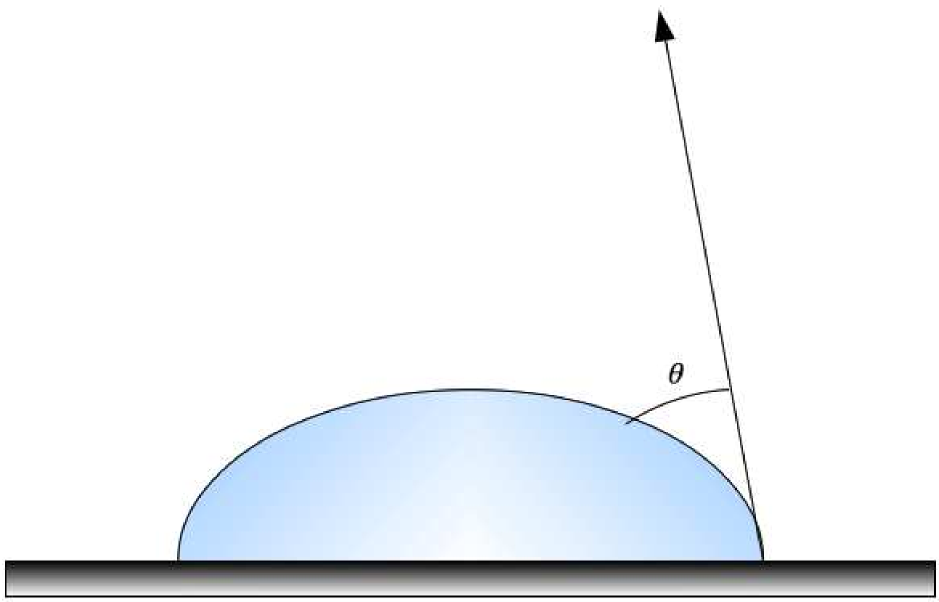

Figure 2.9: Contact angle .

For the characterisation of the solid wettability by a liquid, one should have a good knowledge about the surface energy of the solid and the surface tension of the liquid. However, two solids having similar surface energy can display different wettability against the same liquid (Chris Rulison 2009). If the values of the surface tension, surface energy and their contact angle are given, the inter-facial surface tension could be identified using Young's Equation. Once the two force components in a material's surface (dispersed for oil and polar for water) are found, they can be used together with the contact angle of the fluid on the media to calculate the surface tension of the dispersed component. This surface tension is calculated for each sample, in dependence on temperature, using the following equation:

$$\gamma_l^d = \frac{{\gamma_l}^2}{4 \times \gamma_s (1 + cos\theta)^2} \tag{2.2}$$

where γ_I^d is the surface tension of the dispersed part of the liquid, γ_s is the surface tension of the polar solid, γ_l is the surface tension of the liquid and θ is the contact angle of the liquid on the solid.

2.5 Calculating Mare's Tail efficiency

Several papers explained filtration and separation in porous media and coalescence in fibrous media based on the gravity separation technique. Only few explained the coalescence efficiency on fibrous media using particle size analysing equipment. Before the start of this project, the coalescence efficiency was calculated in Opus Plus by comparing the improvement in the separation efficiency of a downstream equipment, like hydro-cyclone or a Compact Floatation Unit, with and without the Mare's Tail. This method was useful to calculate the separation efficiency improvement, but did not clearly explain the coalescence efficiency of the droplets. Therefore other methods to determine the coalescence efficiency were investigated.

In this work, five different methods were attempted:

- Drop size cut Method
- Area of Plot
- Weighting Area Plot
- Trapezoidal Method
- Setting and Separation Method

Each of these methods is explained in the following sections.

Table 2.1: Inlet and outlet droplet size and their concentration data. The last row contains the sum of all above rows and acts as a validation where appropriate.

Drop Sizes Range (μm)	b_i %	Cumulative Inlet %	C_i (ppm)	b_o %	Cumulative Outlet %	C_o (ppm)	NC_i (ppm)	Δ (ppm)
a_1	b_{i1}	b_{i1}	C_{i1}	b_{o1}	b_{o1}	C_{o1}	NC_{i1}	Δ_1
a_2	b_{i2}	$b_{i1}+b_{i2}$	C_{i2}	b_{o2}	$b_{o1}+b_{o2}$	C_{o2}	NC_{i2}	Δ_2
.	.	$b_{i1}+b_{i2}+b_{i3}$	C_{i3}	.	$b_{o1}+b_{o2}+b_{o3}$	C_{o3}	.	Δ_3
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
a_n	.	.	.	.	.	.	NC_{in}	Δ_n
a_{n+1}	.	.	.	.	.	.	$NC_{i(n+1)}$	Δ_{n+1}
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
a_N	b_{iN}	100	C_{iN}	b_{oN}	100	C_{oN}	NC_{iN}	Δ_N
Sum	100		C_i	100		C_o	C_i	0

2.5.1 Drop size cut method

Table 2.1 shows the calculation to find the coalescence efficiency.

For each Droplet Size a_n, there is an Inlet Volume percentage b_{in} and an Outlet Volume percentage b_{on}. With that, the Cumulative volume percentage for both the inlet (Cumulative Inlet) and outlet (Cumulative Outlet) droplet sizes can be calculated and these are then used to calculate the concentration for the inlet droplet size C_{in} as well as for the outlet droplet size C_{on} using Formula 2.3.

$$C_{in} = \frac{C_i \times b_{in}}{100} \qquad C_{on} = \frac{C_o \times b_{on}}{100} \tag{2.3}$$

where C_i is the Inlet Concentration and C_o is the Outlet Concentration.

Then the outlet droplet size concentration C_{on} to the Inlet Concentration C_i is normalised according to Formula 2.4:

$$NC_{on} = F \times C_{on} \qquad where\ F = \frac{C_i}{C_o} \tag{2.4}$$

Finally, the difference between the normalised outlet droplet size concentration NC_{on}

and the inlet droplet size concentration C_{in} is calculated using Formula 2.5.

$$\Delta = NC_{on} - C_{in} \tag{2.5}$$

If there is any negative Δ_n where Δ_{n+1} is positive, then the concentration of uncoalesced oil droplets in the outlet S is:

Therefore overall efficiency $\eta$is:

$$\eta = \frac{C_i - S}{C_i} \times 100 \tag{2.6}$$

Example

In order to explain the Droplet size cut method more clearly Table 2.2 (See page 21) shows an example calculation to find the coalescence efficiency. The raw data of droplet size distribution from the Malvern master sizer for an inlet concentration of 1805ppm, outlet concentration of 195ppm and flow rate of 2.1m^3/hr is used in this Table 2.2. The droplet size, inlet volume% and outlet volume% are the data that is obtained from the Malvern master sizer. From these data the cumulative volume% of both the inlet and the outlet are determined.

In order to calculate the concentration of the inlet and the outlet, a specific droplet size of 0.20 microns is used as an example. The concentration is determined using Formula 2.3.

$$C_{in} = \frac{1805 \times 0.18}{100} = 3.21ppm \tag{2.7}$$

$$C_{on} = \frac{195 \times 0.06}{100} = 0.12ppm \tag{2.8}$$

Then the outlet droplet size concentration 195ppm is normalised to the Inlet Concen-

Table 2.2: Example calculation to find the coalescence efficiency for an inlet concentration of 1805ppm, outlet concentration of 195ppm and flow rate of 2.1m^3/hr.

	Inlet			Outlet				Concentration
Drop size	Volume %	Cumulative	Concentration	Volume %	Cumulative	Concentration	Normalise	difference
Microns	%	%	ppm	%	%	ppm	ppm	ppm
0.06	0.01	0.01	0.21	0.00	0.00	0.00	0.02	-0.20
0.07	0.02	0.04	0.45	0.00	0.00	0.00	0.04	-0.41
0.08	0.04	0.08	0.71	0.00	0.01	0.01	0.07	-0.64
0.09	0.06	0.13	1.01	0.01	0.01	0.01	0.12	-0.90
0.11	0.08	0.21	1.36	0.01	0.02	0.02	0.19	-1.17
0.13	0.10	0.30	1.75	0.02	0.04	0.03	0.31	-1.44
0.15	0.12	0.43	2.19	0.03	0.07	0.05	0.48	-1.71
0.17	0.15	0.57	2.68	0.04	0.11	0.08	0.74	-1.94
0.20	0.18	0.75	3.21	0.06	0.17	0.12	1.09	-2.12
0.23	0.21	0.96	3.80	0.09	0.26	0.17	1.58	-2.22
0.27	0.25	1.21	4.47	0.12	0.38	0.24	2.23	-2.23
0.31	0.29	1.50	5.21	0.17	0.55	0.33	3.04	-2.17
0.36	0.34	1.84	6.07	0.22	0.77	0.43	4.00	-2.07
0.42	0.40	2.23	7.16	0.29	1.06	0.56	5.17	-1.99
0.49	0.48	2.71	8.64	0.37	1.43	0.73	6.72	-1.92
0.58	0.59	3.30	10.67	0.49	1.92	0.95	8.78	-1.89
0.67	0.74	4.04	13.29	0.62	2.54	1.22	11.27	-2.02
0.78	0.92	4.96	16.64	0.80	3.34	1.55	14.38	-2.27
0.91	1.12	6.08	20.26	0.97	4.31	1.90	17.55	-2.71
1.06	1.30	7.39	23.55	1.14	5.44	2.21	20.50	-3.05
1.24	1.45	8.84	26.14	1.27	6.71	2.47	22.84	-3.30
1.44	1.53	10.37	27.64	1.34	8.05	2.61	24.15	-3.49
1.68	1.54	11.91	27.80	1.33	9.38	2.60	24.09	-3.71
1.95	1.48	13.39	26.74	1.26	10.65	2.47	22.83	-3.91
2.28	1.38	14.77	24.86	1.16	11.80	2.26	20.90	-3.96
2.65	1.25	16.02	22.64	1.03	12.84	2.02	18.66	-3.98
3.09	1.15	17.17	20.71	0.92	13.76	1.80	16.69	-4.02
3.60	0.79	17.95	14.20	0.61	14.38	1.19	11.06	-3.14
4.19	0.80	18.76	14.46	0.62	14.99	1.20	11.11	-3.35
4.88	0.94	19.69	16.90	0.73	15.72	1.41	13.10	-3.81
5.69	1.22	20.91	22.02	0.97	16.69	1.89	17.52	-4.50
6.63	1.70	22.61	30.64	1.40	18.08	2.72	25.19	-5.45

Drop size	Inlet			Outlet				Concentration difference
	Volume %	Cumulative	Concentration	Volume %	Cumulative	Concentration	Normalise	
Microns	%	%	ppm	%	%	ppm	ppm	ppm
7.72	2.41	25.02	43.48	2.05	20.13	3.99	36.92	-6.56
9.00	3.37	28.39	60.80	2.94	23.07	5.73	53.07	-7.72
10.48	4.54	32.93	81.92	4.05	27.12	7.90	73.11	-8.82
12.21	5.83	38.75	105.15	5.29	32.41	10.31	95.44	-9.70
14.22	7.08	45.83	127.78	6.48	38.89	12.64	117.00	-10.78
16.57	8.16	53.99	147.21	7.42	46.31	14.47	133.94	-13.27
19.31	8.99	62.98	162.32	7.91	54.22	15.42	142.76	-19.56
22.49	9.65	72.63	174.25	7.83	62.05	15.27	141.32	-32.92
26.20	8.80	81.43	158.75	7.20	69.24	14.03	129.88	-28.87
30.53	7.26	88.68	130.97	6.16	75.40	12.01	111.20	-19.77
35.56	5.36	94.04	96.66	4.96	80.37	9.68	89.60	-7.06
41.43	3.56	97.60	64.30	3.40	83.77	6.63	61.40	-2.90
48.27	1.91	99.51	34.51	2.09	85.86	4.07	37.72	3.21
56.23	0.49	100.00	8.81	1.12	86.98	2.19	20.27	11.46
65.51	0.00	100.00	0.00	0.50	87.48	0.98	9.03	9.03
76.32	0.00	100.00	0.00	0.17	87.65	0.33	3.05	3.05
88.91	0.00	100.00	0.00	0.02	87.67	0.04	0.36	0.36
103.58	0.00	100.00	0.00	0.00	87.67	0.00	0.00	0.00
120.67	0.00	100.00	0.00	0.00	87.67	0.00	0.00	0.00
140.58	0.00	100.00	0.00	0.00	87.67	0.00	0.00	0.00
163.77	0.00	100.00	0.00	0.00	87.67	0.00	0.00	0.00
190.80	0.00	100.00	0.00	0.00	87.67	0.00	0.00	0.00
222.28	0.00	100.00	0.00	0.00	87.67	0.00	0.00	0.00
258.95	0.00	100.00	0.00	0.00	87.67	0.00	0.00	0.00
301.68	0.00	100.00	0.00	0.13	87.80	0.25	2.30	2.30
351.46	0.00	100.00	0.00	0.74	88.54	1.44	13.30	13.30
409.45	0.00	100.00	0.00	2.10	90.64	4.09	37.90	37.90
477.01	0.00	100.00	0.00	4.09	94.72	7.97	73.80	73.80
555.71	0.00	100.00	0.00	5.28	100.00	10.29	95.22	95.22
Sum	100.00		1805.00	100.00		195.00	1805.00	249.63
					9.26		Overall efficiency	13.83

tration 1805ppm according to equation 2.10

$$NC_{on} = F \times 0.12 \qquad where\ F = \frac{1805}{195} = 9.26 \tag{2.9}$$

$$NC_{on} = 1.09ppm \tag{2.10}$$

The difference between the normalised outlet droplet size concentration 1.09ppm and the inlet droplet size concentration 3.21ppm are calculated as given in the equation 2.11.

$$\Delta = 1.09 - 3.21 = -0.12 \tag{2.11}$$

In this example the concentration difference between the inlet and the outlet droplet size is calculated for every single droplet size using the steps given from equation 2.7 to equation 2.11 If there is any coalescence happening in the fibres, the value of the concentration difference will be positive above the benchmark droplet size, if not it will be negative. For the sake of separation, the benchmark droplet size as 6 microns was identified. This is because the separators used in the experiments were capable of removing droplets above 6microns. The separators considered here are Hydrocyclones and Opus's Compact Floatation Unit.

From the Table 2.2 it can be seen that from droplet size of 48.27microns the concentration difference is positive. Therefore all the positive concentration above 6 microns are added together as given in the equation 2.12.

$$S = 3.21 + 11.46 + 9.03 + \ ... \ + 13.30 + 37.90 + 73.80 + 95.22 = 249.63 \tag{2.12}$$

Finally the overall efficiency for that trial run is calculated as given in equation 2.14

$$\eta = \frac{1805 - 249.63}{1805} \times 100 = 13.83 \tag{2.13}$$

$$\eta = 13.83\% \tag{2.14}$$

2.5.2 Area of the plot

Figure 2.10 shows an example graph of the oil droplet size concentration for both the inlet and outlet, based on droplet size range. Where the outlet droplet size concentration of the Mare's Tail exceeds that of the inlet, the area between both lines is calculated (e.g the light blue area, between droplet sizes 41.4 and 163.8 in Figure 2.10). This area can be said to be the coalescence efficiency of the Mare's Tail fibres.

Note that droplets below ~ 5 microns are not included in the area calculation because they can not be removed by the separation equipment downstream of the Mare's Tail. This is the reason why the smaller light blue area from droplet size 3.6 to 6.6 is ignored.

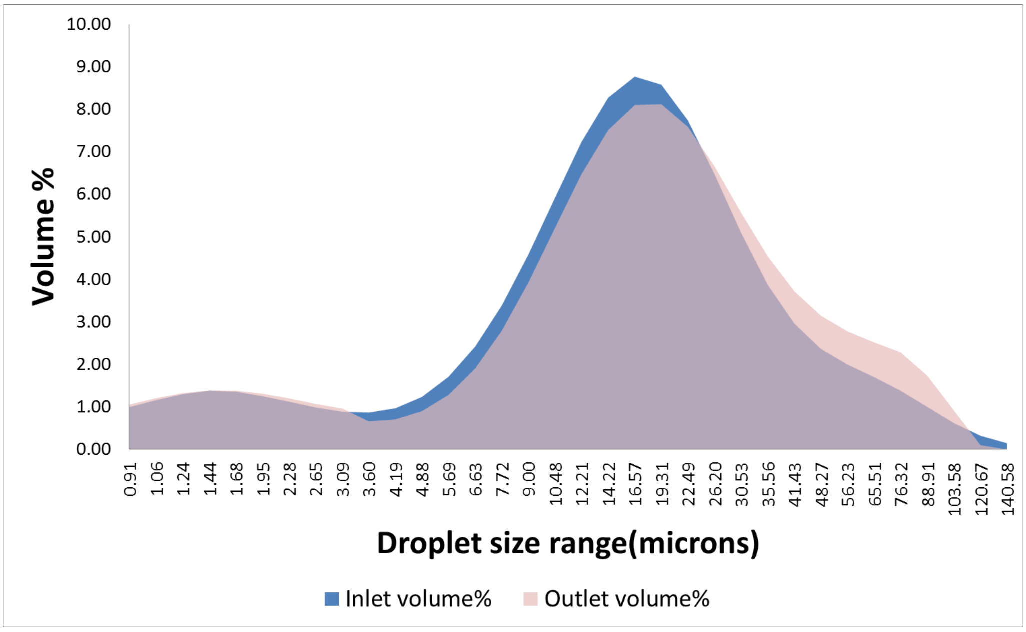

Figure 2.10: Inlet and outlet droplet distribution graph.

The downsides of this method is that it is time consuming to determine coalescence efficiency and that the available graph sheets can be inaccurate.

2.5.3 Weighing Area plot

This method is also using the graph of the inlet and outlet droplet size concentration, based on droplet size range shown in Figure 2.10. The area between the line for the Inlet Droplet Size and the outlet droplet size , from 5.69 to 26.20 for the inlet value and the area between both lines droplet sizes from 26.20 to 120.67 for the outlet value from Figure 2.10 are cut out of a printout or a graph sheet are subsequently weighted on a scale. If, W_i is the weight of the inlet area and W_o is the weight of the outlet area that exceeds the inlet area, then the coalescence efficiency can be calculated as follows:

$$Coalescence\ efficiency = (\frac{W_o}{W_i}) \times 100 \tag{2.15}$$

The downsides of this method is that it is time consuming to determine coalescence efficiency and that the available graph sheets can be inaccurate. Furthermore, a printer is not always available in a platform.

2.5.4 Trapezoidal method

Using the Trapezoidal method, the area under the curve is identified by using trapezoidal rule formula integration method (Atkinson 1989). This method was not continued due to the mathematical skills that an offshore analyser might require when the droplet measurement is taken offshore. Furthermore, this method only gives an approximation of the area under the curve.

2.5.5 Settling and Separation method

Settling and Separation is a traditional method where the samples of the inlet and outlet are collected at same time in a separating vessel. They are then allowed to settle for a specific period of time, say 30 seconds, and the samples from the bottom of the vessel are collected and their concentration is analysed. Finally, the coalescence efficiency can be calculated as follows:

$$Coalescence\ efficiency = \frac{(C_i - C_o)}{C_i} \times 100 \tag{2.16}$$

where C_i is the concentration of the inlet oil in ppm and C_o is the concentration of the outlet oil in ppm.

This method has several downsides:

- it is time consuming,
- an extra apparatus is needed,
- the results could potentially be inaccurate, if an inappropriate settling time is used,
- this method is not suitable for offshore trials because a test lab is required. Furthermore, if an equipment breaks, a replacement is not easily available on the oil platform.

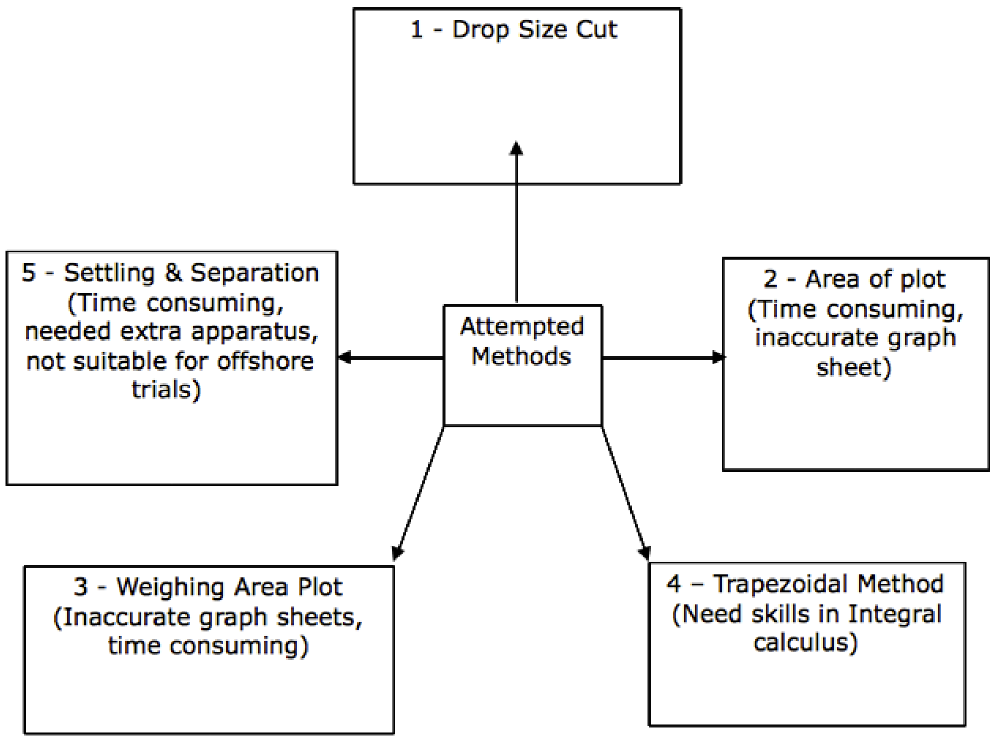

Figure 2.11: Five different methods to calculate coalescence efficiency.

2.5.6 Chosen Method

The five methods that were considered in order to measure the efficiency of the Mare's Tail are shown in Figure 2.11). Out of the those five methods, the Droplet Size Cut method was selected for two reasons. First, the level of technical skill required is lower and second, no extra equipment is required in the offshore platform and the coalescence efficiency can easily be calculated using an excel spread sheet. The equipment used for analysing the particle sizes are Malvern particle size analyser and Galai particle analyser.

Chapter 3

Development of Semi Emperical Model (SEM) to Predict the Separation and Coalescence Efficiency

A SEM was developed to calculate the coalescence efficiency of the Mare's Tail.

3.1 Coalescence and Separation Efficiency

Two types of efficiencies were chosen to quantify the performance of a coalescer: *coalescence efficiency* and *separation efficiency.*

3.1.1 Coalescence Efficiency

Coalescence efficiency is described by the growth of droplets from one size to another size. The coalescence efficiency in the fibrous coalescer is measured as the increase in concentration of the number of bigger droplets that are present in the outlet when compared to the intlet.

3.1.2 Separation Efficiency

Separation efficiency is described as the increase in the separation of oil from water by separation equipment, like hydro-cyclones or a compact floatation unit. A comparison was made between the separation efficiency with and without the Mare's Tail upstream.

3.2 Parameters

A number of parameters were grouped to be used in the SEM (some of which have already been mentioned in Section 2.4). The important parameters are, flow rate, viscosity, density, length of the fibre, porosity, Cumulative volume of produced water, inlet droplet size, Pack structure, Specific surface area of the media and oil, Density of fibre, Production time and spool and cartridge diameter. These parameters were chosen because they have been proved to have an effect in coalescence in the research conducted to determine the coalescence and separation efficiency by (Oyeneyin et al. 1992),(Li & Gu 2005), (Opus Plus Ltd 2005).

Flow rate q (Li & Gu 2005) Flow rate plays an important role in the coalescence of the oil droplets. When the fluid flows through the media they initially saturate the media with the oil droplets. It generally takes around 10 to 15 minutes for a complete saturation of the media. This saturation is based on the concentration of the oil droplets and the size of the oil droplets. The optimum flow rate is designed based on the velocity which is determined by the Spool section diameter. The maximum velocity at which the efficiency is achieved was identified as 0.4m/s from the experiments. Irrespective of the flow rate, if the maximum velocity is maintained at 0.4m/s, the turbulence in the fluid is reduced and the flow will be in the laminar to transient region. It is in this region that the flow rate improves coalescence. The flow rate was measured using a flow meter.

Spool diameter D_s (Li & Gu 2005) Spool diameter plays an important role in the design of the Mare's Tail. From the experiments it was found that for a given flow rate the maximum velocity in which the minimum acceptable efficiency achieved is 0.4 m/s.

Therefore to achieve the optimum efficiency, the diameter should be made smaller or bigger based on the flow rate and other pipe connections in the platform. The inner diameter of the spool is taken for calculation purposes.

Cartridge diameter D_c (Li & Gu 2005) The cartridge is the frame that holds the fibres in place for the coalescence to happen. They also help to insert the fibre into the spool section. Cartridge diameter used in the calculation is the diameter of the overall fibres enclosed within the cartridge and not the diameter of the ring in the cartridge.

Fluid density ρ_{fluid} (Li & Gu 2005) Density of the fluid plays a vital role in the coalescence and the separation process. It is because the higher the density difference between the oil and water the better is the coalescence. Fluid density in the efficiency calculation is the overall density of the fluid, which includes the density of the oil and water based on the oil concentration.

Fluid viscosity μ_{fluid} (Li & Gu 2005), (Oyeneyin et al. 1992) Viscosity of the fluid plays a vital role in the coalescence of the oil in the Mare's Tail type fibrous coalescer. It was identified from the KTP project experimental results that the higher viscous fluids have higher coalescence efficiency but lower separation efficiency.

Cumulative volume of produced water Q (Li & Gu 2005),(Oyeneyin et al. 1992) The cumulative volume of produced water is used to determine the total amount of fluid the media has handled as well as the deterioration rate of the media based on the fluid conditions.

Production time t (Li & Gu 2005),(Oyeneyin et al. 1992) Production time is the total expected time that the Mare's Tail will be used in the platform.

Length of the Spool L_s (Secerov Sokolovic et al. 2007) This is the total length of the spool from the fibre-holding flange to the outlet end of the Mare's Tail.

Porosity ϕ (Li & Gu 2005) (Oyeneyin et al. 1992) (Hong, Fane & Burford 2003) Fibre Occupancy or porosity relates to the amount of fibres that are present in the spool piece to coalesce the oil droplets. Porosity depends on the type of fibre that is being used, based on the fluid conditions in the offshore platform. The fluid conditions involve other parameters like viscosity, concentration, available pressure drop, oil and fluid density and flow rate.

Inlet oil diameter d_i (Li & Gu 2005), (Hetsroni 1982), (Secerov Sokolovic et al. 2007) This is the mean size of oil droplets ($D50$) in the produced water before entering the Mare's Tail. This is measured using the Malvern master sizer.

Inlet oil concentration C_i (Li & Gu 2005), (Hetsroni 1982), (Secerov Sokolovic et al. 2007) This is the concentration of the oil present in the produced water before entering the Mare's Tail. This concentration should also be checked in the outlet of the Mare's Tail to make sure that there is no accumulation of the oil or bulk release of the oil from the fibres in the outlet. The outlet droplet sizes of the Mare's Tail should be measured only when the inlet and the outlet concentrations are equivalent.

Density of polypropylene ρ_{pp} (Li & Gu 2005) The density of polypropylene is a measured value, which is available from the manufactures or the supplier.

Differential pressure across the Spool/cartridge ΔP (Li & Gu 2005), (Oyeneyin et al. 1992) Pressure drop plays an important role in the separation efficiency. This is because the equipment down stream of Mare's Tail requires a certain amount of pressure to do the separation process. This is an important process because the oil coalesced should be removed from the produced water to serve the purpose of this process. It is usually preferred to utilise the full system pressure to drive De-oiler Cyclones to maximise their oil recovery and throughput. In order to separate effectively, the fluid inlet pressure in the separator, like hydro-cyclone, should be above a certain limit that depends on the manufacturer. In order to maintain the high inlet pressure, the process equipment upstream of the hydro-cyclone should not create high pressure difference. Therefore it is important that Mare's tail does not produce high pressure drop, which would have an adverse effect on the separation of the oil down stream. Other than that, there should be a certain amount of pressure drop across the Mare's Tail spool to enable the residence time of the fluid/oil in the produced water to have contact with the fibre to aid coalescence. Pressure drop is generally measured closer to the inlet and the outlet end of the spool section.

Specific surface area of the media S_{pp} (Li & Gu 2005) This is the ratio of the surface area of the fibre to the total volume of the fibre used for the coalescence.

Specific surface area of the oil droplet S_{oil} (Li & Gu 2005) This is the ration of the surface area of the $D50$ of the oil droplets to the total volume of the oil in the produced water.

Pack structure B (Li & Gu 2005), (Oyeneyin et al. 1992) The pack structure is defined as the ratio of the fibre's surface area to the surface area of a sphere with the same volume.

Inter-facial surface tension γ (Oyeneyin et al. 1992), (Hetsroni 1982) Inter-facial surface tension is explained in Section 2.4.

3.3 Semi Empirical Model

All the above individual factors have been grouped into one SEM which is given in Equation 3.2 (See (Oyeneyin et al. 1992) and (Secerov Sokolovic et al. 2007)). The parameters were grouped using general dimensionless numbers using Reynolds number (Reynolds 1883) (Rott 1990), Kozeny-Carman equation (McCabe, Smith & Harriott 2005), modified Bond number (Clift, Grace & Weber 1979) and the other groups were arranged together as dimensionless numbers (Oyeneyin et al. 1992). The SEM was developed with the offshore test rig data and was equated to the hydro-cyclone efficiency as the dependent variable.

Using the Buckingham π theorem of dimensional analysis equation, efficiency of the Mare's Tail can be defined using individual groupings as follows:

n1 $= \left(\frac{D_s - D_c}{D_c}\right)^a$

n2 $= \left(\frac{\varphi}{(1-\varphi)\times S_{pp}\times B\times L_c}\right)^b$

n3 $= \left(1 - \left(\frac{C_i}{\rho_{pp}}\right)\right)^c$

n4 $= \left(\frac{S_{oil}}{S_{pp}}\right)^d$

n5 $= \left(\frac{\Delta P\times D_{pp}}{\gamma}\right)^e$

n6 $= \left(\left(1 - \frac{\rho_{pp}}{\rho_{fluid}}\right)\times\frac{D_c}{D_{pp}}\right)^f$

n7 $= \left(\frac{D_c}{d_i}\right)^g$

n8 $= \left(\frac{D_c\times\rho_{fluid}}{\mu_{fluid}\times q}\right)^h$

n9 $= \left(\frac{Q}{q\times t}\right)^i$

where $a, b, c, d, e, f, g, h,$ and i are empirical constants. [1]

All these groupings are then combined into one equation:

$$\eta_c = K \times n1 \times n2 \times n3 \times n4 \times n5 \times n6 \times n7 \times n8 \times n9 \tag{3.1}$$

$$\begin{aligned}\eta_c = K &\times \left(\frac{D_s - D_c}{L_c}\right)^a \times \left(\frac{\varphi}{(1-\varphi)\times S_{pp}\times B\times L_c}\right)^b \times \left(1 - \left(\frac{C_i}{\rho_{pp}}\right)\right)^c \\ &\times \left(\frac{S_{oil}}{S_{pp}}\right)^d \times \left(\frac{\Delta P\times D_{pp}}{\gamma}\right)^e \times \left(\left(1 - \frac{\rho_{pp}}{\rho_{fluid}}\right)\times\frac{D_c}{D_{pp}}\right)^f \\ &\times \left(\frac{D_c}{d_i}\right)^g \times \left(\frac{D_c\times\rho_{fluid}}{\mu_{fluid}\times q}\right)^h \times \left(\frac{Q}{q\times t}\right)^i \end{aligned} \tag{3.2}$$

where K is also an empirical constant.

Three different SEMs were developed in this work: Initial-SEM, SEM1 and SEM2. Each of them uses Equation 3.2 but a different set of Empirical Constants.

3.3.1 Initial-SEM

The first phase was to develop an initial-SEM using the existing data available from the previous research before KTP project. The working of the model and its accuracy of

[1] n1 $= \left(\frac{D_c}{L_c}\right)\times\left(\frac{D_s - D_c}{D_c}\right)$ Until the fine tuning of the SEM2 these two enities were used for all 3 models, therefore except for revised SEM2 there were 10 dimensionless groupings for Initial SEM and SEM1

prediction was tested through stochastic analysis. This initial model was able to predict the separation efficiency, but the confidence of determination was only around 60%. Also, this model was not trusted to predict the coalescence efficiency because the datasets used to develop it were taken from the offshore test results of a hydrocyclone with the Mare's Tail. These results only contained the separation efficiency with and without Mare's Tail but not the information about droplet sizes growth which would be necessary to determine the coalescence efficiency.

3.3.2 SEM1

There was a lack of available complete data sets due to a low amount of tests having been conducted before the KTP project started.Therefore more tests were designed to improve the prediction accuracy using the previously obtained stochastic analysis from the initial SEM. These experimental tests involved variation in velocity, fibre length, temperature, concentration, fibre type and effect of cartridge in coalescence. The results were used, in conjunction with the already available previous results to generate the empirical constants which were then used to develop a new SEM referred to as SEM1. The empirical constants are given as follows K = -34.2, a = -13.1, b = -0.99, c = 7.78, d = 68, e = -0.084, f = 0.153, g = -3.1, h = -1.05, i = -0.738, j = 0.391,

SEM1 is used to calculate the separation efficiency of the hydro-cyclone with Mare's Tail. It has a better performance than the initial-SEM.

3.3.3 SEM2

The Drop Size Cut method explained in Section 2.5.1 was used to determine the coalescence efficiency of the Mare's Tail without the hydro-cyclone. A set of further experiments was also conducted in order to get the required droplet size information. The results were then used to generate another set of empirical constants. These constants are given as follows. K = -15.505, a = -0.826, b = 0.0021, c = -83, d = 0.1439, e = -0.1353, f = -1.598, g = 1.0991, h = 0.1336, i = 0.2176. these constants in the SEM2 are used to calculate the coalescence efficiency of Mare's Tail.

Chapter 4

Experiments, Results and Discussions

The Semi empirical models (See Chapter 3) for the Mare's Tail were developed and tested and their working boundaries were investigated. In order to achieve this, two sets of experiments were conducted. The first set of experiments was conducted to test the parameters for the models, the second set of experiments was conducted to develop and testSEM1 and SEM2. Finally, the predictions of the chosen SEM were analysed and compared with the real world observations. This chapter will first describe the experiments which were conducted and will then present the results and observations which were made in the process.

4.1 Experimental set up description

In all our experiments sea water was first filtered through the filtration vessel, to avoid the growth of shell fish and other organisms in the pipe section, and then pumped into the Mare's Tail set up. The temperature of the sea water was noted daily while the tests were running. The crude oil, which was used in the test, was taken from the Talisman oil terminal in Flotta. The density of the crude oil is shown in Figure 4.1.

Oil is injected into the flow line with an oil injection pump which is a positive displacement pump. The volume of oil injection can be varied by adjusting the length of the pump

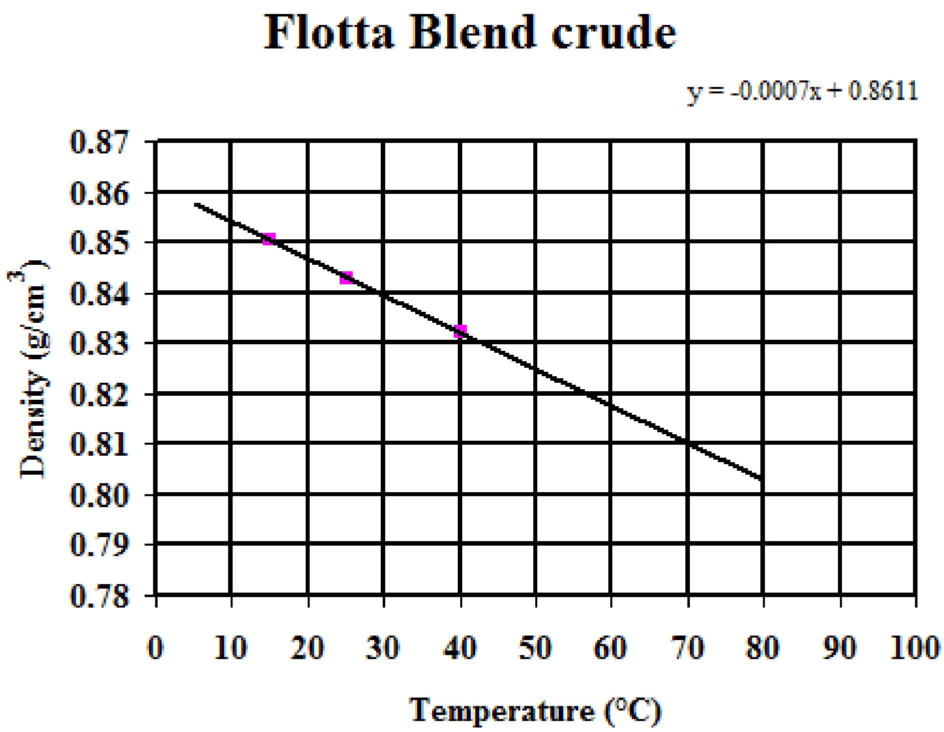

Figure 4.1: Flotta crude density.

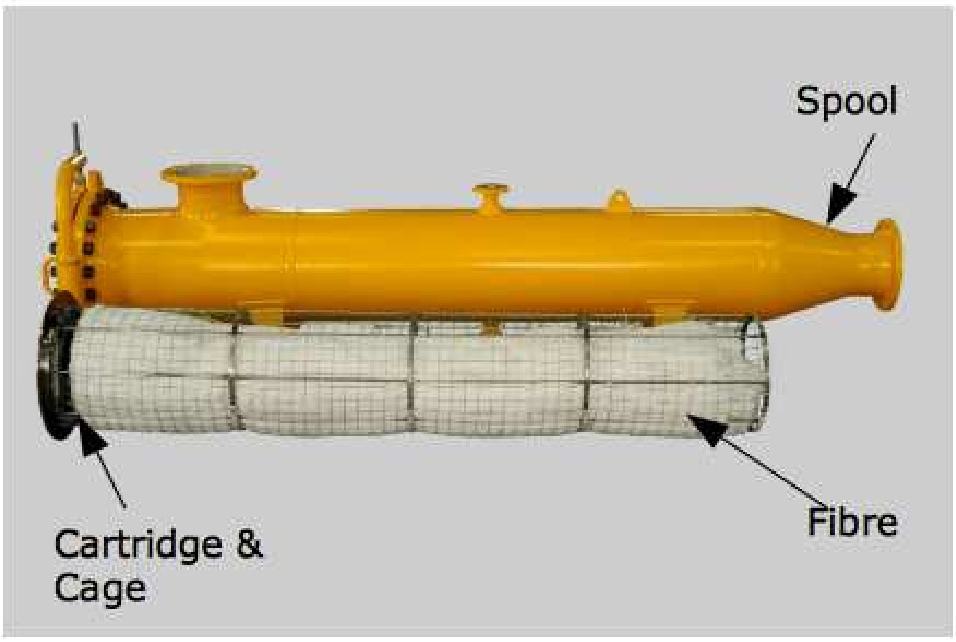

Figure 4.2: Mare's Tail spool, cartridge and fibre arrangement.

axis. As shear valve, a Caboc valve is used to shear the oil droplets to any particular D50 range and mix the oil with the seawater. The Mare's Tail (See Figure 4.2) is the equipment for which the coalescence efficiency is to be identified. Three different Mare's Tail spools were used in the experiments: 2", 4" and 6" . An extra pump and sea water tank were added to the experiment set up to conduct high velocity and high flowrate. There are two sampling points: one in the inlet and the other in the outlet. During the initial experimental period a sample bomb was attached to the inlet and the outlet of sample point to check the consistency of the D50 of samples. At the later stage due to the offshore work in the company the sample bombs were taken offshore frequently so the later experiments,where the coalescence efficiency was determined were conducted without the sample bomb. Due to tough time constraints this decision was made by the supervisory team insisting in not delaying the experiments by waiting for the sample bomb. The sampling points are used to collect samples to measure the concentration and droplet size. The concentration of the oil water mixture is measured regularly until it is within an appropriate stable region. The concentration of each of the oil in the water samples taken during the experiments was measured using Infrared Spectroscopy. Prior to these measurement the oil in each of these samples had to be solvated in Tetrachloroethylene (TCE). The samples to be measured were taken in a measuring jar, which is three fourth filled with distilled water, in order to stabilise the oil droplets from coagulating. This sample is then sent through the Malvern master sizer immediately to analyse the D50 and the volume percentage of the droplet size ranges.

A visual observation section, which is a cylindrical glass tube attached in the downstream of the Mare's Tail, was used to visually observe the size and the nature of the droplets during their flow in the spool section. A Malvern master sizer was used to analyse the size of the droplets in both the inlet and the outlet of the Mare's Tail, which was necessary to calculate the coalescence efficiency. A Compact Floatation Unit (CFU) and a hydro-cyclone separator were used downstream to the Mare's Tail to identify the separation efficiency. The CFU was used for high volumetric flow rate tests, which were conducted with a 6" spool section. The hydro-cyclone was used in the experiments conducted with the 2" spool sections. The parameters that were varied for the experiments are the length and number of strands of the fibres, fluid velocity, concentration of the oil and oil droplet sizes.

The length ranged from 1m to 1.9m. The number of fibres was varied from 500 to 5700 for 2" to 6" Mare's tail spool. Velocity ranged from 0.15m/s to 0.8 m/s. Concentration was tested between 150ppm and 500ppm. Oil droplets sizes were varied between 5 microns and 56 microns.

4.2 Testing initial parameters

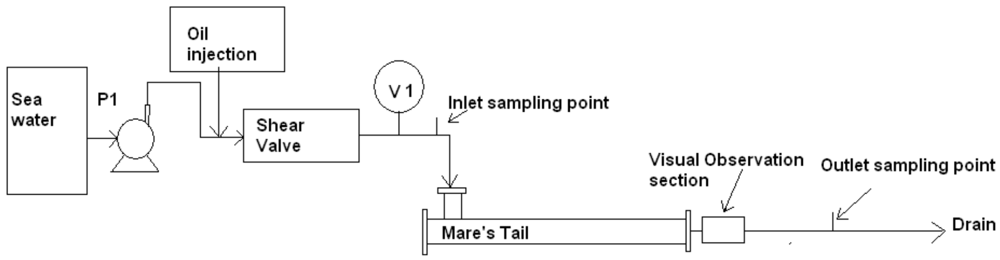

Figure 4.3: Mare's Tail experimental set up to identify the basic parameters.

The basic parameters which have an effect on coalescence were identified using the Mare's Tail experimental set up shown in Figure 4.3, where V1 is a flow meter measured in m^3/hr and P1 is a pump.

4.3 Experiments to develop and test the SEM

The effect of different diameters of Mare's Tail on the coalescence efficiency was investigated using the the experimental set up shown in Figure 4.4. The test conditions that were used for the two 2" Mare's Tail and one 4" Mare's Tail were maintained to be constant with the experimental process.

The experimental setup shown in Figure 4.5 was used to investigate whether the internal component, the cage of the cartridge present in the Mare's Tail, has an effect on the coalescence or the separation efficiency of the Mare's Tail.

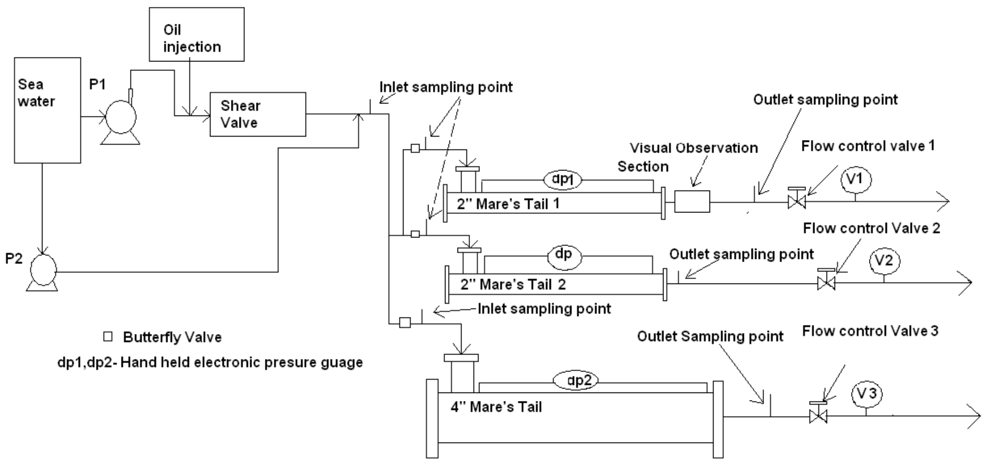

Figure 4.4: Mare's Tail experimental set up to develop and test the model for different diameters.

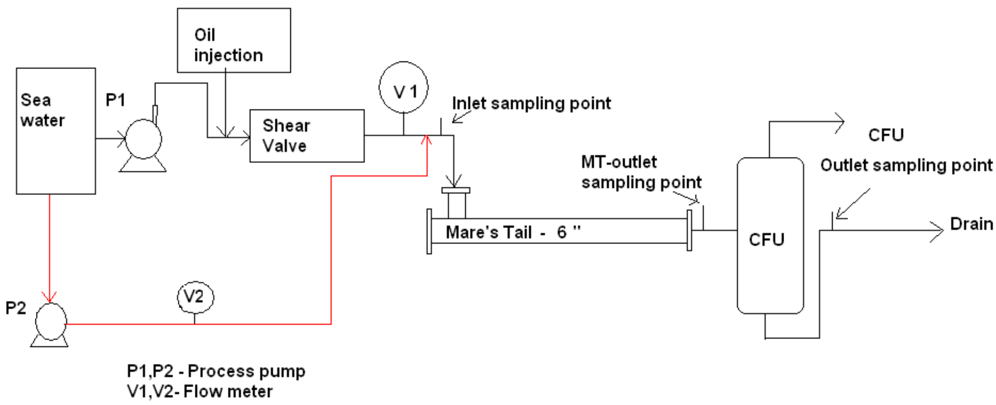

Figure 4.5: Mare's Tail experimental set up to test the impact of the cage on the coalescence or separation efficiency.

4.4 Results of experiments conducted

A number of factors were tested in the experiments: velocity, length of fibre, concentration, temperature, fibre type, the effect of using a cartridge cage as well as the impact of woven fibres.

4.4.1 Velocity

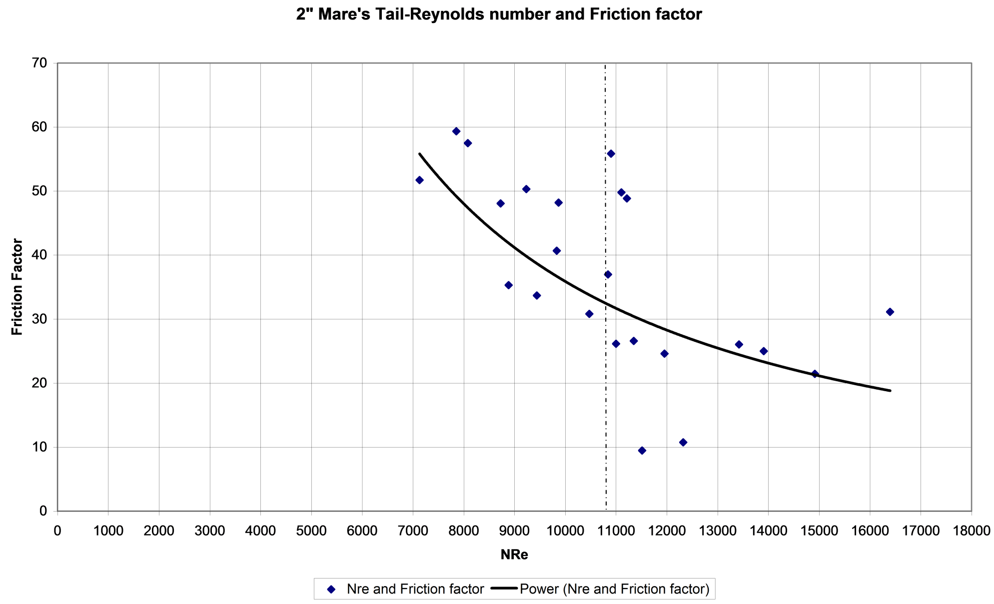

Figure 4.6: Graph of Reynolds number and friction factor.

The fluid velocity has a major impact on the coalescence of the droplet sizes. The lower the velocity the higher the coalescence. This is because of the higher residence time available for the oil droplets to have contact with the fibres to coalesce. These are early graphical data for familiarisation and operational experience. In a porous bed coalescer filter, increase in velocity increases the effluent concentration therefore it decreases the coalescence efficiency (Secerov Sokolovic et al. 1997). Figure 4.6 plots the friction factor against the Reynolds Number for a 2" Mare's Tail while Figure 4.7 plots the efficiency against the Reynolds Number, also for 2" Mare's Tail. Both these figures show that an increase in velocity (and as such an increase in the Reynolds Number) reduces the friction factor which in turn reduces the fibre oil contact and the efficiency.

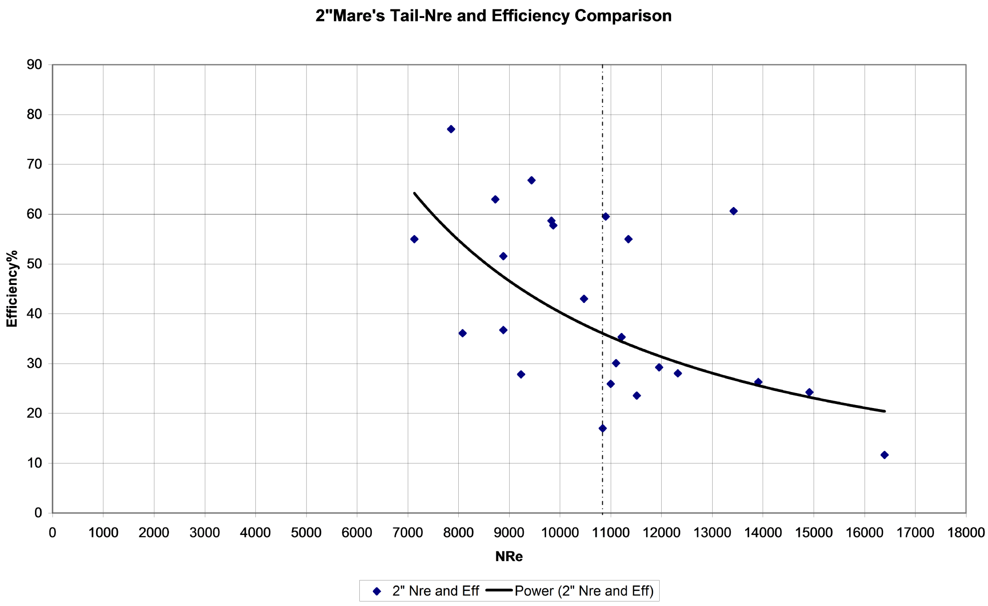

Figure 4.7: Graph of Reynolds number and Efficiency profile.

4.4.2 Length

It was identified that there are limits in the length of the fibre media. Initially, it was understood that an increase in the length of the fibre media will increase the size of the outlet drop size and thus increase the coalescence efficiency. The experiments proved that the coalescence efficiency increased with the increase in length up to a critical point as shown in Figure 4.8. Beyond this critical point, increase in length decreases coalescence efficiency. Even though there are only two length comparisons in the Figure4.8, it still proves that there is a critical length beyond which the fibre length should not be reduced or increased. The decrease in coalescence efficiency beyond the critical length could be due to the shearing of the droplets after growing to a particular size. At this critical length, the maximum efficiency is achieved. There is another factor that governs the critical length, which is the porosity of the fibre. The existence of the critical point was identified only using a 2” spool, with two fibre length for poly propylene fibres. It is expected that a different critical length exists in other spool diameters as well as other fibre material, however it was not possible to test this hypothesis due to restriction in the spool length for other diameters and availability of huge quantity of different fibre material.

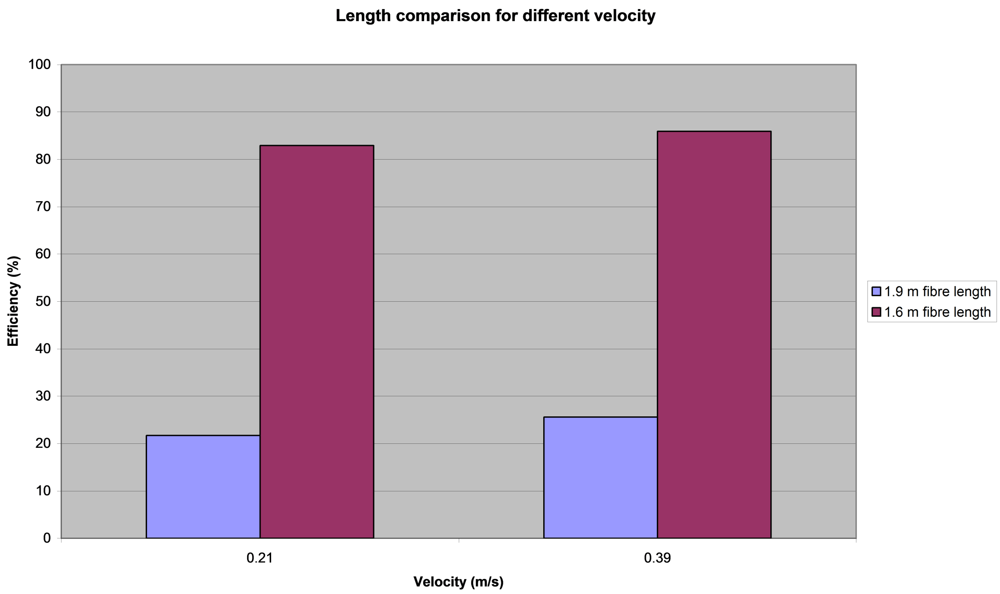

Figure 4.8: Length comparison for different velocities compared with coalescence efficiency.

The tests were repeated to reconfirm the data, and the results were reproduced. This could be due to the inner arrangement of the fibres which has pores within the fibres that allows the cross flow filtration. The separation efficiency was not affected by the afore mentioned critical length. Previous research conducted before the start of the KTP project shows that increase in length beyond the critical point leads to a slight increase in separation and flattens down further as shown in figure 4.9 (Environmental Resource Ltd 2000).

4.4.3 Concentration

Figure 4.10 shows that as the concentration decreases, the coalescence efficiency increases. When the concentration is high, the droplets in the inlet are generally larger in size due to pre-coalescence of the droplets before contacting the fibres. Therefore the coalescence efficiency decreases as there will not be a significant size increase of the droplets in the outlet of the Mare's Tail. When the concentration is low, the droplet sizes in the inlet are generally smaller in size and they tend to grow into bigger droplets in the outlet and the relative coalescence efficiency is increased.

Figure 4.11 states that, as the concentration decreases the separation efficiency also

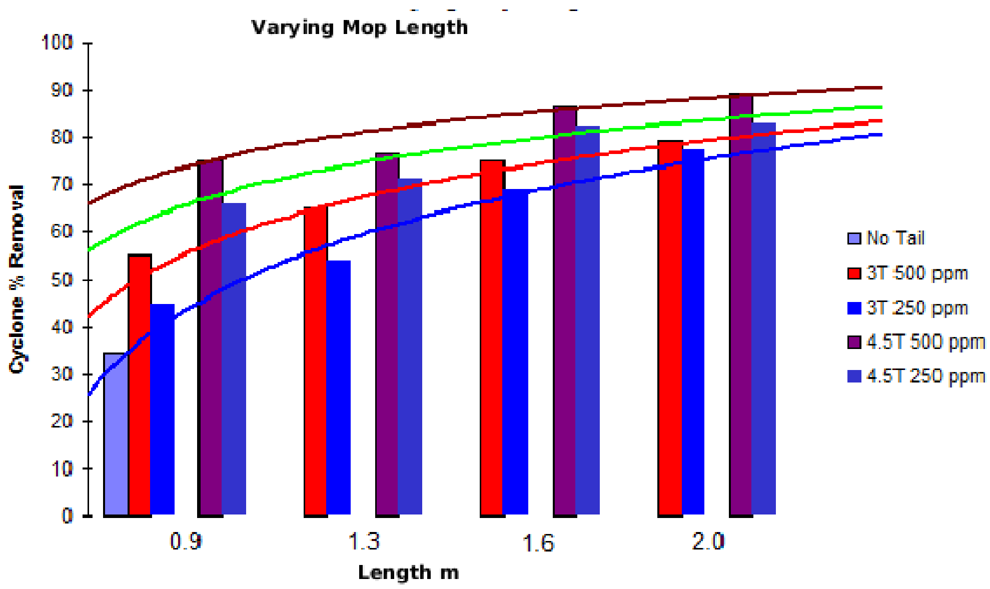

Figure 4.9: Effect of length on separation efficiency.

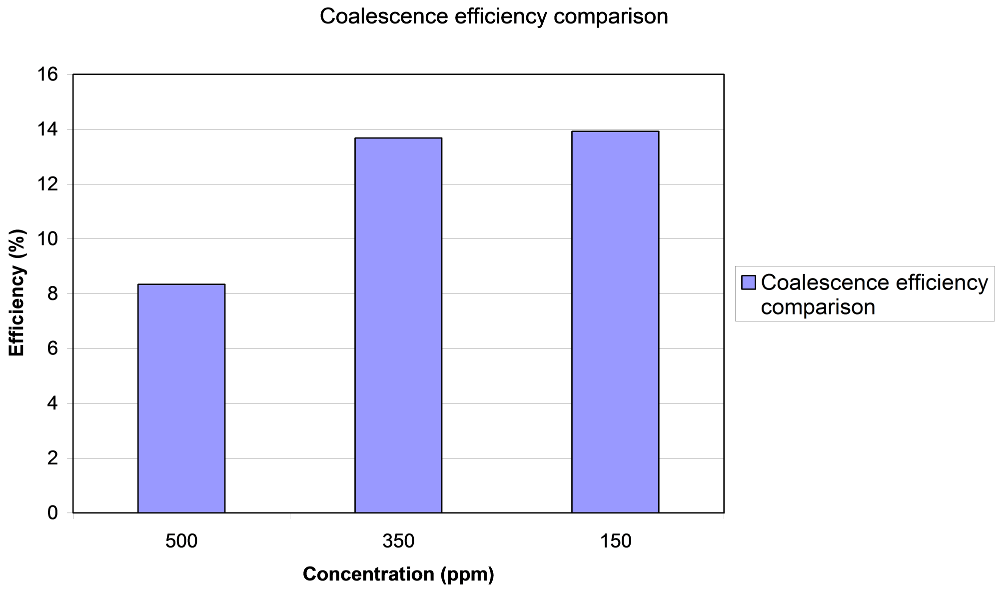

Figure 4.10: Coalescence efficiency variation due to concentration.

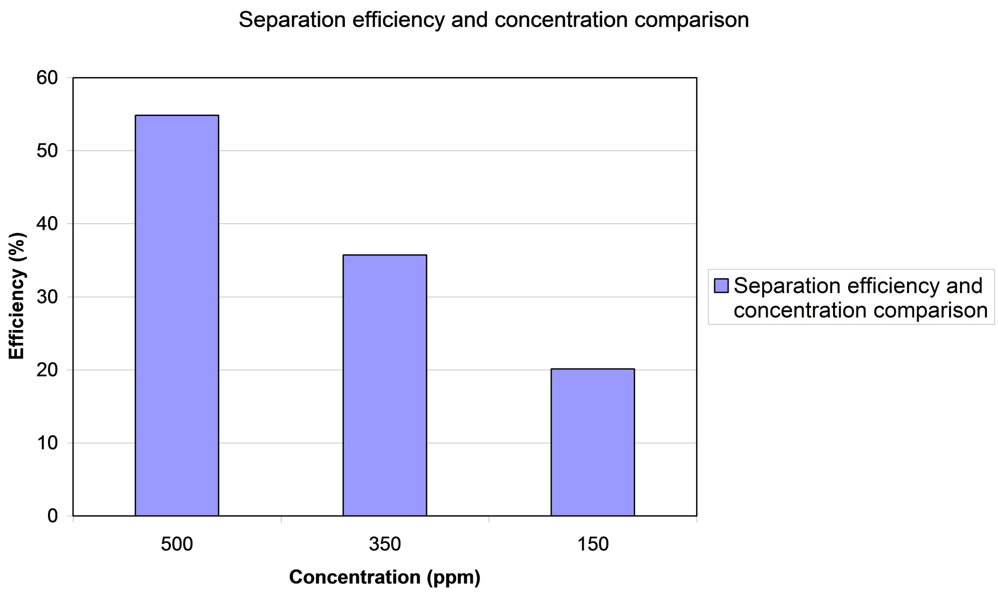

Figure 4.11: Separation efficiency variation due to concentration.

decreases. This is because, when the concentration is high, even at the higher shear position of the Caboc valve the droplet starts to coagulate even before the reaching the Mares Tail. This was determined by measuring the droplet size using a Malvern Master sizer. Since the majority of the droplets have coagulated to a bigger size, only a small quantity of the smaller droplets requires the help of the Mares Tail to grow bigger. Therefore most of the oil droplets are in a separable size range and hence increases the separation efficiency. On the other hand when the concentration is low the coagulation of the droplets before entering the Mares Tail doesnt take place. The separation efficiency is highly dependent on the Mares Tail in coalescing all of the tiny droplets. As Mares Tail doesnt yet have the potential to coalesce all oil droplets smaller than 2microns most of the oil droplets smaller than 2microns tend to escape from coalescing and hence escape from getting separated. This phenomenon decreases the separation efficiency of the Mares Tail when the concentration decreases. Finally, a comparison of Figure 4.10 and Figure 4.11 shows that there is an inverse relationship between coalescence efficiency and separation efficiency.

This means that either way, the Mare's tail can handle both high and low oil concentration by producing bigger oil droplets to be easily removed by the separation equipment downstream. However the coalescence efficiency of the Mare's Tail increases if the oil

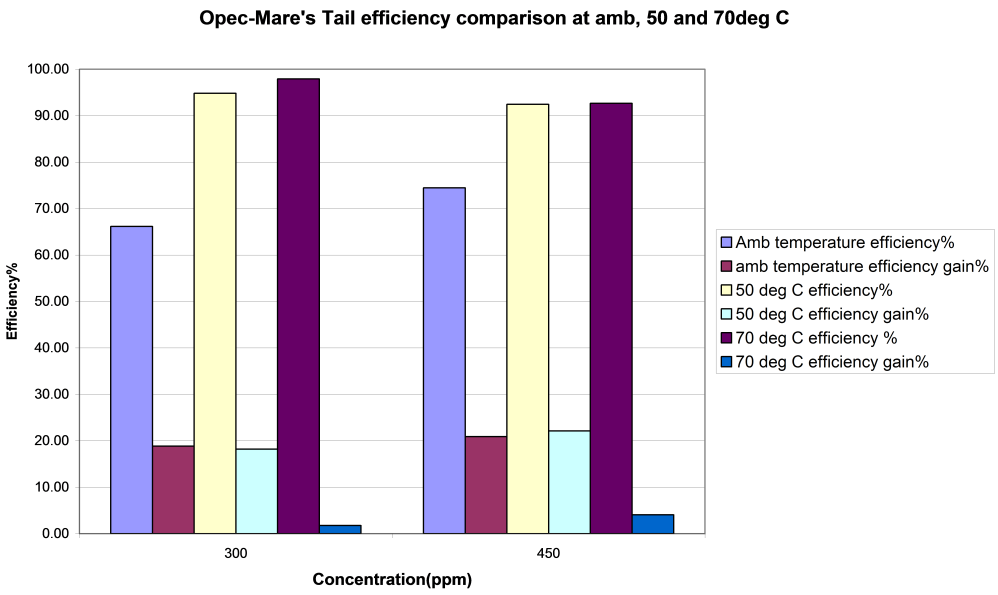

Figure 4.12: Separation efficiency and efficiency gain at $15°C$, $50°C$, $70°C$. Amb temperature refers to he ambient temprature, the temperature of the sea water, which was $15°C$.

droplets are of lower concentration, which make it an ideal equipment for produced water treatment.

4.4.4 Temperature

The effect of the temperature was tested with the Flotta crude oil with a hydro-cyclone downstream. The temperature was varied from $15°C$, $50°C$ and $70°C$. Figure 4.12 shows the efficiency and efficiency gain under the three different temperatures using two different concentrations ($300ppm$ and $450ppm$). Here, $efficiency\ gain$ is a measure indicating how much more efficiency is gained from a separation equipment with and without the use of Mare's Tail. It is defined as:

$$efficiency\ gain = efficiency_{with\ Mare's\ Tail} - efficiency_{without\ Mare's\ Tail} \tag{4.1}$$

It can be observed that as the temperature increases, the separation efficiency gain decreases while the separation efficiency increases.

Although the above test was done with temperature variation, the main parameter that was affected by the temperature was the viscosity and density of the oil. As the temperature increases, the density difference between the seawater and oil increases and the viscosity difference between the seawater and the oil decreases. At an increased temperature, the heavy oil viscosity can be reduced significantly, especially at a high asphaltene content (Luo & Gu 2007). This makes it easier for the separation equipment to the separation very easily with less or no influence of the Mare's Tail, however using a Mare's tail still improves the performance of the separation equipment. Future work could be performed in understanding the benefits of Mare's tail with different oil types with different concentration.

Figure 4.12 also states that when the temperature was increased, there was no significant improvement in the Mares tail performance at 70°C. So there exists a point somewhere between 50°C and 70°C where the Mares Tail would not make much difference. Even though this experiment was conducted with only one type of fibre material, which is the traditional fibre material used for the Mares Tail, the opportunity to test other filter media or to know whether this phenomenon exists in all fibre material was not achievable due to time restrictions of the project. Therefore in future several other fibre materials should be tested and compared to determine the optimum temperature that the Mares Tail could be used for a particular fibre and to check whether this is the case with all fibre material.

Figure 4.13: Microscopic image of the Polyester fibre which has high surface area.

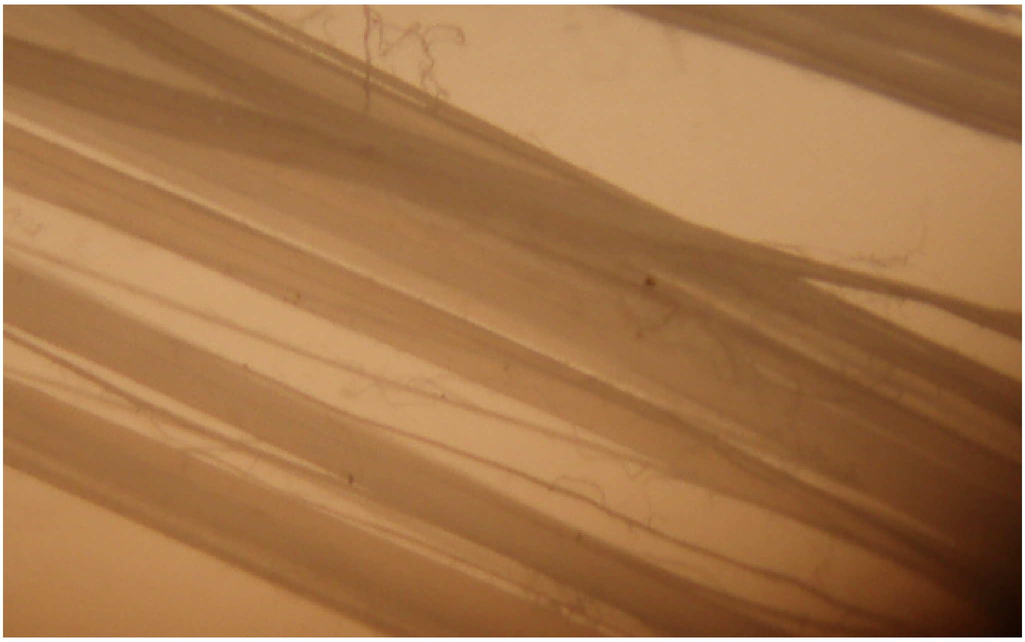

Figure 4.14: Microscopic image of a Polypropylene fibre which has low surface area.

4.4.5 Fibre type

The fibre type is an important factor which helps study the performance of different fibres in coalescence (Kulkarni, Patel & Chase 2012). Different fibres available in the market were compared based on performance. The performance depends on factors like inter-facial surface tension between the fluid and the fibre, surface area and surface energy of the fibres. There were two types of fibres used for testing: polypropylene and polyester. The surface energy of the polypropylene was lower than that of the polyester, where as the inter-facial surface tension between polypropylene and oil was slightly higher than the inter-facial surface tension between polyester and oil. The values of surface energy and inter-facial surface tension are not revealed in this work due to information protocol restrictions. Both, coalescence and separation efficiencies were recorded for polyester as well as polypropylene.

The polyester (45mN/m) (See Figure 4.13) has higher surface area than the polypropylene (31.7mN/m) (See Figure 4.14), therefore the coalescence and the separation efficiency of the polyester was higher than that of the polypropylene. This shows that the surface area has more influence on the efficiencies than the surface energy.

Figure 4.15 plots the efficiency gain against the concentration for both Polyester and Polypropylene. It shows that for Polypropylene, if the concentration decreases, the separation efficiency will decrease as well.

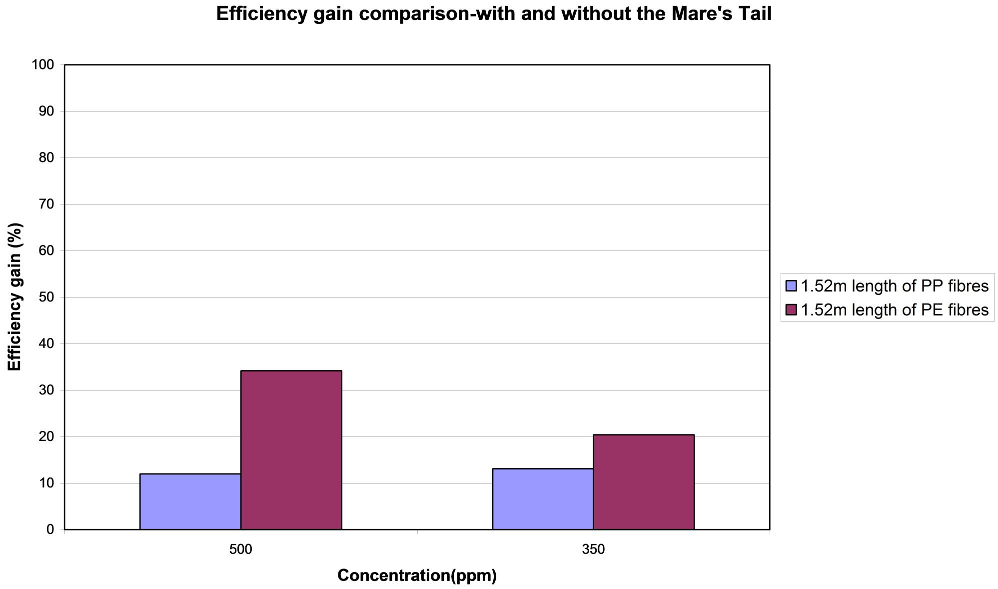

Figure 4.15: Efficiency gain comparison between Polypropylene (PP) and Polyester (PE).

4.4.6 Effect of the cartridge cage in coalescence and separation efficiency

The cartridge cage is the metallic structure that helps in inserting the fibres to the spool section. It was tested with the 6" spool using the experimental set up shown in Figure 4.5. The results showed that the use of the cartridge cage did not affect the separation efficiency but did affect the coalescence efficiency.

Figure 4.16 plots the separation efficiencies and droplet sizes, for tests with and without the cartridge cage, against the concentration. It shows that the separation efficiency between the different concentrations remain almost the same, if a cage is used or not. However the droplets from the outlet of the Mare's Tail always remained bigger in the trials without the cage when compare with the trials with the cage. Thus the coalescence efficiency is affected by the cage. This means that there is a possibility of the droplets getting sheared and or the fibres being restricted by the cage from spreading around the internal spool cross sectional area. The restriction in the fibres might lead to oil droplets

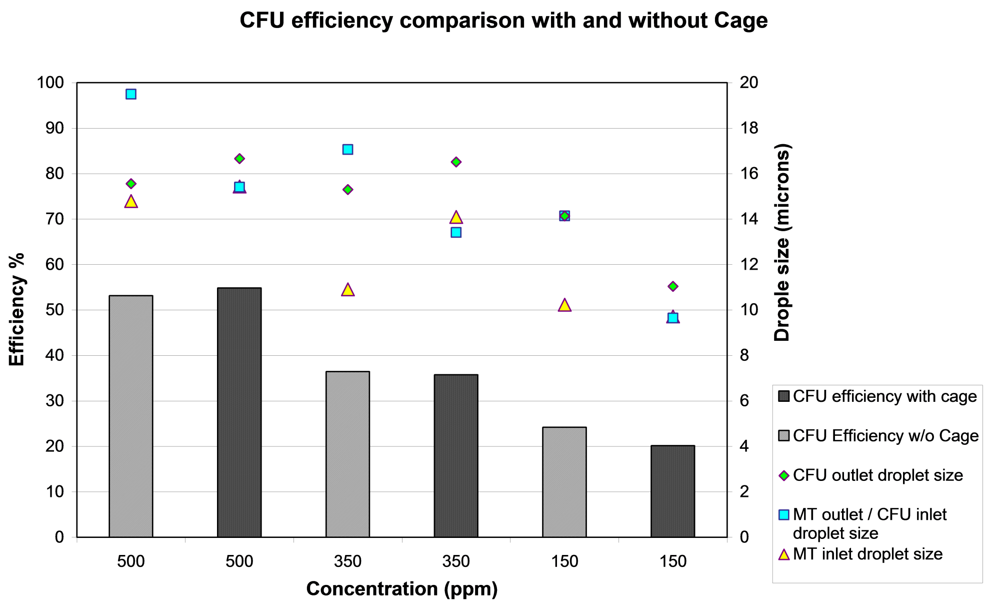

Figure 4.16: CFU Separation efficiency comparison; with and without cage.

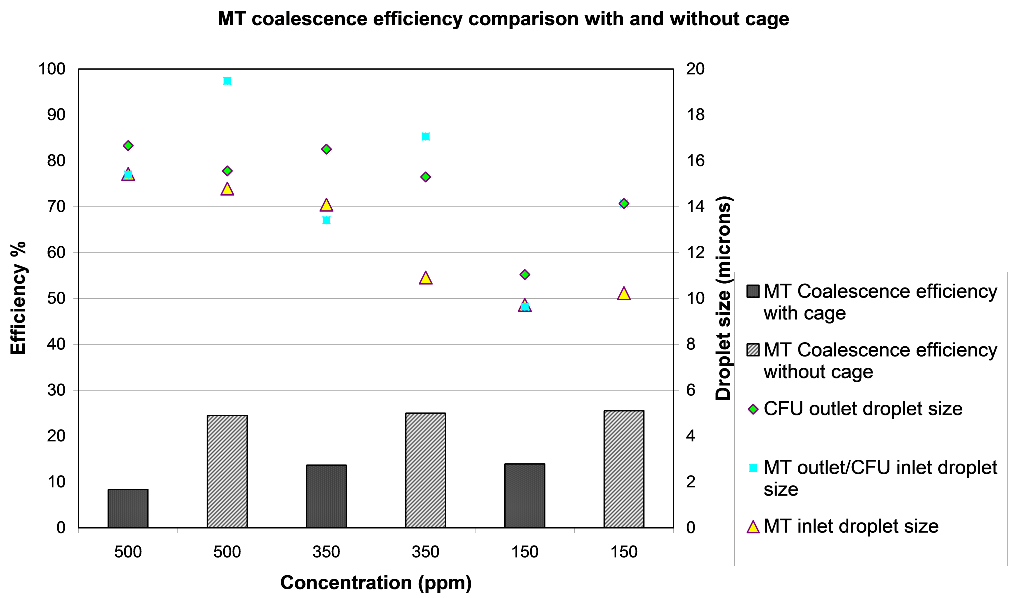

Figure 4.17: Mare's Tail Coalescence efficiency comparison; with and without cage.

escaping without being coalesced.

Figure 4.17 plots the coalescence efficiencies and droplet sizes, for tests with and without the cartridge cage, against the concentration. It shows that the droplet size in the outlet of the Mare's Tail is always higher in the experiments conducted without the cage.

Thus coalescence efficiency is increased when the cage is not used. However the important function of the produced water treatment process is removal of oil from the produced water. The separation of oil from water is done by hydro-cyclones or compact floatation units. As separation efficiency is more important than the coalescence efficiency, it was concluded that the use of cage does not affect the oil removal of the separation equipment downstream of the Mare's Tail.

4.4.7 Woven Fibers

An experiment was conducted to find whether the coalescence efficiency is improved by the use of woven fibres. Its was not possible to get any results from this set of experiments as the high density of the fibres in the spool section almost clogged the flow. Some of the experiments showed that the droplet size in the outlet of the Mare's Tail were smaller when compared to the inlet. This could be due to shearing of droplets. As the pressure drop across the spool region was at least 5bar, for an inlet pressure of 5.51bar, using a separator to quantify the efficiency was not feasible. Therefore no results from set of experiments were not taken into the development of the semi empirical model.

4.5 Model Prediction Analysis

An analysis was conducted to investigate the predictive accuracy of the SEM model. A number of different variables were tested.

Using spreadsheets, each of the variables were in turn iterated in between reasonable minimum and maximum values, while all other variables in the model were kept constant. Only one variable was changed for each set. This way it was possible to investigate the precise influence of each of these variables on the resulting efficiency. The variables investigated are:

- length of fibre,
- pack structure,
- porosity,

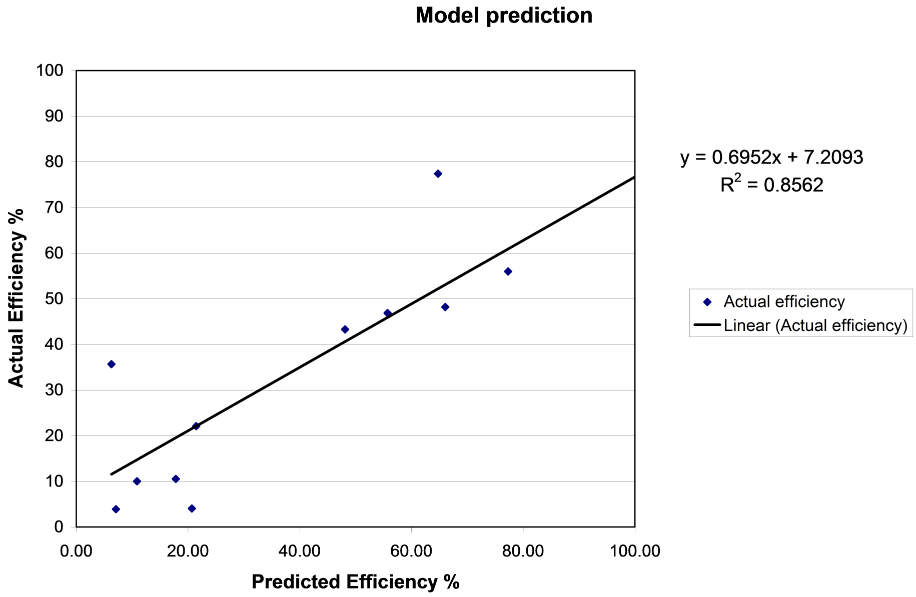

Figure 4.18: Comparison between predicted separation efficiency and actual separation efficiency using SEM1.

- concentration,
- velocity.

4.5.1 Choosing the appropriate SEM

In this work, two different SEMs have been developed: SEM1 (See Section 3.3.2) gives the separation efficiency and SEM2 (See Section 3.3.3) gives the coalescence efficiency. SEM1 was developed using the trial test on the offshore oil platform as well as in-house experiments in which the hydro-cyclones and compact floatation units were used. SEM2 was developed using the experiments conducted only with the Mare's Tail, without the separation equipments.

Figure 4.18 plots the Actual Separation Efficiency against the Predicted Separation Efficiency while Figure 4.19 plots the Actual Coalescence Efficiency against the Predicted Coalescence Efficiency. Figures 4.18 and 4.19 show that the confidence of determination of the variables for both SEM1and SEM2 were high. This indicates that all the variables that are used in the model have an impact on both the SEM1 and SEM2. Among the two models, the coalescence efficiency model SEM2 was preferred, as it solely represents the

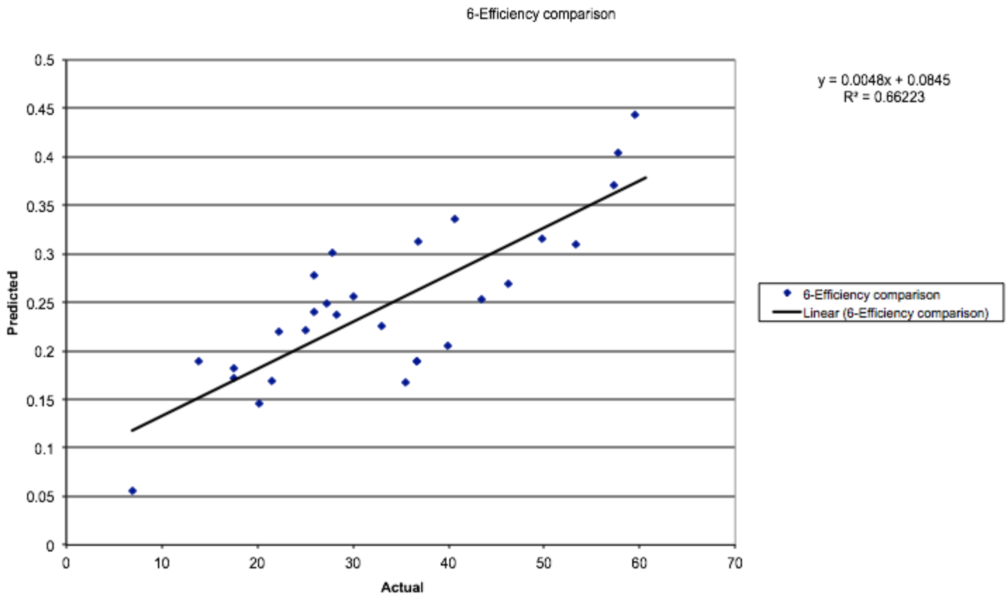

Figure 4.19: Comparison between predicted coalescence efficiency and actual coalescence efficiency using SEM2.

performance of the Mare's Tail without the influence of any separation equipment down stream.

4.5.2 Length of fibre

The analysis of the length of the fibre has shown that as the length of the fibre increases, so does the efficiency. However there is a *critical length* for every individual spool diameter, at which the efficiency peaks at a maximum value. If the length of the fibre is increased beyond its critical length, then the efficiency decreases gradually. This behaviour can clearly be seen in Figure 4.20, plots the efficiency against the the fibre length for three different spool diameters.

4.5.3 Pack structure

Figure 4.21, which plots the efficiency against the pack structure, shows that up until the critical point, the relationship between pack structure and efficiency is similar as that between length of the media and efficiency: if pack structure increases, so does the efficiency. However beyond the critical point, the efficiency drops drastically with just a

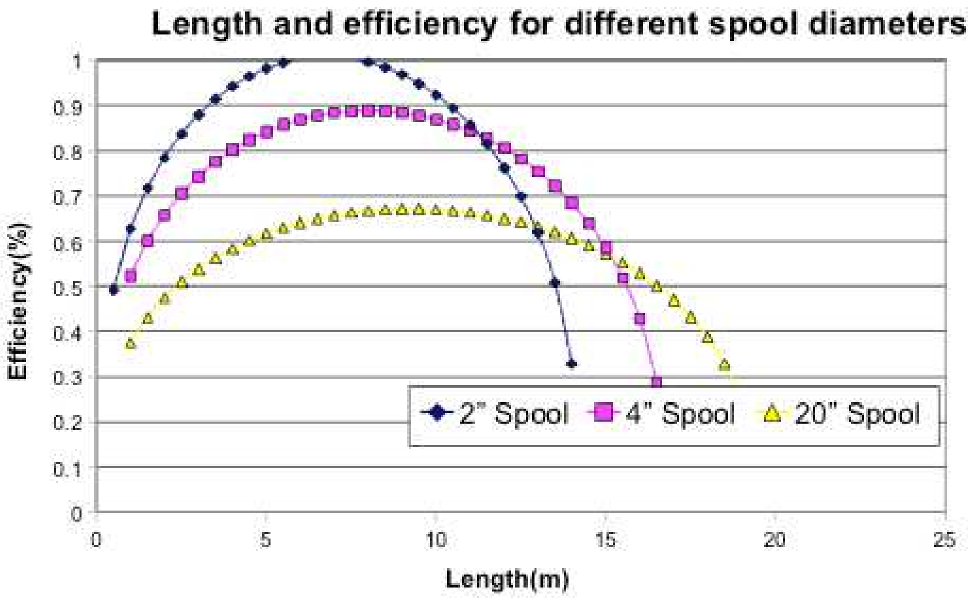

Figure 4.20: Length and efficiency of different spool diameters.

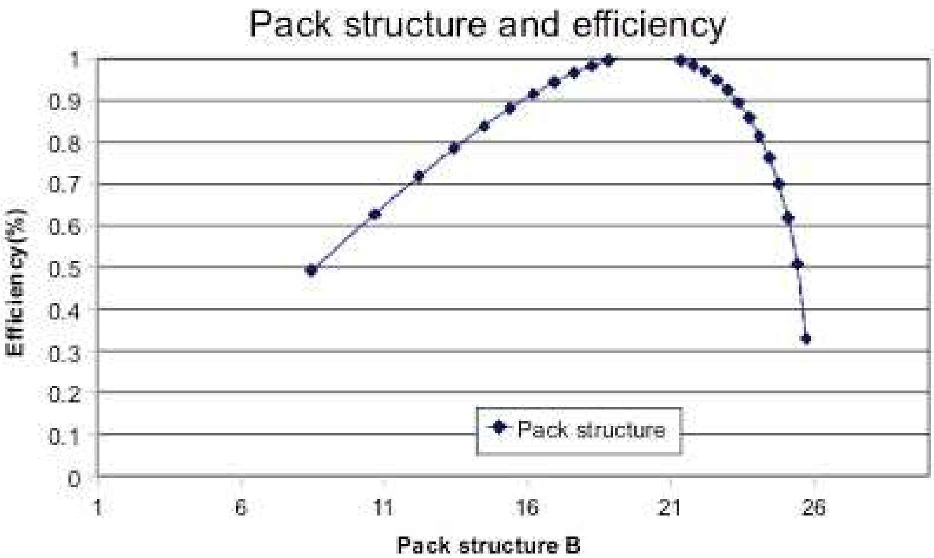

Figure 4.21: Pack structure and efficiency.

little increase in pack structure. This is different from the length of the media, where an increase will only cause a gradual decrease in efficiency.

4.5.4 Porosity

The efficiency of the media decreases with an increase in porosity. However this does not mean that efficiency will increase with lower porosity. As this porosity is based on the cross sectional occupancy of the fibres, there is an optimum length for the total number of strands used in the spool and the porosity incorporates both length and the total number of fibre. As the analysis performed allowed for only one single parameter to be varied at a time, the effect of the number of strands and that of the length of the fibre have to be analysed separately: Figure 4.22 shows the relationship between efficiency and the *Number of strands Porosity* and Figure 4.23 shows the relationship between efficiency and the *Length Porosity.* Notre that the influence of combinations of both length of fibre and the total number of strands could only be analysed at a later stage, using the Mare's Tail Optimisation Software which will be introduced in Section 4.6 page 56.

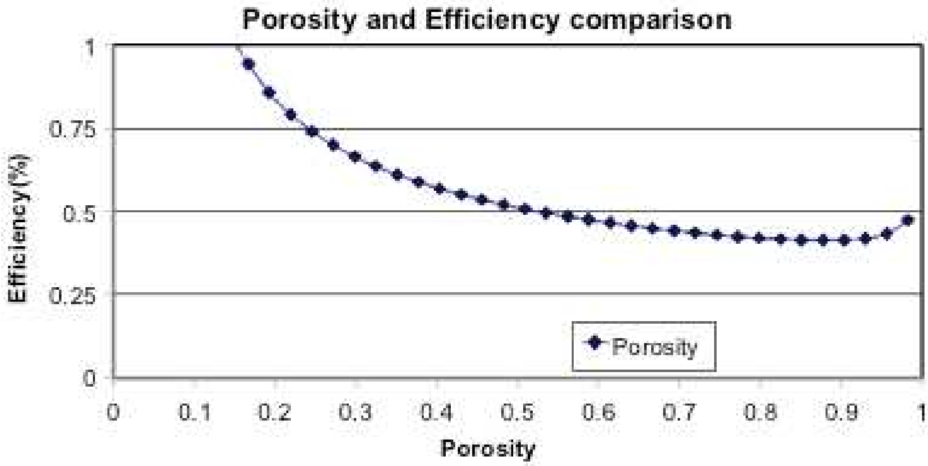

Figure 4.22: Number of strands Porosity and Efficiency comparison.

4.5.5 Concentration

Figure 4.24 plots the coalescence efficiency against the inlet concentration. It shows that as the concentration increases the coalescence efficiency deceases. Even though the efficiency dropped drastically from zero concentration to 200 ppm and then the slope of the line was dropping very low for the rest of the concentration. A trend similar to this was observed

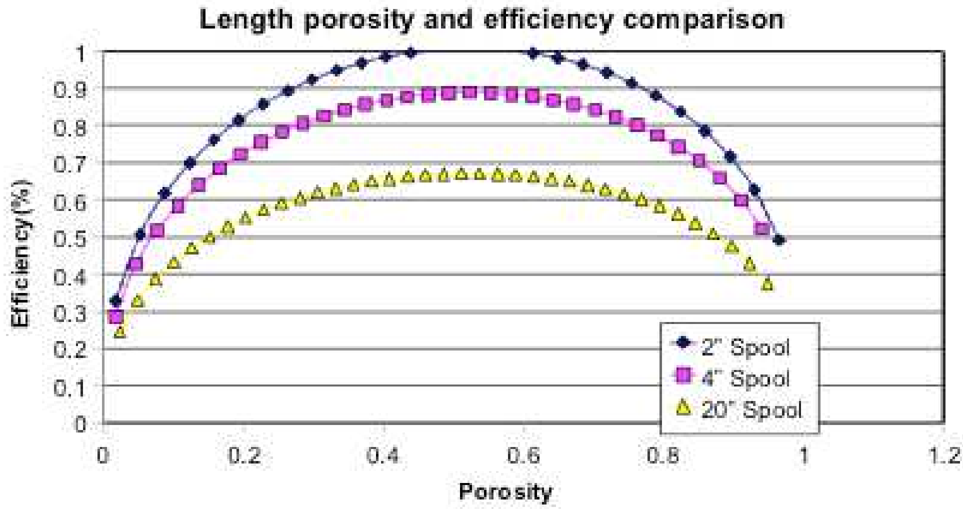

Figure 4.23: Length Porosity and efficiency comparison.

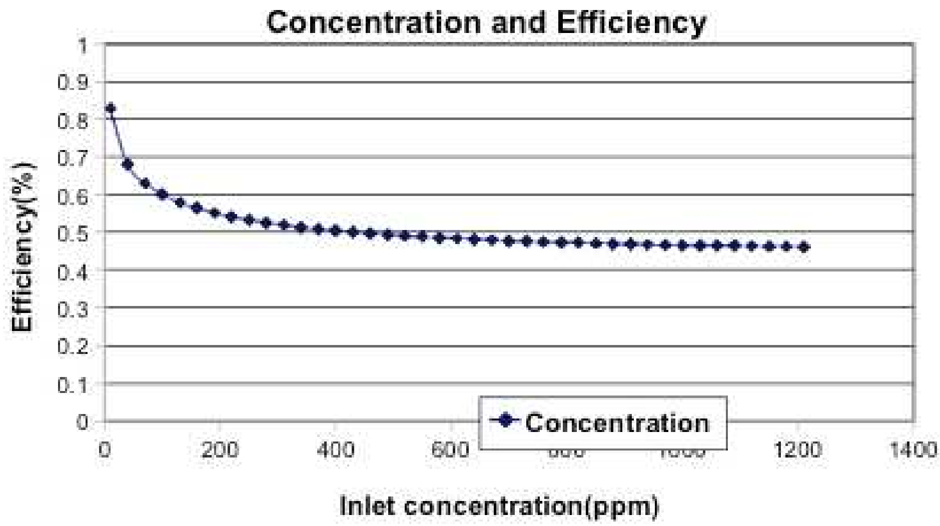

Figure 4.24: Concentration and efficiency.

in the experimental results as given in Figure 4.10 in Section4.4.3. Even though the trend is similar, the prediction is not accurate as the dependency is only 66% therefore lot more data has to be obtained to improve the accuracy of the model in order to predict correctly.

4.5.6 Flow rate and Velocity

Figure 4.25 plots the efficiency against the flow rate. It shows that as the flow rate increases, the efficiency decreases. This is similar to the real time experiments. This is

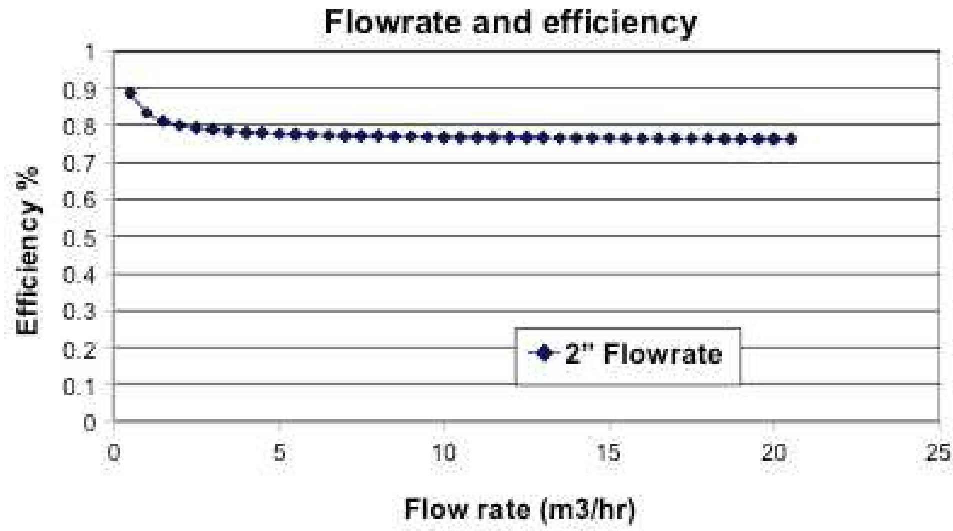

Figure 4.25: Flow Rate and efficiency.

due to the lower residence time for the oil droplets to have contact with the fibre media. As the model is not accurate enough, it only shows about the trend but according to real time experiments it has been identified that as long as the fluid is in transient region in the Reynolds number profile there is a better coalescence.

4.6 Mare's Tail Optimisation Software

As part of this work, a software package was developed and delivered to Opus Plus. That software can be used to design the optimised Mare's Tail coalescer technology for a given set of process conditions in an oil platform. It reduces the complications of the design of a Mare's Tail by using the SEM2, as described in Section 3, to test the equipment itself. There are two types of tasks that can be performed using the software:

Design Optimisation (See Figure 4.26) deals with the initial design of the Mare's Tail, i.e. the first installation of the equipment. The initial process conditions of the oil platform are given in the required blanks and the model will generate the best possible design for the given condition. The resulting design values will be the best flow rate, Mare's Tail spool diameter, total number of fibres, fibre length, porosity, pack structure, mean diameter of the fibre, spool length and the expected efficiency improvement.

Process Optimisation (See Figure 4.27) is used only after the completion of the Design Optimisation. The purpose of the Process Optimisation is to optimise the Mare's Tail after the installation in the Platform. The parameters that could be changed will be the flow rate, the expected number of days and the number of hours the Mare's Tail is being used per day. The remaining values will be taken from the design data of the equipment i.e the design optimisation value. The result will be the best possible flow rate, fibre length, total number of strands and the highest efficiency.

In addition to the above two tasks, the software also produces a number of graphs and a detailed report of the results which are used for the design and optimisation of the Mare's Tail. A detailed overview of the Software package can be found in Appendix A

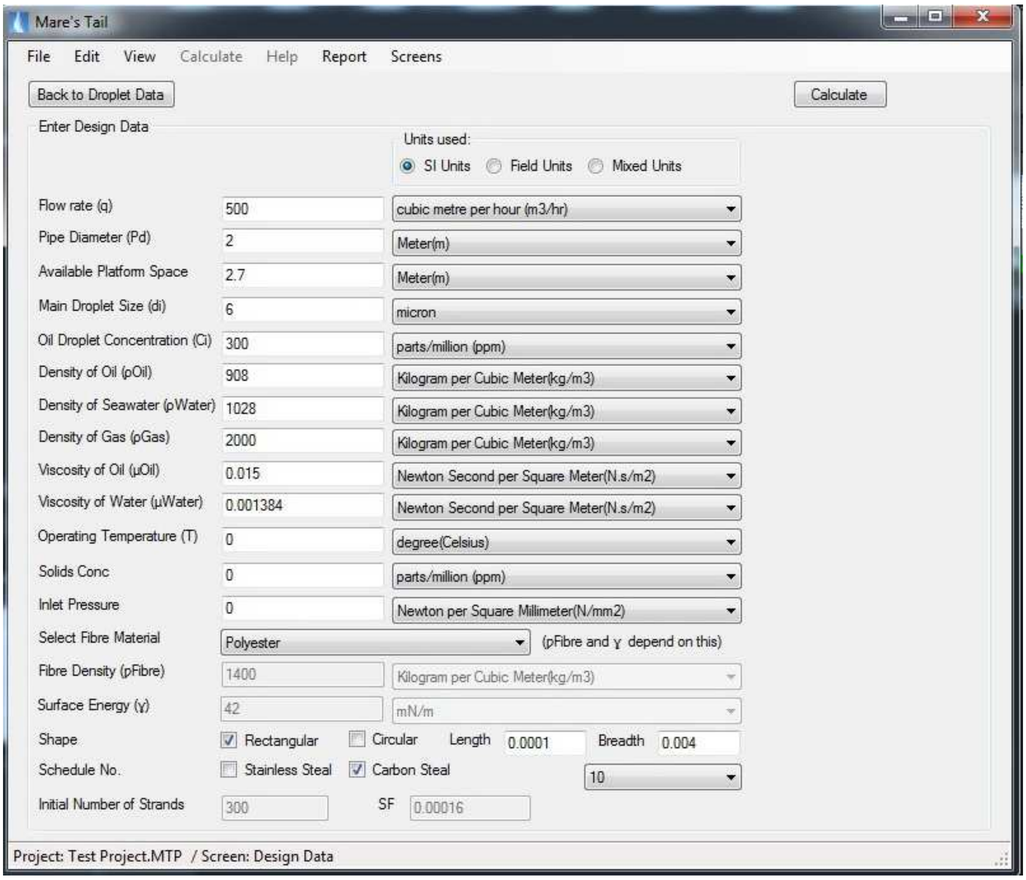

Figure 4.26: Mare's Tail Optimisation Software Design Optimisation Screen.

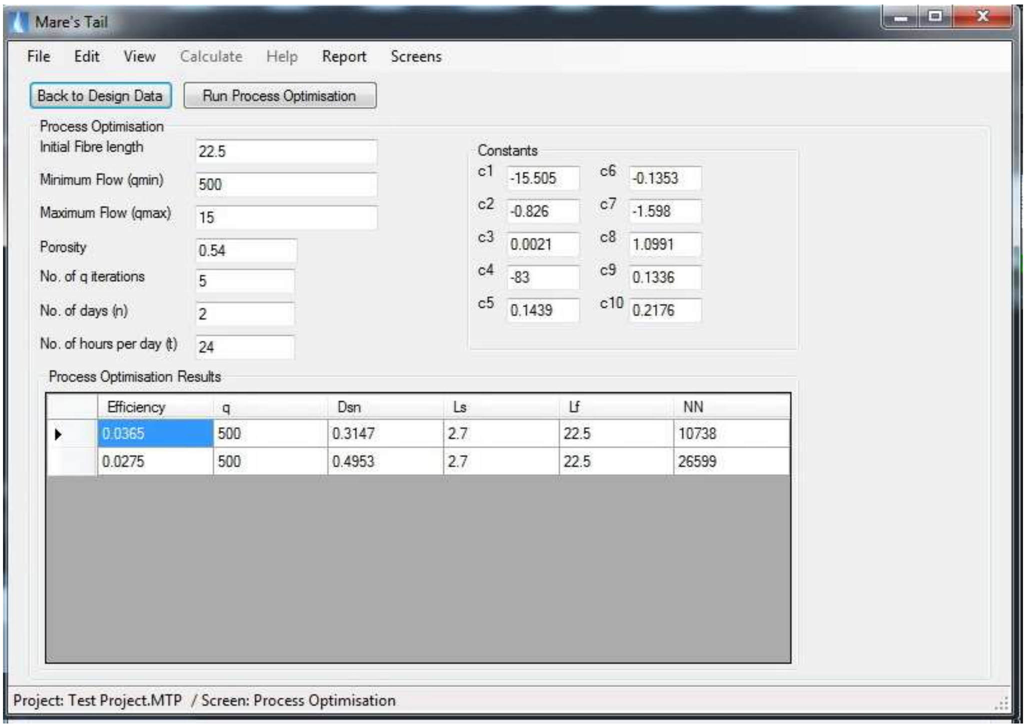

Figure 4.27: Mare's Tail Optimisation Software Process Optimisation Screen.

Chapter 5

Conclusions and Suggestions for Further Work

Several conclusions can be drawn from this work. First, a *Design Conclusions* document was produced and submitted to the company. Second, it was discovered that there is a distinct difference between *Separation Efficiency* and *Coalescence Efficiency* and finally, recommendations about Subsea application of Mare's Tail were drafted.

5.1 Design Conclusions

5.1.1 Length porosity and number of strands

The porosity plays an important role in determining the fibre length and the number of strands in determining the efficiency of the Mares Tail. From the analysis. It was identified that there exists an optimum porosity for the fibres. This optimum porosity ranges from 0.54 to 0.51 for a spool diameter of 2 to 20.

5.1.2 Velocity and flow rate

Based on the stochastic analysis, the optimum velocity is 0.4m/s. Incases where the pressure drop cannot be compromised the velocity can be increased upto 0.52m/s but should not exceed beyond this values, as this would plateau or reduce the coalescence further due to lower residence time. This velocity value applies to all the diameters

5.1.3 Spool diameter

This is determined based on the flow rate in the location where the Mares Tail is to be installed. From the analysis, according to SEM2; to improve coalescence, the pressure drop across the Mares Tail should be high, this is achieved by reducing the diameter of the spool to the minimum which is 2, by doing this we increase the friction between oil and fibre and therefore increase the contact time. This might lead to use of multiple 2″ spools arranged in parallel to handle the given flow rate in the location. This analysis results according to SEM2 leads to a draw back in a situation where the process pressure is very low for separation equipments and or unavailability of space to stack the Mares Tail in parallel in an oil platform. However SEM1 analysis results suggests that bigger spool diameters show higher efficiency than smaller spool diameters. This is due to the pressure influence on the separating equipments due to bigger diameters and the SEM1 cares mainly about the band of droplets that are bigger enough to be separable and not the growth size of individual droplets. At this current status of the Mares Tail being a coalescer, all it has to do is to help the separating equipment to increase its separation, considering this, it is best to use bigger spool diameter and maintain the best acceptable velocity of 0.52m/s to increase the fluid residence time. Either way there is a compromise between pressure drop, coalescence efficiency and availability of space. So any designer should consider these parameters before commissioning a Mare's Tail.

5.1.4 Surface energy and surface tension

It has been proved to the team members experimentally that increase in surface energy increases the separation efficiency and the SEM2 also shows that increase in surface energy increases the coalescence efficiency.

5.1.5 Pack Structure

Pack structure plays an important role in the coalescence efficiency. The parameters that influence the pack structure are the porosity, length of the strands, number of strands, expandability and the thickness of individual strands and the arrangement of the fibres. The stochastic analysis SEM2 shows that as the pack structure increases the efficiency increases. From the model this higher pack structure was achieved by weaving the fibres, which were in the range of 20-24 , whereas for the non wovenlinear strands the pack structure was less than 15 for a given spool length. Weaving as a packed bed lead to the following drawbacks;

Increase in pressure drop across the spool.

Potential solids hold up

Expensive to manufacture.

Release of bulk of oil (slug) during velocity fluctuation

Problems in building a holding mechanism of the packed bed.

5.1.6 Inlet oil droplet size

It has been proven both experimentally and theoretically that increase in inlet oil droplet sizes reduces the coalescence efficiency.

5.2 Separation Efficiency vs Coalescence Efficiency

Results showed that fibres, length, concentration and the combined parameters: temperature, viscosity and density, show opposite trends in separation efficiency and coalescence efficiency, which means that if one of efficiency value increases, the other decreases. All other parameters show similar trends between separation efficiency and coalescence efficiency. This clearly shows that that coalescence efficiency and separation efficiency are not the same.

At lower temperature the viscosity of the oil increases and leads to higher frictional force between the oil and the fibre which increases coalescence efficiency but does not increase the separation efficiency. However, at higher temperature the density difference between the fluids increases, which increases the separation of the oil from the water.

High concentration leads to coalescence of droplets before coming in contact to the Mares Tail and reduces coalescence efficiency, but the separation of the oil droplets in the downstream equipment is high due to high concentration difference between the inlet and the outlet of the separator. The maximum velocity to obtain better coalescence efficiency is 0.4 m/s.

The fibre length has a limit called the critical length, increasing the length beyond the critical point reduces coalescence efficiency.

5.3 Further work

The Mare's Tail can potentially be applied in water treatment, food and beverages industry and pharmaceutical industry. Though this might be achievable in the near future, the optimisation of the current Mare's Tail working conditions could be achieved by testing the equipment with different oil from different platforms and different produced water, different fibre material, different weaving pattern for different pack structure at different temperatures etc.

In order to obtain proper sampling process in future an online monitoring of the droplet size and the concentration could be beneficial to know the performance of the Mare's Tail according to different flow conditions.

The fluid inlet mechanism could be studied to optimise the design further. Apart from that the positioning of the Mare's tail i.e the arrangement of it being vertical instead of horizontal, with fluid inlet arrangement from the top or from the bottom should be studied to identify the best position, if this proves to produce bigger or almost same droplet sizes, it might even save space in the oil platforms.

The future challenge for the Mare's Tail will be to extend its application to subsea, however further research is needed to identify suitable fibre media and design requirements of the Mare's Tail for it to be used in a subsea environment. Still to make it into a subsea processing equipment, further study of all the parameters in the model has to be revisited in accordance with the high pressure high temperature conditions that exists in subsea operations.

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Appendix A

Mare's Tail Optimisation Software - Architecture & User Guide

This chapter describes the contents of the different views which are available in the Mare's Tail Optimisation Software. This text was submitted with the software as part of its user manual.

A.1 Startup View

When Mare's Tail is opened, the first screen that is seen is the Startup Screen. Here, the user has to choose between Design Optimisation and Process Optimisation.

Design Optimization When you choose Design Optimisation, the software will go into Design Optimisation mode. The user then has the choice to either start a new project or to open an existing project.

Process Optimization When you choose Process Optimisation, the the software will go into Process Optimisation mode. The user then has to choose an existing project file on which to perform Process Optimisation.

A.2 File Details Screen

The File Details Screen enables the user to specify certain details of the Project. The user can enter the following information:

- File Name
- Enquiry No
- Project No
- Project Manager
- Client
- Customer Contact

A.2.1 Description of the buttons in this view

Back to Start Screen Clicking this button will bring the user back to the Start Screen.

Go to Droplet Size Data Clicking this button will bring the user to the Droplet Size Data screen.

Go to Design Data Clicking this button will bring the user to the Design Data Screen.

Navigation Buttons to navigate back and forth.

A.3 Droplet Size Data Screen

The Droplet Size Data screen (See Figure A.1) enables the user to enter droplet size information. The first time it is seen, it contains an empty Data Grid. Here, the user has three choices:

Load Droplet Size Data from file To load a set of previously saved droplet size data the user can click the Load Droplet Size Data button. An Open File dialog will appear, and the user just has to direct this dialog to a saved Droplet Size data file. After a Droplet Size data is loaded successfully, the Data Grid should be filled.

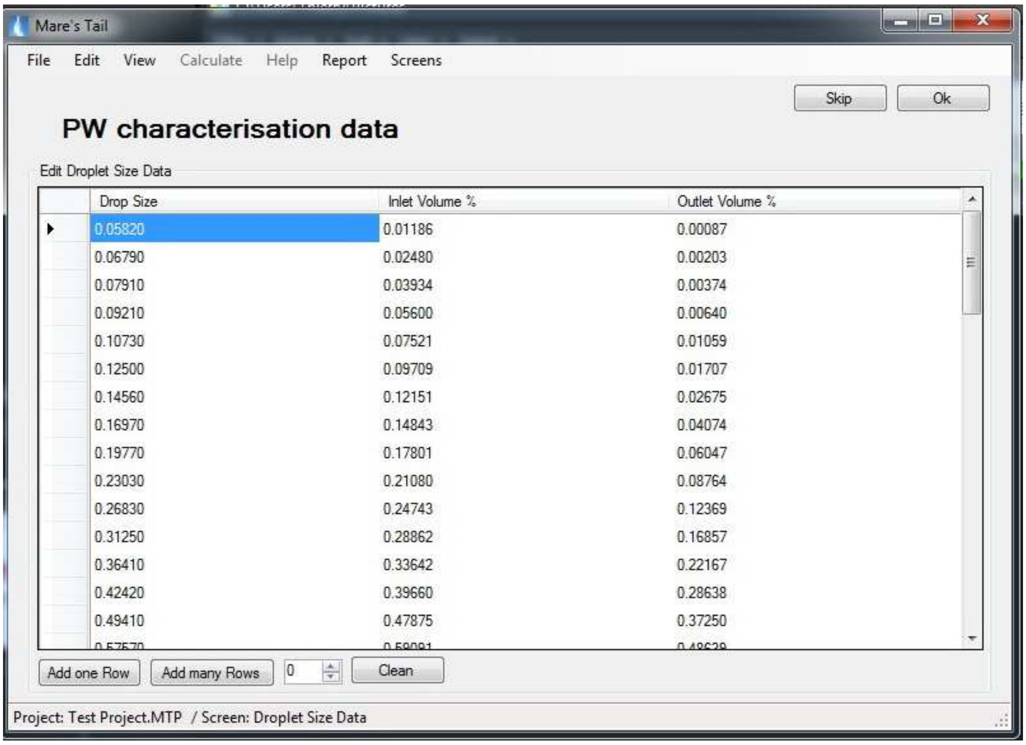

Figure A.1: Mare's Tail Optimisation Software Droplet Size Screen.

Enter droplet size data manually When the Droplet Size screen is loaded, the Data Grid is empty. The user has to insert rows before they can be populated. The controls necessary for this are found at the bottom of the Data Grid:

- To add new rows the user can either click **Add one Row**, to add individual rows one by one or **Add many Rows**, to add a number of rows with one click. The number of rows to be added is given by the box to the right of this button.
- To start over, the user can click **Clean**, to remove all contents from the Data Grid.

Ignore Droplet Size Data As the presence of Droplet Size data is not crucial to the running of Mare's Tail software, this Data Grid can be left empty. To move on, simply click on Go to Design Optimisation or use the navigation buttons

A.3.1 Description of the buttons in this view

Back to File Details to go back to the File Details Screen

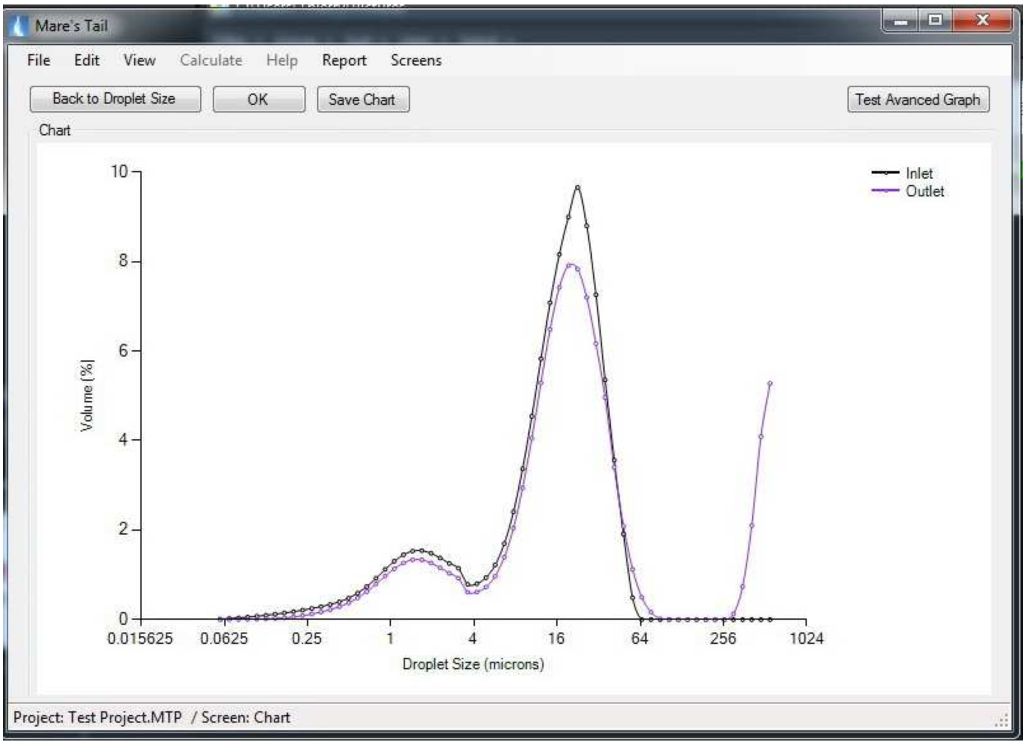

Figure A.2: Mare's Tail Optimisation Software Droplet Size Chart.

Go to Design Optimisation to go to the Design Optimisation Screen

See Droplet Size Chart to see the Droplet Size Chart (See Figure A.2), drawn using the Droplet Size data (if there is enough available)

Load Droplet Size data to load a Droplet Size data file.

Save Droplet Size data to save a Droplet Size data file.

Navigation Buttons to navigate back and forth.

A.4 Design Optimisation Screen

The Design Optimisations Screen (See Figure 4.26 page 58) enables the user to enter, change or review Mare's Tail Design Data. If an existing Mare Tail project is loaded, then this data should be visible already. If a new project was created, then the data has to be entered manually.

A.4.1 Enter new Data

Choice of Units

Before data can be entered in the Design Data screen, the user has to choose what units are to be used for this project. On the top right of this screen the following radio-buttons can be found. The user has to choose one out of 3 options:

- SI Units - to use only SI units in this project.
- Field Units - to use only Field units in this project.
- Mixed Units - to be able to use both SI units and Field Units in this project.

Once a choice has been made, the software will populate the drop-down boxes with the appropriate units and data can now be entered.

Choice of Fibre Material

The user has to choose among the available fibre materials. As the Fibre Density and the Surface Energy depend on this choice of Fibre Material, the user is not allowed to edit those details. As soon as the user has picked one of the available choices of Fibre Material, The Fibre Density and Surface Energy are populated accordingly.

Choice of Shape

Here are two possible choices for the shape of the Fibre:

- Rectangular - If this is chosen, then two boxes will appear to enable the user to enter Width and Length of the fibre
- Circular - If this is chosen, then one box will appear to enable the user to enter a Diameter of the fibre

Choice of Schedule

There are several schedule numbers to choose from, but first the user needs to decide on what steel is used: Either Stainless Steal or Carbon Steal. Once that choice is made, the drop-down box that follows the check-boxes will be populated with the appropriate schedule numbers.

A.4.2 Description of the buttons in this view

Back to Droplet Size Data to go back to the Droplet Size Data Screen

Go to Design Optimisation Results to compute and display the results of the Design Optimisation in the Design Optimisation Results Screen

Navigation Buttons to navigate back and forth

A.5 Design Optimisation Results Screen

Once the user decides to run the Design Optimisation process, the Design Optimisation Result screen (See Figure A.3) is displayed and the results of the Design Optimisation will be visible inside the data grid.

When the results are displayed there will be one or more rows of data in the data grid. One row for each Spool Diameter that is calculated in the Design Optimisation process. For each Spool Diameter that is calculated in the Design Optimisation process, we take the result with the best efficiency. The variables that correspond to this optimal result are displayed:

- Efficiency
- Cartridge Diameter
- Fibre Length
- Spool Length
- Spool Diameter
- Total Number of Strands
- Fibre Diameter

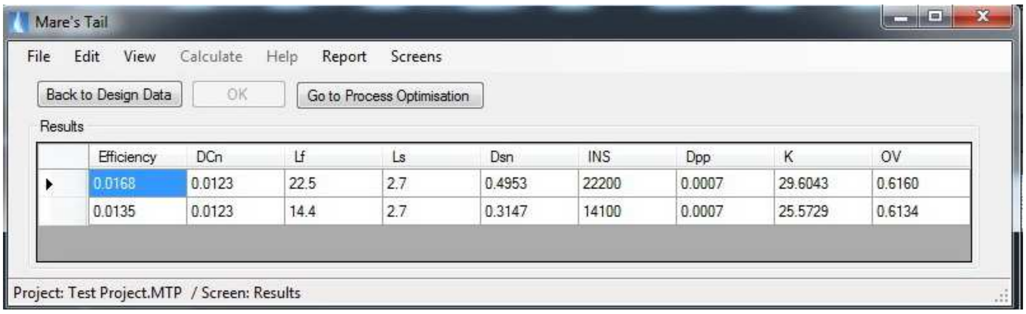

Figure A.3: Mare's Tail Optimisation Software Optimisation Result Screen.

- Pack Structure
- Porosity
- Flow Rate

A.5.1 Description of the buttons in this view

Back to Design Data to go back the the Design Optimisation Screen

Go to Process optimisation To go to the Process Optimisation Screen

Navigation Buttons to navigate back and forth.

A.6 Process Optimisation Screen

The Process Optimisation Screen (See Figure 4.27 page 59) can be divided into three different parts:

- Process Optimisation Parameters
- Desired Efficiency
- Process Optimisation Results

A.6.1 Process Optimisation Parameters

This part enables the user to enter, view and modify the Process Optimisation parameters. Values that can be changed here:

- Minimum Flow
- Maximum Flow
- No. of Iterations
- No. of days
- No. of hours per day

A.6.2 Desired Efficiency

This part enables the user to specify a desired efficiency. The desired efficiency gives the user the chance to search for a specific efficiency. If no result has the exact efficiency that the user is asking for, then the closest one will be displayed. When the user clicks on Run Process Optimisation, then the results are calculated and displayed below accordingly.

A.6.3 Process Optimisation Results

After the Process Optimisation process has been run successfully, the results are displayed in the data grid. Like in Design Optimisation, the best results are chosen for each Spool Diameter that has been calculated by the system and all relevant variables are given. The relevant values are:

- Efficiency
- Flow Rate
- Spool Diameter
- Spool Length
- Fibre Length
- Total Number of Strands
- Porosity

A.6.4 Description of the buttons in this view

Back to Design Data to return to the Design Optimisation Screen.

Run Process Optimisation to start the Process Optimisation calculation.

Navigation Buttons to navigate back and forth.

A.7 Report Settings Screen

This screen enables the user some control over what graphs will be included in the report. The check-boxes indicate what graphs (if available) will be included in the report. Clicking the All check-box will include all graphs, clicking the None check-box will include no graphs.

A.7.1 Description of the buttons in this view

Save Report to call up the dialog box asking the user where to save the report and under what name.

Navigation Buttons to navigate back.

A.8 Mare's Tail file types

The software has two different file types, **Mare Tail Project files** and **Droplet Size data files**. Mare Tail Project files contain a whole project, all the data needed to open the project are saved into one file. The file-extension of a Mare Tail Project is: .MTP. Droplet Size data files contain the Droplet Size data, which is not saved as part of a Mare Tail Project and has to be loaded and saved separately. This enables users to use the same Droplet Size Data files for several Mare Tail projects. The file extension of a Droplet Size data file is: .MTDS

A.9 Report

Mare's Tail enables the user to save a report of a project. All data is only included in a report if it is available (e.g. if no Droplet Size data is available, it will not be included in the report).

A.9.1 Report Settings

The user has the chance to decide what graphs will be included in the report. This can be set in the Report Settings Screen. The report can contain all of the following:

Project Details All the information seen in the File Details Screen

Droplet Size Data The contents of the data-grid seen in the Droplet Size Data Screen

Droplet Size Graph The graph seen in the Droplet Size Graph Screen

Design Optimisation Data All the information seen in the Design Optimisation Screen

Design Optimisation Results The contents of the data-grid seen in the Design Optimisation Results Screen

Design Optimisation Graphs There are 3 different kind of design optimisation graphs: Porosity and Efficiency comparison, Fibre Length and Efficiency comparison and Number of strands and Efficiency comparison.

Process Optimisation Data All the information seen in the Process Optimisation Screen top half

Process Optimisation Results The contents of the data-grid seen in the Process Optimisation Screen bottom half

Process Optimisation Graphs there are two different process optimisation graphs: Flow Rate and Efficiency comparison and Fibre Length and Efficiency comparison.

A.10 Software Algorithm

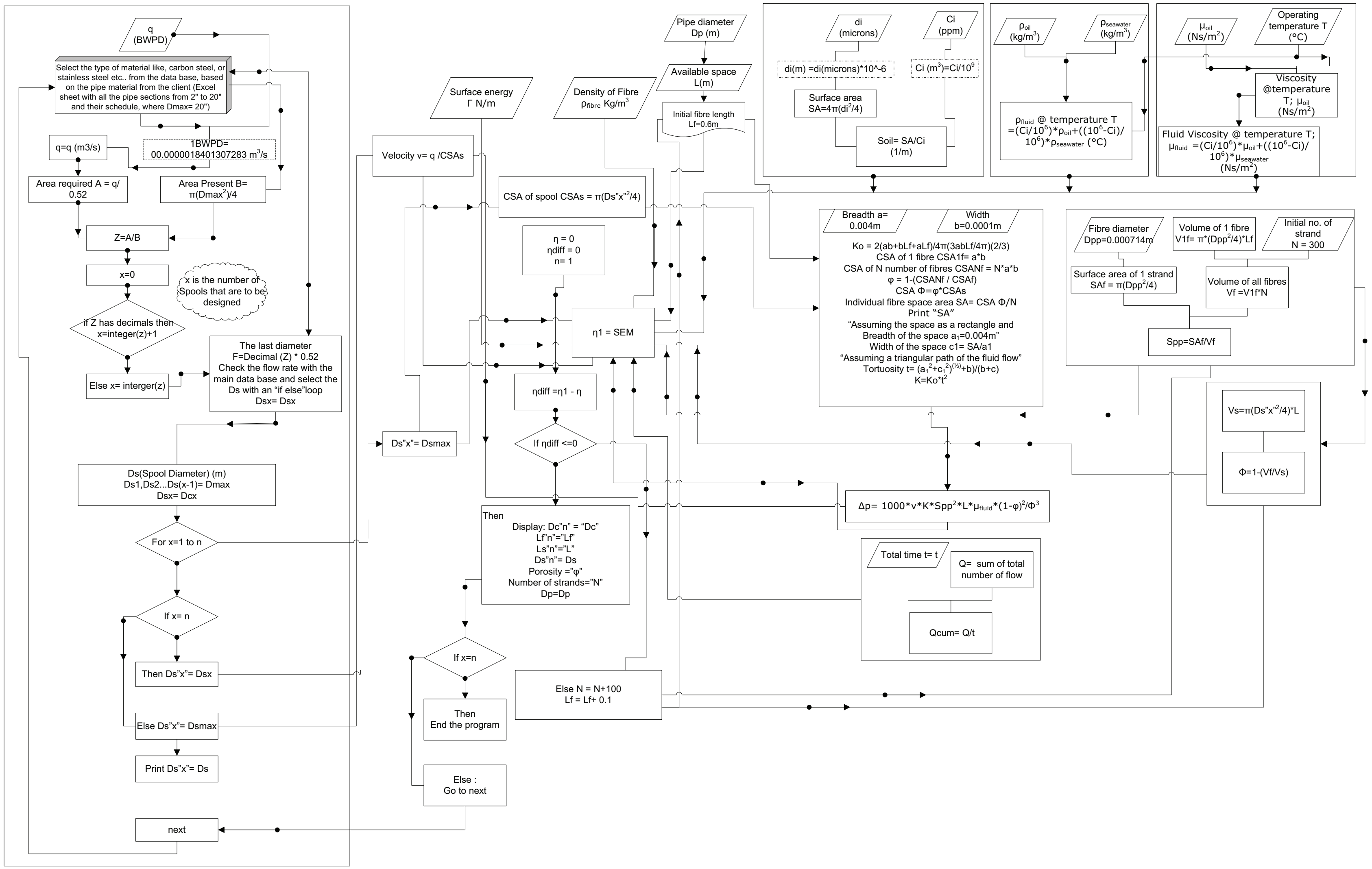

Figure A.4: Mare's Tail design and optimisation software algorithm

Appendix B

Tables of Experimental Data

B.1 Effect of fibre length on different flowrates, oil concentration and droplet sizes

The parameters in the TableB.1, were varied to identify their effect on coalescence efficiency Spool diameter D_s is 0.052m

Spool length L_s is 2 m

Fibre length L_f is 1.9 m

Total number of strands used is 700

Type of fibre used is Polypropylene

B.2 Effect of temperature

Spool diameter D_s is 0.052m

Spool length L_s is 2 m

Fibre length L_f is 1.9m

Total number of strands used is 784

Type of fibre used is Polypropylene

Table B.1: Effect of fibre length in different oil concentration and droplet sizes

η %	L_f m	q m^3/hr	C_i mg/l	d_i μ	Δp bar
17.53	1.9	3.09	459	14.49	0.75
47.49	1.9	3.09	235	12.52	0.5
6.90	1.9	3.05	4377	65.16	0.75
7.99	1.9	3.05	406	15.45	0.75
51.28	1.9	1.50	632	10.01	0.25
15.05	1.9	1.39	294	8.15	0.25
27.83	1.9	1.39	294	8.15	0.25
21.45	1.9	1.70	311	18.34	0.25
17.50	1.9	1.76	306	14.93	0.25
35.45	1.9	1.62	258	18.93	0.25
43.62	1.6	1.68	276	16	0.25
28.35	1.6	1.68	276	12.19	0.25
36.75	1.6	1.68	253	16.27	0.25
36.75	1.6	1.68	253	16.27	0.25
51.59	1.6	1.68	253	16.27	0.25
11.67	1.6	3.10	221	12.38	0.751
20.21	1.6	2.05	435	20.01	0.39
13.83	1.6	2.06	435	14.55	0.39
30.09	1.6	2.10	394	11.18	0.551
35.34	1.6	2.12	553	17.3	0.551

Table B.2: Experiment to identfy the effect of temperature

η %	q m^3/hr	C_i mg/l	d_i micro m	Temperature $^\circ C$	Δp bar
21.93	1.4	476	14.6	15	0.45
20.03	1.6	349.4	14.4	15	0.7
20.42	1.91	270	12.09	15	0.3
4.08	1.4	400	12.03	70	0.5
10.56	1.6	389.7	11.7	70	0.4
11.47	1.91	405.8	9.32	70	0.6
22.12	1.4	344	10.7	50	0.2
23.91	1.6	422	10.2	50	0.2
11.00	1.91	370	10.28	50	0.5

B.3 6" Spool Tests

Spool diameter D_s is 1.52m

Spool length L_s is 2.7 m

Fibre length L_f is 2.1m

Total number of strands used is 5700

Type of fibre used is Polypropylene

B.3.1 6" Coalescence Efficiency with and without Cartridge Cage

Table B.3: 6" spool section without cage

η %	D_s m	q m^3/hr	C_i mg/l	d_i μ	Δp bar
24.48	0.152	12.00	501.6	14.61	0.135
25.02	0.152	22.00	365	12.16	0.239
25.51	0.152	37.00	153	11.3	0.239

Table B.4: 6" spool section with cage

η %	D_s m	q m^3/hr	C_i mg/l	d_i μ	Δp bar
8.34	0.152	12.00	485	13.93	0.239
13.68	0.152	22.00	361	12.33	0.239
13.92	0.152	37.00	144	11.51	0.239

B.3.2 6" spool Test With CFU Efficiency

These set of experiments were run to find the effect of Mare's Tail cartridge and cage arrangement on separation efficiency. As the cartridge and cage arrangement are used only from 6" spools and spools bigger than that, 2" and 4" spools cannot be used for these experiments.

The parameters in TableB.5 and TableB.6 are explained below MC_i is Mare's Tail inlet oil concentration

MC_o is Mare's Tail outlet oil concentration

CC_i is CFU inlet oil concentration

CC_o is CFU outlet oil concentration

Md_i is Mare's Tail inlet oil droplet size

Md_o is Mare's Tail outlet oil droplet size

Cd_i is CFU inlet oil droplet size

Cd_o is CFU outlet oil droplet size

Table B.5: 6" spool section without cage

No	q m3/hr	MC_i ppm	MC_o CC_i ppm	CFUC_o ppm	η %	ηgain %	Md_i microns	CFUd_i microns	CFUd_o microns	Δp bar
1	12	501.6	418.6	235	53.15		14.79	19.49	15.56	0.135
1a	12		504	282	44.05	9.10		15.82	17.45	
2	22	365	308	232	36.44		10.91	17.06	15.3	0.239
2a	22		376	299.99	20.22	16.22		12.66	15.22	
3	37	153	155	116	24.18		10.23	14.14	14.14	0.389
3a	37		148	126	14.86	9.31		10.92	12.51	

Table B.6: 6" spool section with cage

No	q m3/hr	MC_i ppm	MC_o CC_i ppm	CFUC_o ppm	η %	ηgain %	Md_i microns	CFUd_i microns	CFUd_o microns	Δp bar
1	12	485	391	219	54.85		15.43	15.4	16.66	0.155
1a	12		520	297	42.88	11.96		14.48	17.71	
2	22	361	380	232	35.73		14.09	13.41	16.51	0.277
2a	22		361	278	22.99	12.74		11.74	17.34	
3	37	144	153	115	20.14		9.72	9.64	11.04	0.532
3a	37		159	131	17.61	2.52		9.29	10.8	

B.4 Effect of different Spool Diameter

Two 2" and one 4" spools were arranged in parallel to each other and tested with different flowrates , oil concentration and droplet sizes. These tests were conducted to find the effect of using parallel Mare's tail coalescers and to identify the effect of different spool diameters when exposed to same test conditions.

D_s is Spool diameter

D_c is Cartridge diameter

L_s is Spool length

L_f is Fibre length

C_i is inlet oil concentration

d_i is inlet oil droplet size

q is flowrate

Table B.7: Effect of different Spool Diameter arranged in paralell to each other

η %	D_s m	L_f m	L_s m	D_c m	q m^3/hr	C_i mg/l	d_i μ	Δp bar
55.11	0.053	1.9	2	0.020	2.15	447	9.46	0.365
49.73	0.102	2.1	2.4	0.043	0.70	423	6.62	0.027
27.87	0.053	1.9	2	0.020	1.75	767	8.37	0.457
25.94	0.053	1.9	2	0.020	1.53	850	9.37	0.4
46.29	0.053	1.9	2	0.020	1.53	513	9.37	0.4
35.59	0.102	2.1	2.4	0.043	0.65	555	7.3	0.3539
36.26	0.102	2.1	2.4	0.043	4.80	464	5.24	0.013
58.69	0.053	1.9	2	0.020	1.86	406	10.18	0.419
59.54	0.053	1.9	2	0.020	2.06	77	7.03	0.707
43.02	0.053	1.9	2	0.020	1.98	77	7.02	0.36
57.35	0.102	2.1	2.4	0.043	7.93	85	6.55	0.358
40.64	0.102	2.1	2.4	0.043	17.00	80	7.38	0.366
53.34	0.102	2.1	2.4	0.043	15.20	134.8	7.77	0.289
36.84	0.102	2.1	2.4	0.043	15.20	213	7.96	0.289
23.39	0.102	2.1	2.4	0.043	30.40	130.9	6.99	0.779
25.95	0.053	1.9	2	0.020	2.08	327	13.01	0.337
16.44	0.053	1.9	2	0.020	1.50	360	13.71	0.18
25.06	0.102	2.1	2.4	0.043	8.00	288	11.57	0.127
44.63	0.102	2.1	2.4	0.043	13.00	250.6	9.49	0.668
60.63	0.053	1.9	2	0.020	2.54	207	8.89	0.5
57.76	0.053	1.9	2	0.020	1.87	212.4	9.88	0.5
33.00	0.102	2.1	2.4	0.043	11.60	202	10.06	0.249
39.89	0.102	2.1	2.4	0.043	8.00	245	10.81	0.127
27.22	0.053	1.9	2	0.019	2.56	304.1	12.31	0.5
43.53	0.053	1.9	2	0.019	2.15	255.6	15.97	0.5
22.26	0.102	2.1	2.4	0.043	9.30	242	9.11	0.248

B.5 Experiments for the Comparison of X-Tex and Polypropylene Fibers

These set of experiments were conducted to test the effect different fibres with different surface energy, in different fibre lengths.

MC_i is Mare's Tail inlet oil concentration

MC_o is Mare's Tail outlet oil concentration

HC_i is Hydrocyclone inlet oil concentration

HC_o is Hydrocyclone outlet oil concentration

Md_i is Mare's Tail inlet oil droplet size

Md_o is Mare's Tail outlet oil droplet size

Hd_i is Hydrocyclone inlet oil droplet size

Hd_o is Hydrocyclone outlet oil droplet size

B.5.1 1.52m Polypropylene Fibers with Hydrocyclone

For the experiments in Table B.8

Length of the fibre is 1.52 m

Total number of stands used is 700

The fibre used is Polypropylene whose surface energy is 31.7mN/m

Table B.8: 1.52m Polypropylene fibers with hydrocyclone

No	q m^3/hr	MC_i ppm	MC_o HC_i ppm	HC_o ppm	η %	ηgain %	Md_i μ	Hd_i μ	Hd_o μ	Δp bar
1	1.40	410	453	129.7	71.37		15.5	24.68	7.5	0.24
1a	1.40		427.01	165.06	61.35	10.02		15.45	9.315	
2	1.64	357.5	441.17	123.52	72.00		16.64	23.13	7.23	0.3
2a	1.64		339.3	141.1	58.41	13.58		18.18	5.85	
3	1.91	263.46	264	88.2	66.59		9.95	14.43	11.02	0.3
3a	1.91		267.9	100	62.67	3.91		12.05	9.34	

B.5.2 1.90m Polypropylene Fibers with Hydrocyclone

For the experiments in Table B.9

Length of the fibre is 1.90 m

Total number of stands used is 784

The fibre used is Polypropylene whose surface energy is 31.7mN/m

Table B.9: 1.9m Polypropylene fibers with hydrocyclone

No	q m^3/hr	MC_i ppm	MC_o HC_i ppm	HC_o ppm	η %	ηgain %	Md_i μ	Hd_i μ	Hd_o μ	Δp bar
1	1.40	476	523.5	161.15	69.22		14.6	14.01	7	0.45
1a	1.40		513.2	270.5	47.29	21.92		14.6	8	
2	1.64	349.4	411.7	120.5	70.73		14.4	18.6	9.8	0.7
2a	1.64		390.1	192.3	50.70	20.03		13.55	8.5	
3	1.91	270	265	69	73.96		12.09	15.67	10.71	3.4
3a	1.91		282	131	53.55	20.42		13.07	8	

B.5.3 1.52m X-Tex Polyester Fibers with Hydrocyclone

For the experiments in Table B.10

Length of the fibre is 1.52 m

Total number of stands used is 450

The fibre used is X-Tex Polyester whose surface energy is 45.3 mN/m

Table B.10: 1.52m X-Tex Polyester fibers with hydrocyclone

No	q m^3/hr	MC_i ppm	MC_o HC_i ppm	HC_o ppm	η %	ηgain %	Md_i μ	Hd_i μ	Hd_o μ	Δp bar
1	1.40	503.3	848.3	105.8	78.98		15.13	16.6	10.7	0.4
1a	1.40		490.1	270.5	44.81	34.17		14.5	11.8	
2	1.64	352.9	420.1	95	73.08		14.11	16.18	10.3	0.8
2a	1.64		435	205.8	52.69	20.39		13.2	9.1	
3	1.91	255.8	239.3	70.5	72.44		9.64	13.083	7.1	1
3a	1.91		264.7	144.1	45.56	26.87		11.1	8.6	

B.5.4 X-Tex Polypropylene at $15°C$ with Hydrocyclone

For the experiments in Table B.11

Length of the fibre is 1 m

Total number of stands used is 450

The fibre used is X-Tex Polyester whose surface energy is 45.3 mN/m

Table B.11: 1m X-Tex Polyester fibers with hydrocyclone at 15 $°C$

No	q m^3/hr	MC_i ppm	MC_o HC_i ppm	HC_o ppm	η %	ηgain %	Md_i μ	Hd_i μ	Hd_o μ	Δp bar
1	1.40	559.3	1047.05	190.2	65.99		13.48	12.3	9.775	0.3
1a	1.40		370	226.1	38.89	27.10		12.9	8.7	
2	1.64	340.1	397.8	121.07	64.40		12.18	13.6	7	0.4
2a	1.64		382.3	200	47.69	16.71		12.9	8.9	
3	1.91	294.1	308.5	87.6	70.21		11.7	7.9	7.17	0.6
3a	1.91		241.6	137.9	42.92	27.29		11.1	7.17	

B.5.5 X-Tex Polypropylene at 50 $°C$ with Hydrocyclone

For the experiments in Table B.12

Length of the fibre is 1 m

Total number of stands used is 450

The fibre used is X-Tex Polyester whose surface energy is 45.3 mN/m

Table B.12: 1m X-Tex Polyester fibers with hydrocyclone at 50 $°C$

No	q m^3/hr	MC_i ppm	MC_o HC_i ppm	HC_o ppm	η %	ηgain %	Md_i μ	Hd_i μ	Hd_o μ	Δp bar
1	1.40	400	986	29.4	92.65		9.02	9.23	5.44	0.5
1a	1.40		388	100	74.23	18.42		8.62	4.66	
2	1.64	396	1397	27.6	93.03		9.15	8.02	6.24	0.45
2a	1.64		386.3	105.8	72.61	20.42		7.37	4.93	
3	1.91	450	1354	33.3	92.60		8.7	9.86	6.05	0.7
3a	1.91		415.1	97	76.63	15.97		9.35	5.33	

B.5.6 X-Tex Polypropylene at 70 $°C$ with Hydrocyclone

For the experiments in Table B.13

Length of the fibre is 1 m

Total number of stands used is 450

The fibre used is X-Tex Polyester whose surface energy is 45.3 mN/m

Table B.13: 1m X-Tex Polyester fibers with hydrocyclone at 70 $°C$

No	q m^3/hr	MC_i ppm	MC_o HC_i ppm	HC_o ppm	η %	ηgain %	Md_i μ	Hd_i μ	Hd_o μ	Δp bar
1	1.40	388.2	1803.5	12.8	96.70		12.03	15.04	5.45	0.5
1a	1.40		435	38.2	91.22	5.48		10.87	5.51	
2	1.61	305.88	1102.9	12.3	95.98		11.6	11.56	5.95	0.4
2a	1.61		288.6	48.2	83.30	12.68		10.53	6.24	
3	1.90	456	1354	33.3	92.70		11.49	19.5	6.57	0.55
3a	1.90		388.2	35.9	90.75	1.95		11.36	6.03	

B.6 Experiment and Offshore Data Used for SEM1

These experiments were conducted by the company staff in the offshore platform before the commencing of the Knowledge Transfer Partnership (KTP) between RGU and Opus Plus Ltd. For the offshore data in TableB.14

The Spool length is 2 m

Fibre length is 1.9 m

The fibres used for these tests are polypropylene

Table B.14: Experiment and Off-shore data used for SEM1

η %	q m^3/hr	C_i mg/l	d_i μ	Temp $^\circ C$	dp bar
4.70	2.21	28	5	10	0.5
30.50	1.61	25	4.89	10	0.1
16.20	2.07	29	4.98	10	0.1
30.20	1.98	80	4.94	10	0.6
33.20	2.19	75.5	5.05	10	0.5
37.30	2.14	124	4.47	10	0.5
33.90	2.18	136	5.03	10	0.5
52.50	1.92	84	4.22	10	0.5
32.60	1.65	109.5	5.04	10	0.4
45.30	1.62	89.5	4.5	10	0.3
41.60	2.14	121.1	4.97	10	0.5
47.60	2.13	89.8	4.03	10	0.5
44.10	2.04	103.8	4.44	10	0.5
19.50	2.04	49.3	6	10	0.5
18.80	1.98	33.76	5	10	0.6
12.10	1.96	16.71	5.45	10	0.4
31.80	1.52	32.45	5.91	10	0.4
6.10	1.95	356.6	10.94	10	0.9
21.70	1.97	40	5.45	10	0.9
20.90	2	26	5.92	10	0.8
13.59	1.6	357.5	16.64	15	0.3

Appendix C

Paper Publication

This paper was written using the information obtained during the Knowledge Transfer Partnership project and was presented in an SPE conference in Nigeria.

Title:	The Mares Tail - The answer to produced water management in deepwater environment?
Authors:	Oyeneyin, M. B.; Glen MacLellan; Bhavani Vijayakumar; Mamdud Hussain; Roy Bichan and Nigel Wier
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SPE 128609

The Mare's Tail – The answer to a cost effective produced water management in deepwater environment?

Oyeneyin, M.B, SPE[1]; Glen McLellan[2]; Bhavani Vijayakumar[1]; Mamdud Hussain[1]; Roy Bichan[2]; and Nigel Weir[2]

[1]The Robert Gordon University, UK [2]Opus Plus Limited UK

Abstract

The deepwater environments form the cornerstone of future oilfield developments many of the hydrocarbon reservoirs of which are characterised by High Pressure (HP) and High Temperature (HT). A key feature of HP-HT reservoirs is the rapid depressurisation in the early production life of the reservoir. One of the most critical issues associated with the high drawdown is early water ingress and sand production. Continuous water production is also a key phenomenon with mature/depleted reservoirs. Keeping production costs to a minimum whilst keeping production targets high, requires putting in place an effective management of the produced water either by re-injection or by discharge. The challenge is in meeting the stringent operational requirements and environmental disposal regulations that define the level of oil in water and solids content before re-injection or discharge. In the UK, for example, legislation is becoming increasingly strict with the ***Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)*** *commission – which came into force in 2007 – reducing the total discharge tonnage of oil allowed by 15% compared to the levels permitted in 2000. The 1st generation of the Mare's Tail coalescer was initially developed by Opus Plus through a joint industry project in 1998 to meet this challenge. Through utilising the technology, clients have enjoyed a number of key benefits, including a greatly improved quality of produced water being discharged to the sea – without the use of deoiling chemicals.*

The Mare's Tail works by coalescing small oil droplets found in produced water, into significantly larger sizes so that the droplets can then be separated more efficiently. A spool cartridge contains a fibrous coalescer element, which is fixed at the inlet end to facilitate inspection and removal. Fluids enter the inlet nozzle and flow along the spool piece in the same direction as the coalescer media and then, as the fluids travel along the oleophilic fibres, small oil droplets are attracted to the surface and coalesce with other droplets as they migrate towards the outlet. The direction of flow along the fibres, rather than across it as with more conventional technologies, means that any solids are passed through the Mare's Tail rather than building up within the media. The technology has proved to be particularly suited to FPSO applications but never tried out for any subsea processing.

Environmental regulations relating to the discharge of oil into the sea continue to tighten significantly across the globe. To meet this new challenge and improve the efficiency of the Mare's tail, the development of a second generation of the system has now been initiated in a collaborative project between RGU & Opus Plus funded through the UK Knowledge Transfer Project Scheme.

In this paper the 2nd generation Mare's Tail development programme is presented. The paper presents the unique coalescence operating mechanism of the 2nd generation Mare's Tail, planned improvements over the 1st generation system and its importance/relevance to improved produced water management in deepwater environment. Potential for application in subsea processing compared to FPSO installation is also highlighted.

Supporting this optimisation process is a newly developed support design and optimisation algorithm the details of which are also presented. Preliminary validation of algorithm predictions have been carried out using selected field data the results of which have been found to be in agreement. Stochastic analysis has been carried out the results of which are presented to demonstrate how the algorithm can be utilised in the optimisation of the design parameters such

that every developed Mare's Tail is fit for purpose. The algorithm can also be utilised to optimise operational parameters in real time as well as any onsite problem diagnosis thus minimising any flat time or loss of production.
The paper is concluded with a presentation of the Opus test facility which will be used to test the Mare's Tail.

Introduction

The International Energy Agency[1] forecasts that oil demand by 2015 will be about 95 million barrels/day with a total supply of 85 million barrels/day of conventional oil whose worldwide reserve stands at about 1.3 trillion barrels [2].
The deepwater environments form the cornerstone of future oilfield developments many of the hydrocarbon reservoirs of which are characterised by High Pressure and High Temperature (HP-HT). A key feature of HP-HT reservoirs is the rapid depressurisation in the early production life of the reservoir. One of the most critical issues associated with the high drawdown across the reservoir sand face is very high water ingress and sand production. Continuous water production is also a key phenomenon with mature/depleted reservoirs with over 98% of water production in mature fields like Brent and Forties fields in the UKCS for example. Keeping production costs to a minimum whilst keeping production targets high, requires putting in place an effective management of the produced water either by re-injection or by discharge. In the challenging and environmentally sensitive Arctic and ultra deepwater regions, regulations for the discharge of oil to sea are tightening considerably across the globe and resulting in an ever expanding market for water clean up technologies. The challenge is in meeting the stringent operational requirements and environmental disposal regulations that define the level of oil in water and solids content before re-injection or discharge. In Europe, for example, legislation is becoming increasingly strict with the OSPAR commission[3] – which came into force in 2007 – reducing the total discharge tonnage of oil allowed by 15% compared to the levels permitted in 2000[3].

Due to tightening legislative targets for oil in water discharge to the marine environment, the worldwide market for water clean up technology is huge. This trend is continuing across the industry worldwide especially for ultra deepwater operations and subsea developments.

Challenges of Produced Water

Produced water from oil/gas reservoirs usually contain in various concentrations oil droplets, dissolved gas, suspended solids [mainly associated and non-associated fines/debris and sand grains], inorganic chemicals such as iron, calcium and magnesium ions and organic chemicals.
Produced water is now disposed off either by re-injection for water flooding to improve recovery or by discharge. To meet injectivity requirements the produced water needs extensive treatment to remove a substantial percentage of the oil droplets, suspended solids and inorganic/organic chemicals. The challenges are in:

1. The deoiling of the water possibly to about 2microns droplet size and 10ppm concentration
2. Removal of base sediments/suspended solids
3. Inorganic iron, calcium and magnesium removal
4. Soluble organic chemical removal

There are now many deoiling, suspended solids and associated organic/inorganic substances treatment technologies. The challenges are:

1. Which individual or combination of technologies to use that will be fit-for-purpose considering different reservoir lithologies and properties as well as produced water characteristics and operating conditions.
2. Design optimisation and real time on-site process optimisation

Produced Water Management Technologies

The produced water management technologies can be divided into four main groups[4]:

1. The Deoiling Technologies
2. The Suspended Solids Removal Technologies
3. The Inorganic Chemical Removal Technologies
4. The Soluble Organic Substance Removal Technologies

A. Deoiling Technologies

There is a number of separation technologies for the deoiling of base water produced with oil.
The most popular deoiling technologies include:

- Centrifugation – In this method the settling rate of the oil droplets can be enhanced by increasing the acceleration the droplets are subjected to using a centrifuge. The system is only efficient in removing droplets over 2microns.
- Membrane Ultra Filtration – The use of a suitable membrane can yield low produced water oil concentration. The technology lacks the ability to handle large flow rates and can readily clog necessitating high degree of replacement maintenance. Surfactant

addition can improve the separation efficiency.

- Plate Separation – The separation system is made up of a packet of parallel plates through which produced water can be diverted. Presence of the corrugated plates leads to a reduction in settling distance of the oil droplets. It is a relatively simple system to produce and needs little maintenance. It is however incapable of handling very small droplets.
- Hydrocyclone Separator – This is a conical device wherein the produced mixture of oil and water is separated out by centrifugal forces. The produced water enters the cyclone tangentially with centrifugal acceleration promoting gravitational separation. The hydrocyclone is very good in separating the large droplets but lacks the ability to handle very small droplets.
- Induced Gas Flotation – In this case the rising velocity of oil droplets is enhanced through the injection of gas bubbles to suspended droplets creating a lighter and bigger droplet size enhanced by the gas expansion. The suspended droplets form a froth layer which can be skimmed off.
- API Separator – This is a well established separator usually designed to promote quiescent separation of water and free oil. It is usually good with high oil concentration only.
- Coalescence – The process of coalescence involves the aggregation of small droplets into bigger particles which can then readily separate out the oil from the produced water mixture.

Of all the above separation techniques only the coalescence process has the ability to remove very small droplets below 2microns.

The Mare's Tail, the subject of this paper, operates on the coalescence principle.

B. Suspended Solids Removal

This technique includes:

- Sedimentation – Process involves long retention time in a tank designed to establish quiescent condition
- Cartridge Strainer Unit – This is a tube support system that holds sized filter cartridges for solids filtration
- Hydrocyclone – Process similar to deoiling hydrocyclone, but designed to remove solids particles from the flow stream into an accumulation vessel.

C. Inorganic Chemical Removal

This is made up of the following processes:

- Aeration and Sedimentation – This is primarily for iron removal. In the process, water is aerated in a sedimentation tank where the soluble ferrous iron can be oxidised into a ferric hydroxide precipitate that settles out in the tank
- Lime soda ash softening – This is a water softening process in which added hydrated lime or caustic soda is used to adjust the pH to above 10 resulting in the formation of calcium carbonate that precipitates and can be filtered out.
- Cation Exchange – Resin additive can promote the exchange of sodium ion for calcium or magnesium ion in the hard water.

D. Soluble organic removal – Treatment includes biological and activation processes involving the use of activated carbon, reverse osmosis, electrodialysis methods to name a few[4].

Many of the separation systems are used individually or packaged with other units. A typical example of such systems is the Compact Floatation Unit (CFU) that has found wide application in deepwater environments[5]. The CFU is a combination of gas floatation and centrifugal separation.

The Mare's Tail® [MT]

The Mare's Tail [Figure 1] works by coalescing small oil droplets found in produced water, into significantly larger sizes so that the droplets can then be separated more efficiently. The 1st generation of the Mare's Tail coalescer was initially developed by Opus Plus through a joint industry project (JIP) in 1998[6] to meet this challenge. A spool piece within the technology contains a fibrous coalescer element, which is fixed at the inlet end to facilitate inspection and removal. Fluids enter the inlet nozzle and flow along the spool piece in the same direction as the coalescer media and then, as the fluids travel along the oleophilic fibres, small oil droplets are attracted to the surface and coalesce with other droplets as they migrate towards the outlet. The direction of flow along the fibres, rather than across it as with more conventional technologies, means that any solids are passed through the Mare's Tail rather than building up within the media.

The coalescing action occurs within two seconds in the bundle, making a very compact device.

The combination of flow along the fibres, rather than across it, as in many conventional coalescers, results in a self cleaning operation because solids pass through the coalescer.

The system can be installed upstream of any other deoiling separation technology previously described where droplet size can have an effect on performance. The Mare's Tail has the competitive advantage of delivering greatly improved quality of produced water without the use of chemicals [Figure 2].

There are many configuration options including:

- Units spooled into existing pipe work [Figure 3]
- Installed parallel to existing pipe work facilitating by-pass[Figure 4]
- Horizontal, inclined or vertical orientation
- Can be supplied packaged with other deoiling equipment[Figure 4]

Figure 1: The Mare's Tail

Figure 2: Produced Water Quality

Figure 3: Spooled Mare's Tail

Figure 4: Mare's Tail Unit with other facilities

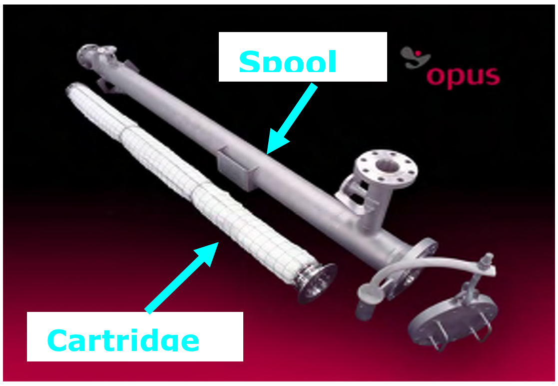

Figure 5: Mare's Tail showing the separated Cartridge and Spool

The technology has proved to be particularly suited to fixed platform and FPSO applications but never tried out for any subsea processing. As a unit that can readily be spooled into existing pipe works, the MT has the potential for application in subsea production system [SPS] modules. The challenges are in the ability to develop and utilise a spool material that can meet the harsh deepwater environmental conditions in terms of seawater corrosion effect and prevailing high pressure and temperature.

Specifically The Mare's Tail is made up of the following key components [Figure 5]:

1. A spool
2. Fibre cartridge

To date 2'', 4'' and 6'' nominal spool sizes with designated pipe schedule numbers [Table 1] have been developed and utilised for the initial JIP studies[6, 7]. These same schedules will be utilised for the ongoing studies.

Eighteen successful field trials have been conducted for 13 different leading oil companies worldwide and 20 units of 4'', 6'', 10'' and 18'' MT full-scale installations have been executed.

Table 1: Mare's Tale Pipe Schedules

Nom. Size	O.D	Schedule No	Wall Thickness, mm	Wt, kg/m
2''	2.375'' (60.3mm)	10	2.77	3.93
		40	3.91	5.44
		80	5.54	7.48
4''	4.5'' (114.3mm)	10	3.05	8.36
		40	6.02	16.07
		80	8.56	22.32
6''	6.625 (168.3mm)	40	7.11	28.26
		160	18.26	67.56

During the JIP, tests were conducted initially with different type of fibres to test their surface area, availability and affinity towards coalescing oil droplets of different sizes used[Figure 6] and to confirm which type of fibre is the most appropriate to be used as the Mare's Tail fibre. The materials tested were horse hair, hemp rope and fibres, poly propylene rope, poly propylene mop, sobaide, sysal string, cotton string and nylon rope. From the tests it was confirmed that polypropylene mop showed the better results. It was also identified during the JIP that length has a major impact on the efficiency of the Mare's Tail, which states that the efficiency increases along with the length, but beyond a certain length, there is no significant improvement in the efficiency of the Mare's Tail [Figure 7].

Current Mare's Tail development solely comes from performance feedback from offshore trials or full scale installations [See Table 2]. This has proved to be unreliable as units can either not be on-line for specific platform reasons or the installation itself does not support the resource to provide adequate feedback. This has restricted any Mare's Tail related work to design and fabrication for full scale applications. The requirement is to have the knowledge of the technologies operating limits given the vast array of production conditions both in national and global oil fields.
Environmental regulations relating to the discharge of oil into the sea continue to tighten significantly across the globe. To meet this new challenge and improve the efficiency of the Mare's Tail, the development of a second generation of the system has now been initiated in a collaborative project between The Robert Gordon University and Opus Plus funded through the UK Knowledge Transfer Project Scheme (KTP). This partnership allows further research and development to gain a better understanding of the operating parameters, absolute knowledge of the operating envelope, capabilities and limitations of the Mare's Tail.
The key challenges in the new KTP project are in:

1. The provision of a detailed understanding of why the Mare's Tail works
2. The development of a second generation of a stand alone Mare's Tail that is fit for purpose and meets the customer's needs. This requires adopting appropriate design optimisation strategy
3. Developing the strategy for laboratory and on-site performance and process optimisation

The background JIP results to date confirm there is a complex relationship between the parameters that affect coalescence. The underlying umbrella strategy adopted therefore is to develop a semi-empirical model that:

(i) clearly defines the coalescence efficiency of the Mare's Tail (MT)
(ii) identifies the key parameters and combined effects of all the parameters on the coalescence efficiency.

The model supported by selective experiments form the foundation of any design and on-site process optimisation envisaged for the 2nd generation MT.

Table 2: Mare's Tail Coalescer Status Update and Reference

Company Name	Title/Subject	Platform/Terminal
Shell	6'', 10'' and 18'' Mare's Tail Units	Haewener Brim FPSO
Schlumberger	2 x 10'' Mare's Tail Units	Offshore Brazil
ExxonMobil	4" Mare's Tail	NSO platform
Hess	2 x 21" Mare's Tail units	Triton FPSO
BP America Inc	14" Mare's Tail	Na Kika Platform
E.ON Ruhrgas UK North Sea	6" Mare's Tail Units	Ravenspurn North platform
Murphy Sarawak Oil Co Ltd	6" Mare's Tail	West Patricia Platform
Lundin Britain Limited	20" unit is being supplied as part of a 50,000 BPD CFU unit	Heather platform.
Total Cameroon	2 x 20" (60,000 BPD) units	BAP and ESP1 platforms

The Coalescence Efficiency Model

Review of MT Coalescence Mechanism

Coalescence in the Mare's Tail can be defined as the aggregation of small oil droplets due to electrostatic forces of attraction between the oil droplets particles and operating fibre medium. The oleophilic fibres used in the Mare's Tail help to coalesce smaller oil droplets into bigger droplets. This is achieved by several forces like interfacial surface tension, dispersion and dipolar effect, cohesive attraction, drag, kinetic and gravity forces acting between oil droplets and the fibres. Coalescence is also affected by zeta potential in the oil droplet.

An oil droplet has an uneven charge distribution, also known as the London Dispersion Effect[8]. This uneven distribution can lead to the dipolar effect i.e. change in the shape of the molecule due to the presence of an external electrical field when it comes into close proximity with the Mare's Tail media. This mechanism promotes an initial attraction of the droplets to the Mare's Tail fibre media. This primary coalescence is followed by cohesive attraction or intermolecular attraction between like molecules. Cohesive attraction can then lead to a weak boundary layer condition, which aggregates the oil droplets further.

The size of an oil droplet plays a vital role in coalescence due to cohesion. If the size of the oil droplet is bigger the charge distribution will be higher, and there will be little or no zeta potential i.e. voltage difference between the inner and the outer layer of the droplet which leads to a weak boundary layer condition. Capillary forces i.e. the ability of a substance to draw another substance into it and the surface tension properties of the Mare's Tail media promote further coalescence. These are forces that occur due to the surface energy of the media towards the oil droplets. The droplets are attracted to and encapsulate the fibre media surface. Drag, gravity and kinetic energy of the oil droplet entering the Mare's Tail system act on the big droplets i.e. droplets that have already coated the media, and break their boundary layer to form a bigger droplet. The force due to gravity helps in increasing the residence time of the droplet, and the drag and kinetic energy helps the droplet to collide with media surface. Thus as the produced water travels along the oleophilic fibres, small oil droplets are attracted to the surface and coalesce with other droplets as they migrate towards the outlet. The direction of flow along the fibres, rather than across it means that any solids are passed through the Mare's Tail rather than building up within the media.

Definition of Mare's Tale Coalescence Efficiency

The coalescence efficiency of the Mare's Tail is here defined as the measure of the concentration of the coalesced oil droplets as a function of the total concentration of the inlet droplets. Expressed mathematically,

$$\eta_c = \frac{C_{oi} - C_{oo}}{C_{oi}} \qquad \ldots 1$$

Where:
C_{oi} = Concentration of oil droplet of size d_i at inlet
C_{oo}= Concentration of effluent oil droplet of diameter d_i

The Coalescence Efficiency Model

The stability and coalescence efficiency of the Mare's are a complex physical and chemical phenomena influenced by the following key parameters:

- Flow rate, q
- Spool diameter, D_s
- Cartridge diameter, D_c
- Fluid density, ρ_{fluid}
- Fluid viscosity, μ_{fluid}.
- Cumulative volume of produced water, Q
- Production time, t
- Length of the Spool, L_s
- Porosity, ϕ
- Inlet oil diameter, d_i
- Inlet oil concentration, C_o
- Density of polypropylene, ρ_{pp}
- Differential pressure across the Spool/cartridge, ΔP
- Specific surface area of the media, S_{pp}
- Specific surface area of the oil droplet, S_{oil}
- Pack structure, B
- Interfacial surface tension, γ
- Production time, t

Expressed mathematically, the coalescence efficiency of the Mare's Tail is given as:

$$\eta_c = f\begin{bmatrix} q, D_s, D_c, \rho_{fluid}, \mu_{fluid}, Q, \\ L_s, \phi, d_i, C_o, \rho_{pp}, \Delta P, \\ S_{pp}, S_{oil}, B, \gamma, t \end{bmatrix} \qquad \ldots .2$$

η_c = Coalescence Efficiency of Mare's Tail

A correlation between the coalescence efficiency and the average coalesced oil droplet size will subsequently be established as part of the project objectives.

The coalescence efficiency model for the Mare's Tail can be derived as:

$$\eta_c = K * \left(\begin{array}{l} \left[\frac{D_c}{L}\right]^a * \left[\frac{(D_s - D_c)}{D_c}\right]^b \\ * \left[\frac{\phi}{L_s * S_{pp} * (1-\phi) * B}\right]^c \\ * \left[1 - \frac{C_o}{\rho_{pp}}\right]^d * \left[\frac{S_{oil}}{S_{pp}}\right]^e * \left[\frac{\Delta P * D_c}{\gamma}\right]^f \\ * \left[\left(\frac{\rho_{pp}}{\rho_{fluid}} - 1\right) * \frac{D_{pp}}{D_c}\right]^g * \left[\frac{D_c}{d_i}\right]^h \\ * \left[\frac{D_c * \mu_{fluid}}{\rho_{fluid} * q}\right]^i * \left[\frac{Q}{q * t}\right]^j \end{array} \right) \quad \ldots 3$$

K, a, b, c, d, e, f, g, h, I, j are empirical constants which have been evaluated from experimental test data.

Results and Discussions

Highlights of the JIP Studies [6, 7]

Highlights of results from the JIP studies are presented in Figures 6-7.

Highlights of Model Predictions

The selected experimental data generated from the JIP studies were compiled to set up a development database and test database. The development database was used to derive the empirical constants which were subsequently tested. The model prediction showed a basic accuracy level of 90% with a regression coefficient of 57%.

The preliminary studies to date based on the analysis of both the original JIP data and ongoing model predictions have confirmed that the major parameters affecting the Mare's Tail coalescence efficiency are:

1. Produced Water Flow rate, q[Figure 8]
2. Mare's Tail Length , Ls[Figure 9]
3. Mare's Tail Spool/Cartridge Diameter, D_s, D_c [Figure10]
4. The Cartridge Diameter to Length ratio, D_c/L_s [Figure 11]
5. The Oil droplet concentration, C_o [Figure 13]
6. The Oil droplet viscosity, μ_{oil} [Figure 14]

Effect of Flow Rate [Figure 8]

The Mare's Tail model prediction indicates that the coalescence efficiency is hyperbolically proportional to the produced water flow rate which is possibly enhanced by the prevailing turbulent flow regime in the spool.

Effect of Spool Length and Diameter [Figures 9 to 13]

The coalescence efficiency appears to increase with increase in length in a power law relationship the magnitude of which is inversely proportional to the spool diameter [Figure 9]. The smaller the diameter the higher the efficiency as depicted by the 2'' and 4'' spools relative to the 6'' spool [Figure 11]. Overall the efficiency plateaus at some critical lengths as illustrated by the Efficiency versus D_c/L relationships [See Figures 12 and 13].
These results substantially validate the initial findings from the JIP studies [See Figure 7]

Effect of Oil droplet Viscosity and Concentration

Detailed comparative analysis carried out on light and heavy crude oil with viscosities of 3cp and 250cp respectively confirms that the Mare's Tail performs better in the presence of heavy oil droplets with the coalescence efficiency increasing with increase in viscosity [Figure 13]. This same trend of increase is also prevalent when reviewing the effect of oil droplet concentration [Figure 14]. A possible exception would be oil-water emulsion [which is usually more viscous than its equivalent individual phases] the analysis of which will be carried out as part of planned further experimental studies.

Future Work

Future work will focus on but not limited to the following:

- Further experimental validation of the MT performance
- Comparative analysis of the efficiency of woven fibres versus MT mop
- Condensate and heavy oil separation analysis
- CFD analysis of the different flow phenomena including the entry and exit effects.
- Finite Element Analysis of the stress mechanics as a precursor towards evaluating the potential of the MT for subsea processing.

The Opus Plus Test Facility

The test facility at Opus Plus Limited was originally opened in 1988 to support the development and testing of full scale offshore water treatment equipment. Initially known as the Orkney Water Test Centre (OWTC), the company is established as an internationally recognised facility specialising in effluent treatment and water handling.

A wide range of industry projects has been conducted since the centre's opening covering numerous onshore and offshore effluent treatments and separation technologies. Work has been carried out for oil and gas operators, equipment vendors, research sponsors as well as consortiums of companies on a Joint Industry Project basis.

The unique facility provides an extension to Operators and suppliers resource for validation and R&D, with the following capabilities:

- Testing at actual or near field conditions to provide high confidence levels.
- Safe, trouble free discharge of effluent from testing, allowing once through flow,
- Maintaining consistent operating parameters.
- The opportunity to verify performance and operating envelopes.
- A cost effective way of gaining comparative data on available technologies prior
- On site heavy and medium crude oil ensures valid operating conditions
- Confidentiality and security in results demanded by the Oil and Gas industry.
- Expertise of the Opus team provides a versatile service for performance validation, product research or product development.
- Extensive support facilities including analytical laboratories and equipment, fabrication workshop and mechanical handling

Conclusions

1.The development and especially the field application of the Mare's Tail for de-oiling produced water have confirmed that the Mare's Tail has a highly competitive advantage over other conventional produced water management technologies in delivering greatly improved quality of produced water without the use of chemical.

2.The Mare's Tail which operates on coalescence principle is the original product of a joint industry project initiated in 1998. The 1st generation of the Mare's Tail is now being utilised in different parts of the world.

3.To improve its performance further especially with respect to achieving a design optimisation that is fit-for-purpose and real-time process optimisation onsite a new support semi-empirical model which can be used in real-time has been developed, tested and in the process of being validated as part of the collaborative programme between The Robert Gordon University and Opus Plus under the Knowledge Transfer Partnership in the UK.

4.The new model can be used to evaluate the coalescence efficiency of the Mare's Tail under different operating conditions.

5.Preliminary testing of the Mare's Tail Coalescence efficiency model shows good agreement with the preceding JIP experimental data.

6.Analysis carried out to date, has confirmed that the Mare's Tail Coalescence Efficiency is substantially affected by flow rate, flow regime, spool length to diameter ratio, oil droplet concentration and viscosity.

7.This new model will form the foundation of the 2nd Generation Mare's Tail development as part of the KTP project study.

Nomenclature

B = Cartridge Fibre Pack Structure
C_o = Inlet oil Concentration, mg/lt
d_i = Inlet oil diameter, m
D_c = Cartridge diameter, m
D_s = Spool diameter, m
L_s = Spool Length, m
ΔP = Spool Pressure Drop, N/m^2
q = Flow rate, m^3/hr
Q = Cumulative Production, m^3
S_{oil} = Specific surface area of the oil droplet, m^{-1}
S_{pp} = Specific surface area of the media
t = Production time, hr
μ_{fluid} = Produced water viscosity, Ns/m^2
ρ_{fluid} = Produced water density, kg/m^3
ρ_{pp} = Polypropylene fibre density, kg/m^3
ϕ = Cartridge porosity
γ = Interfacial tension, mN/m
η_c = Coalescence Efficiency

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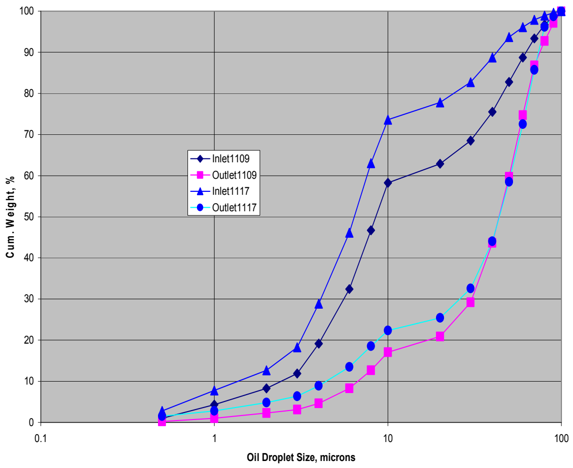

Figure 6: Mare's Tail Oil droplet size distribution at inlet and outlet - Result of JIP Studies [6, 7]

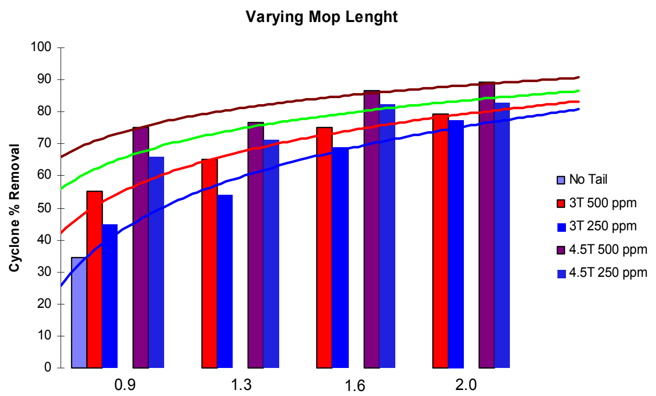

Figure 7: Effect of Mare's Tail Length on Coalescence Efficiency-Result of JIP Studies[6, 7]

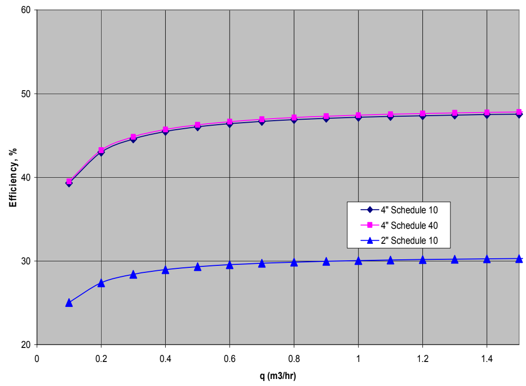

Figure 8: Effect of Flow rate on Mare's Tail Coalescence Efficiency

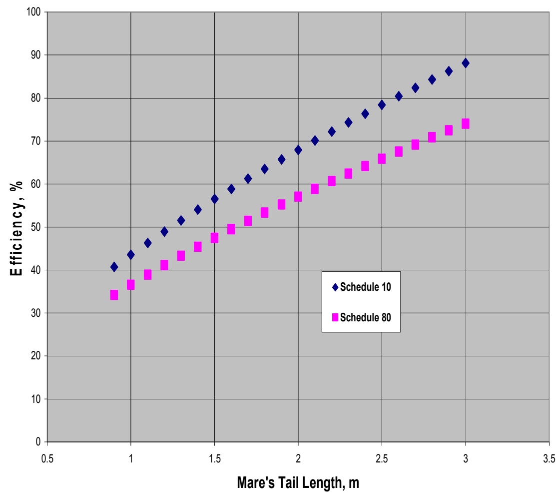

Figure 9: Effect of Spool length and Schedule on Coalescence Efficiency [2'' Spool]

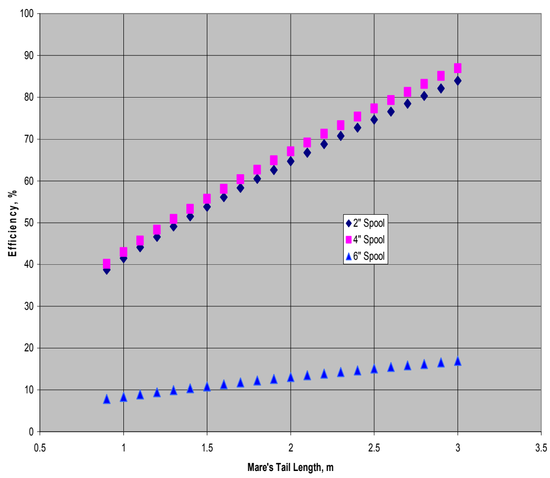

Figure 10: Effect of Spool length and Diameter on Coalescence Efficiency

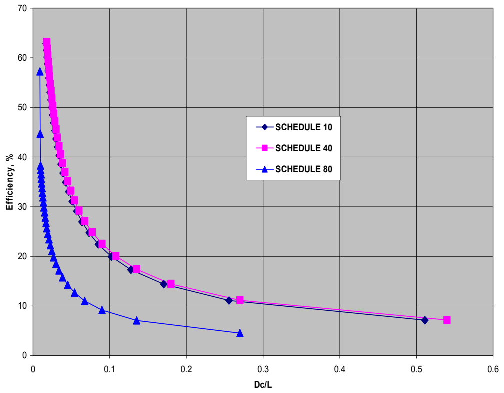

Figure 11: Effect of Dc/L on Coalescence Efficiency

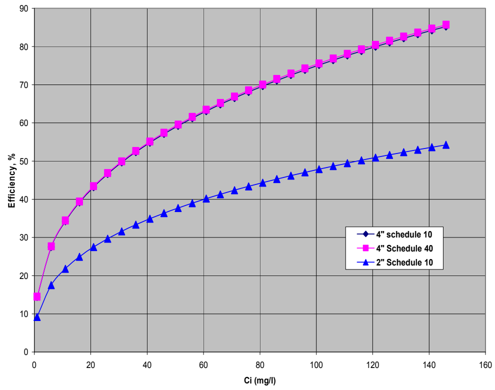

Figure 14: Effect of Oil Droplet Concentration on Coalescence Efficiency

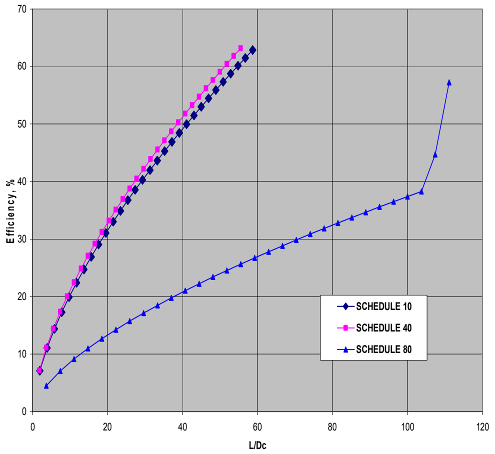

Figure 12: Coalescence Efficiency versus L/DC

Figure 15: Opus Test Facility

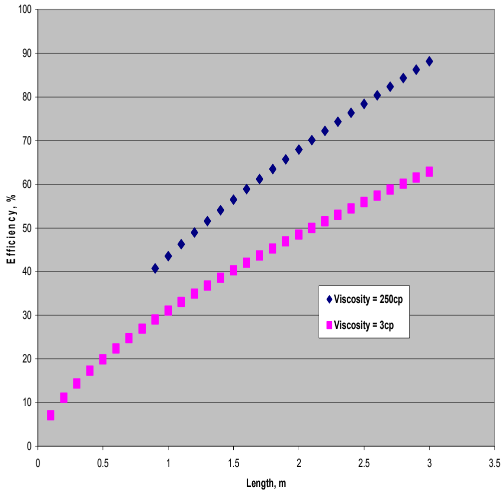

Figure 13: Effect of Viscosity on Coalescence Efficiency

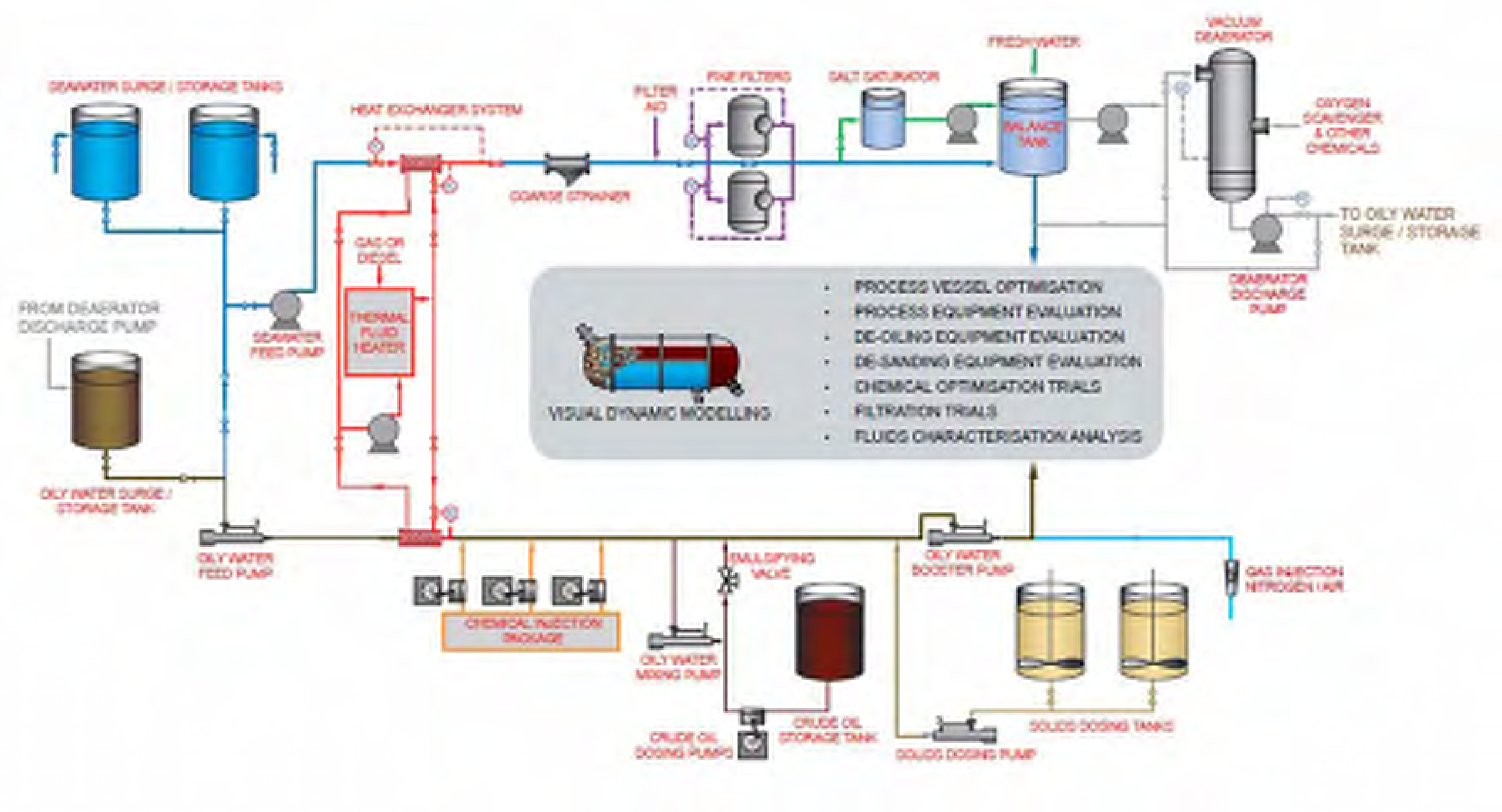

Figure 16: Schematic of Opus Test Facility