University of Exeter coursework header sheet

ECMM102 Group Project (Meng) (A, TRM1+2 2017/8)

Extension
046138

1029795

640025916

Coursework: Group report and presentation
Submission Deadline: Mon 14th May 2018 12:00
Personal tutor: Dr Julian Londono Monsalve

Marker name:	N/A
Word count:	6973

First marker's comments	Indicative mark
Second marker's comments	Second mark
Moderator's comments	Agreed mark

G2 Report

Experimental and Numerical Investigation into the use of Olive Stone Powder as a Substitute for Primary Sludge Modelling

2018

4^{th} Year MEng Group Project

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I certify that all material in this thesis that is not my own work has been identified and that no material has been included for which a degree has previously been conferred on me.

Signed ...... Signatures in above Table ......

College of Engineering, Mathematics, and Physical Sciences

University of Exeter

G2 Report

ECMM102

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Word Count: 6973

Number of Pages: 20

Date of Submission: May 12, 2018

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Programme: MEng Mechanical Engineering

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1 Group Objectives and Deliverables

Wastewater is regarded as the waterborne waste products of man. It has always existed, and the importance of its treatment has only grown due to the large amount created by modern congregated communities. If left untreated, wastewater has negative effects on society and the ecosystem, ranging from waterborne pathogens to endangering local wildlife. Generally, wastewater treatment is divided into four stages: preliminary, primary, secondary and tertiary treatment. The preliminary treatment stage is focused on the removal of larger debris. The primary treatment stage is concerned with the settlement of suspended solids that were not removed during preliminary treatment. A primary settling tank (rectangular or radial) is used, and the by-product, primary sludge, is created [1]. Secondary and tertiary treatment were not within the scope of the project and so will not be discussed.

Several studies have been conducted with the goal of understanding and improving the overall process of wastewater treatment. Specifically, Computational Fluid Dynamics (CFD) has been used to perform numerical simulations of settling tanks to more economically determine design improvements. Other studies have been performed to determine a good substitute for the suspended solids in wastewater that settle to form primary sludge, as to facilitate experimental laboratory work. Olive Stone Powder (OSP) has historically been a substance used as a wastewater and sludge substitute [2, 3].

1.1 Group Aims and Objectives

The aim of this project was to perform CFD simulations of the primary settling process of wastewater treatment. An OSP and water suspension was used as a substitute to real wastewater. The simulations were to be validated with empirical studies carried out in the University of Exeter Fluids Laboratory on a Hydrodynamic Vortex Separator (HDVS) Swirl-Flo® and a modified ARMFIELD W7 model rectangular sedimentation tank. To achieve this, the project was divided into four main objectives:

(i) Determine the characteristics of the OSP and water mixture, i.e. its rheology and settling velocity.
(ii) Create CAD geometries and meshes for the sedimentation devices. Compare different meshing software, investigate mesh parameters and automation.
(iii) Use the CFD code OpenFOAM® to perform CFD simulations of the sedimentation devices.
(iv) Validate the CFD simulations with empirical studies carried out in a controlled laboratory environment.

1.2 Group Deliverables

Successful completion of the objectives leads to the following:

(i) An in-depth literature review of wastewater modelling techniques.
(ii) A mathematical model for both the rheological and settling velocity behaviour of an OSP and water suspension.
(iii) CAD geometries of the sedimentation devices with meshed internal domains.
(iv) Comparison of automated and bottom-up meshing approaches.
(v) Understanding and documenting the parameters that enable good mesh quality generation with irregular geometries.
(vi) Two empirically studied and compared sedimentation devices.
(vii) Two-phase CFD simulations of both sedimentation devices.
(viii) An experimentally validated CFD model for the behaviour of a sedimentation device, using an OSP and water suspension.
(ix) Investigated design improvements for the Swirl-Flo® from CFD and empirical studies.

2 Work Programme - Individual Work Packages

In order to complete the group deliverables, the project was divided into seven individual work packages. The details of each work package are shown in the proceeding sub-sections. Figure 1 shows how the work packages interrelate. It can be seen that they are categorised into 3 sub-groups; Experimental, Meshing and Simulation. As such, the group was divided into these three sub-groups based on the work package assignments.

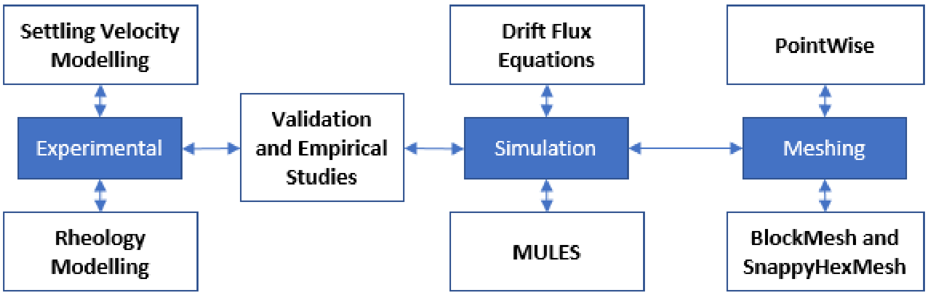


Figure 1: Illustration of individual work packages and how they relate to each other.

2.1 Experimental Sub-Group

2.1.1 Settling Velocity Modelling

This work package focused on the development of a mathematical model to describe the settling characteristics of the OSP. This model was to be used for the CFD simulations on both the rectangular and Swirl-Flo® tanks. The main objective of this was to produce an accurate model that was validated against experimental results. A secondary objective was to compare this settling behaviour with a known mathematical model for wastewater to conclude whether it is a suitable wastewater substitute. Also covered in this work package was the design and manufacture of several pieces of experimental equipment for the group. The group deliverables this package focused on were (i) and (ii) from Section 1.2.

2.1.2 Rheology Modelling

This work package involved the study of what parameters affect the rheological behaviour of the OSP and water suspension. The main objective was to determine a mathematical viscosity model that can accurately describe the behaviour of the suspension at different particle concentrations. This model was to be used in the CFD simulations of the sedimentation tanks. To achieve this, focus was placed on experimental work which included determining particle size distribution, particle shape, maximum packing fraction of the OSP particles and rheological studies with a rotational rheometer at different particle concentrations. The group deliverables this package focused on were (i) and (ii) from Section 1.2.

2.1.3 Validation and Empirical Studies

This work package focused on the validation of the CFD simulations using the experimental results. This involved obtaining the raw data from flow measurements and concentrations and converting it into clear and useful information utilising various plots. These results were then compared to each other and to the simulation results to achieve the stated group deliverables (vi) and (viii) from Section 1.2.

2.2 Meshing Sub-Group

2.2.1 Geometry and PointWise®

The Pointwise® work package was composed of 3 main objectives associated with CFD preprocessing. Initially, geometries for both the rectangular and Swirl-Flo® tanks were created in SOLIDWORKS®. These were used for all the simulations within this report and were created using experimental measurements to ensure an accurate model. Secondly, a structured mesh for the rectangular tank was created. The simpler geometry was used as the basis for a high-efficiency structured mesh. Finally, due to the complexity of the Swirl-Flo® it was decided that the mesh would be based on an unstructured grid. This initiated a study into hybrid mesh performance. Meshing techniques using Pointwise® were then compared. The work package is associated with deliverables: (iii), (iv), (v) and (vii) from Section 1.2.

2.2.2 `BlockMesh` and `SnappyHexMesh`

The native OpenFOAM® meshing utilities `blockMesh` and `snappyHexMesh` were utilised to produce high quality meshes of the sedimentation devices used in the simulation sub-group work packages. `snappyHexMesh` was selected as it is a fully automated cut-cell meshing software [4], thus allowing the generated meshes to be compared to the computational grids produced using the bottom-up meshing approach of Pointwise®. The meshing utilities were also used to generate computational grids for use in two-phase Volume of Fluid (VOF) simulations; these were performed to determine the validity of the rigid lid assumption used in the `driftFluxFoam` simulations. The aim of this work package was to fulfil the group deliverables (iii), (iv), (v) and (vii) in Section 1.2.

2.3 Simulation Sub-Group

2.3.1 Rectangular Tank and Settling Tubes

This work package revolved around the multi-phase simulations for the rectangular tank and the settling tubes, both of which were to be compared to empirical results. An understanding of Multi-Dimensional Universal Limiter of Explicit Solutions (MULES) was to be obtained and its use in solvers studied. Full two-phase simulations of the rectangular tank with differing settling models were to be performed and the results from these analysed. This section provides one of the two models for deliverable (vii) and simulations of the settling tubes provides a computational model to validate the results for the settling velocity in deliverable (ii).

2.3.2 Drift Flux Equations

A multi-phase solver application had to be used in this project. A simplification of the Two-Fluids model, the Drift Flux model, presents a single momentum equation formulated around the mixture centre of mass. This describes the overall motion of the fluid, with the relative motion of the dispersed phase being predicted by a convection-diffusion equation, having drift velocity prescribed by empirical study, [5].

Taking understanding of the techniques of Drift Flux forward allows for creation of accurate case files and efficient manipulation of the subsequent fields and schemes. The primary objective of this work package was to understand the behaviour of the discretised Drift Flux model, whist validating and justifying the use of `driftFluxFoam` as a secondary objective. This is with the aim to produce a computationally efficient and reliable numerical solution, to be comparable and validated by experimental data: group deliverables (vii) and (viii).

3 Methodology

The proceeding sub-sections describe the methodologies followed by the 3 sub-groups.

3.1 Experimental Sub-Group

3.1.1 Powder Modelling

In order to model the powder within the CFD simulations, two important behaviour parameters needed to be modelled: the settling velocity, and the rheology.

To create the settling model for the powder it was first necessary to carry out in-depth research into settling theory. Doing this allowed the selection of the Takacs model [6] to use as a basis for model development. Using this model allowed the identification of several key settling parameters. These were found for the powder using a series of calculations, experiments, and curve fittings. From these, two models were produced for the powder: one using half the parameters for the powder, and half from literature for wastewater, and the other model being a full curve fit of the batch settling experiment data. The results from simulations using these 2 models were compared with experimental results to decide which one produced the most physical results.

To pick the viscosity model, particle characterisation and rheological experiments were carried out. These included using a RETSCH AS 200 Control mechanical sieve shaker to determine the particle size distribution, using a TESCAN VEGA3 Scanning Electron Microscope to directly photograph the particles to determine the mean particle aspect ratio, random-close packing experiments to determine the densest arrangement of randomly packed olive stone particles and finally a rheological study of the olive stone suspension at different particle concentrations with a BROOKFIELD DV-III ULTRA coaxial rotational rheometer. From these experimental results, curve fitting was done to determine the best mathematical viscosity model.

3.1.2 Validation and Empirical Studies

To obtain experimental results, various instruments and methods were utilised. For both tanks the experimental procedure was the same with any differences stated. The tank would be filled with clean water and when full, the pump would start the addition of the OSP slurry to the tank. The experiment times were taken from when the powder first appeared in the tank. The inflow and outflow flow rates were then measured and recorded.

Samples were taken at both the overflow and underflow at predetermined times throughout the experiment, so that concentrations could be determined to identify when a steady-state concentration was achieved. These samples were then filtered to determine the mass of OSP in the known sample volume, enabling the determination of concentration with respect to time. Due to the unknown time to steady-state concentration, velocity measurements commenced 1 hour 30 minutes into the experiment, at predetermined measurement points, with a propeller-meter and Vectrino Profiler (Acoustic Doppler) being utilised to determine velocities through various data processing methods. These processing methods entailed the use of an equation for the propeller-meter and a MATLAB® script for the Acoustic Doppler and the presentation of the velocities in various plots. The experimental results from both tanks were compared with each other and the simulation results.

3.2 Meshing Sub-Group

3.2.1 Pointwise®

3.2.1.1 Rectangular Tank

A structured mesh relies on regular connectivity. Therefore, the distribution of boundary points has been designed so the number of grid points on opposite boundaries are identical. During CAD clean up, all outer edges were removed to isolate only the interior edges. The mesh was cut at a water level height of 5mm above the outlet weir. Doing so reduced computational cost of unused cells. The planning and implementation of a scaffold is vital to mesh quality. It highlights the viability of a structured mesh on a geometry without large time investments. Once planned, a scaffold is produced so all features of a mesh are accounted for before gridding. The multi-block technique is time consuming and requires careful application of both the dimension of connectors and their distribution. The distribution tool was used to create layers with an initial height of 1.6mm; this was chosen by calculating maximum velocities within the tank and using Pointwise®'s y^+ calculator [7] to find an initial spacing for a desired value of 30. Upon completion, skewed domains and blocks are smoothed using Pointwise®'s PDE elliptic solver tool. A successful automation study found limited iterative design improvements were possible through the use of journaling.

3.2.1.1 Swirl-Flo®

A hybrid approach was adopted for mesh generation of the Swirl-Flo® with the aim of reducing mesh construction times. Central cylinder/cone setup, inlets and outlets were to be structured using multi-block OH technique. The tray area was later converted to a structured domain to improve mesh quality. All remaining unstructured surface domains were blocked and initialised using anisotropic tetrahedral extrusion (T-Rex), taking advantage of its flexible attributes, allowing for automation. When extruding using T-Rex, all layers grew to isotropy ensuring a smooth transition to the unstructured Delaunay tetrahedral volume with exception to encroaching fronts interrupted by skew criteria.

`simpleFoam` studies were conducted to highlight regions of high velocity. From this, initial wall spacing could be calculated for a desired y^+ value of 30. Parameter studies were conducted to understand how changes to T-Rex settings affected final results. Attention was given to all hybrid interface regions, ensuring consistent volume ratio between hexahedra and tetrahedra at the interface. This approach attempted to find a consensus between *bottom-up* approaches and *top down* automation and therefore keeping quality metrics from the former and flexibility of the latter.

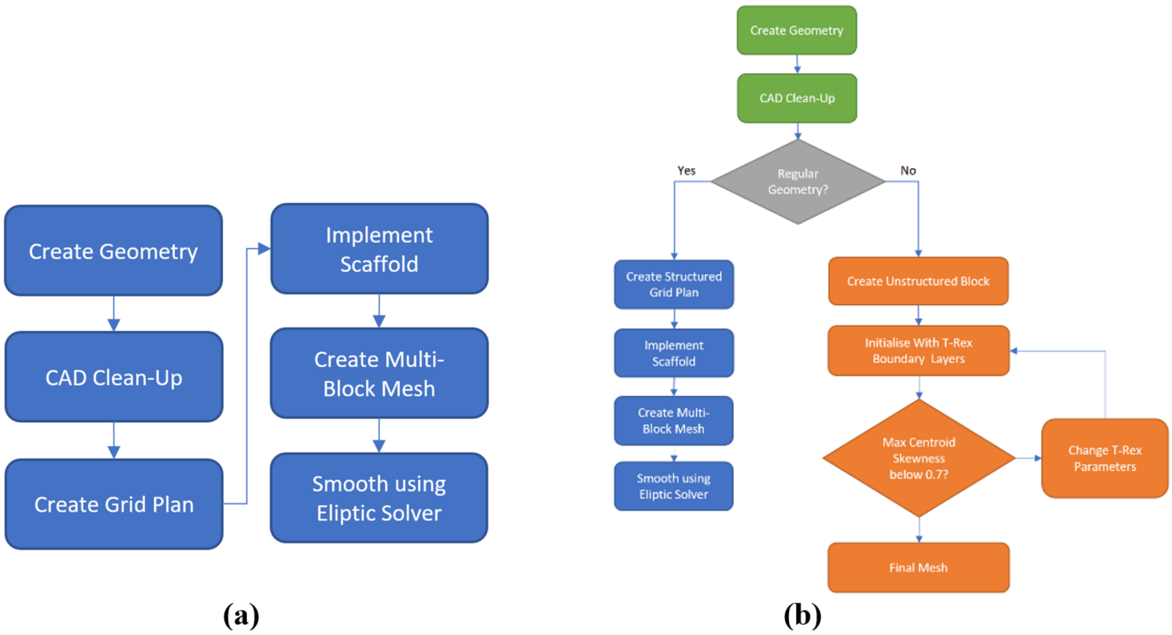


Figure 2: a) Flowchart showing methodology for structured mesh creation within Pointwise® b) Flowchart showing the methodology for hybrid mesh creation within Pointwise®.

3.2.2 BlockMesh and SnappyHexMesh

The native OpenFOAM® meshing utilities `blockMesh` and `snappyHexMesh` were used to generate computational grids of the rectangular tank and the Swirl-Flo®. Compared to Pointwise®, which uses a bottom-up meshing approach, `snappyHexMesh` is fully automated and is controlled using an OpenFOAM® C++ dictionary instead of a graphical user interface. As part of the meshing process, `snappyHexMesh` requires a background mesh containing only hexahedral cells with aspect ratios of one, [4]. These were created using the `blockMesh` utility.

snappyHexMesh also requires that the geometry to be meshed is provided as a closed Stereolithography (STL) file, [4]. High quality closed STLs of the sedimentation devices were created using the open source CAD software SALOME, as those produced by SOLIDWORKS® did not form a closed boundary. A parameter study was also undertaken to gain an understanding of how changes to snappyHexMesh settings affected the quality and geometric accuracy of the meshes produced. The OpenFOAM® checkMesh utility was used to evaluate the former which calculated the maximum and average values of aspect ratio, non-orthogonality and cell face skewness. A custom utility written by Fabritius and Tabor [8] was used to provide a quantitative measure of the meshing accuracy.

Using initial meshes produced for the Swirl-Flo®, the single phase steady-state solver simpleFoam was employed to quickly identify regions containing high velocity gradients. To increase computational efficiency, only cells present in these regions were refined.

3.3 Simulation Sub-Group

3.3.1 Rectangular Tank and Settling Tubes

For the rectangular tank, a Pointwise® mesh was provided by the meshing team. This mesh was inserted into the *polyMesh* subdirectory of the *constant* directory. This directory was also used to enter system constants such as gravity and the turbulent/transport properties. The initial conditions of the system were defined in the *0* directory. The tank was to start full of static, clean water. The inlet flowrate was set to $22.4lmin^{-1}$, the alpha value at the inlet was 0.0002 and the underflow rate was $1.3lmin^{-1}$. The *system* directory was then used to define parameters regarding the solution itself. Details of the runtime and solver were defined here.

The rectangular tank case was then altered to create a settling tube case. Once the cases had been formed, they could be run in parallel over multiple processors on the server using driftFluxFoam. Different settling models and alpha values were tested and Table 1 summarises the simulations which were performed in this section of the project.

Once each simulation had been run, the files were saved both locally and to portable hard drives to be analysed in post-processing.

Table 1: Table showing the different simulations run for the rectangular tank and settling tubes

Simulation Name	Geometry	Time (s)	alphaResidual	v_0 (ms^{-1})	a	a_1	α_{in}
Model1 Armfield	Armfield	1100	$2.086e-08$	0.00824	719	7190	$2e-04$
Model2 Armfield	Armfield	1100	$1.283e-05$	0.0038	719	7190	$2e-04$
Model1_alpha2	Settling Tube	1800	$2.086e-08$	0.00824	719	7190	$3.41e-03$
Model1_alpha3	Settling Tube	1800	$2.086e-08$	0.00824	719	7190	$8.08e-04$
Model2_alpha2	Settling Tube	1800	$1.283e-05$	0.0038	719	7190	$3.41e-03$
Model2_alpha3	Settling Tube	1800	$1.283e-05$	0.0038	719	7190	$8.08e-04$
Model3_alpha2	Settling Tube	1800	$1.283e-05$	0.00109	1064	10814	$3.41e-03$
Model3_alpha3	Settling Tube	1800	$1.283e-05$	0.00109	1064	10814	$8.08e-04$

3.3.2 Drift Flux Equations

Initial simulations were run on the rectangular tank, starting with studies into the justification of using `driftFluxFoam`. Models were run with various viscosity and settling velocity models from the experimental group, and results were compared. Parallel to this, slight variations in *fvSolutions* and *fvSchemes* were made as a computational efficiency study. This was with reference to various integration and interpolation schemes, and how the Drift Flux model is expressed in OpenFOAM®. In particular, loop tolerance for the pressure field, and pressure solver were tested. The complexity of `driftFluxFoam` meant any alteration to running parameters could affect solution time. The aim was to find a balance between accuracy of results and run-time in order to allow for the most efficient solution to the Swirl-Flo® model. From these results, optimum case files for the Swirl-Flo® were fabricated with *system* parameters tuned to the project scenario and behaviour of provided mesh.

3.3.3 Volume of Fluid Simulations

Two phase water-air simulations were performed using the VOF solver `interFoam`. To reduce computational time, the rectangular tank was modelled in 2D using the `blockMesh` utility. This meant that a high level of cell refinement could be employed in the water-air interface region to accurately capture the free surface height. An equation based on the theoretical residence time of the tank was derived for scaling the experimental inlet and outlet flowrates to the 2D case.

A coarse 3D mesh of the Swirl-Flo® with approximately 1.6 million cells was used, with a higher resolution refinement region used at the overflow to more accurately capture the interface. The simulation was performed for 300 seconds, twice the calculated theoretical residence time of the Swirl-Flo®. This was done to allow transient effects to dissipate.

Turbulence was modelled for the Swirl-Flo® simulations using the realisable $k-\epsilon$ model. This was a compromise between using the less accurate standard model $k-\epsilon$ (for swirling flows) and the computationally expensive (but more accurate) Reynolds Stress Model, [9].

For both sedimentation devices, the water level in the domain was set to be just below the overflow at $t = 0s$ using the `setFields` utility, reducing the computational time required to reach stable free surface heights. The interface compression scheme was also used to discretise the VOF compression term, to produce a reasonably sharp interface resolution [10].

4 Data Analysis, CFD Results, and Validation

4.1 Olive Stone Powder Models

4.1.1 Settling Velocity Model

It was found that the model that best represented the physical behaviour of the powder in the rectangular tank was Model 3, shown in equation 1 where α is the particle volume fraction, ρ_f is the density of the fluid, ρ_m is the combined density of the mixture and U_{pj} is the particle phase settling velocity. However, the results for both the mass overflow and underflow were both a factor of 10 away from the experimental results which indicates the model did not perform well. The model produced a sedimentation pattern similar to that of the experiments which, alongside overestimating the underflow mass flow rate and underestimating the overflow mass flow rate, indicates the model overestimates the settling velocity. From this, a fourth slower settling model was developed to test this theory which is ongoing.

$$\mathbf{U_{pj}} = \frac{\rho_f}{\rho_m} 0.00109(e^{-1064(\alpha-1.3\times10^{-5})} - e^{-10813(\alpha-1.3\times10^{-5})}) \quad where\, \mathbf{U_{pj}} > 0 \tag{1}$$

4.1.2 Viscosity Model

The particle size distribution analysis showed that the particle size range that had the largest amount of powder was between $125\mu m$ and $32\mu m$ The average aspect ratio of the particles within this range was 1.52 ± 0.04. The experimental maximum packing fraction of the particles was determined to be 0.46 ± 0.07. The rheological behaviour of the OSP suspension was determined to be rapidly settling, time dependent and shear thinning. The viscosity model that most accurately predicted the behaviour of the suspension was the one proposed by Mueller in 2010 [11]. This is a modified version of the Herschel-Bulkley model [12].

$$\tau = \tau_y + K\,\dot{\gamma}^n \tag{2}$$

Where τ_y is the yield stress (Pascal), K is the consistency (Pa.s) and n is the flow index. Mueller's modified equation has all these parameters as functions of particle volume fraction, maximum packing fraction and average particle aspect ratio.

$$n = 1 - 0.2 r_p \left(\frac{\alpha}{\alpha_m}\right)^4 \quad (3) \qquad K = \mu_0 \left(1 - \frac{\alpha}{\alpha_m}\right)^{-2} \quad (4)$$

$$\tau_y = \tau^* \left(\left(1 - \frac{\alpha}{\alpha_m}\right)^{-2} - 1\right) \quad (5)$$

Where $\tau^*$and α_m are fitting parameters. μ_0 is the dynamic viscosity of the suspending medium and r_p is the average aspect ratio of the particles. For the OSP and water suspension the following values were used: $\tau^* = 0.000065 Pa$, $r_p = 1.52$ and $\alpha_m = 0.33$. However, it was determined that this viscosity model was not viable due to it being computationally expensive: 50 simulated seconds taking 8 and half days to complete. In its place, the Thomas [13] viscosity model was used for the simulations.

4.2 Final OpenFOAM® Meshes

The final meshes produced using `snappyHexMesh` and Pointwise® of the rectangular tank and Swirl-Flo® geometries are shown in Figures 3 and 4. Mesh quality metrics for each computational grid are given in Tables 2 and 3.

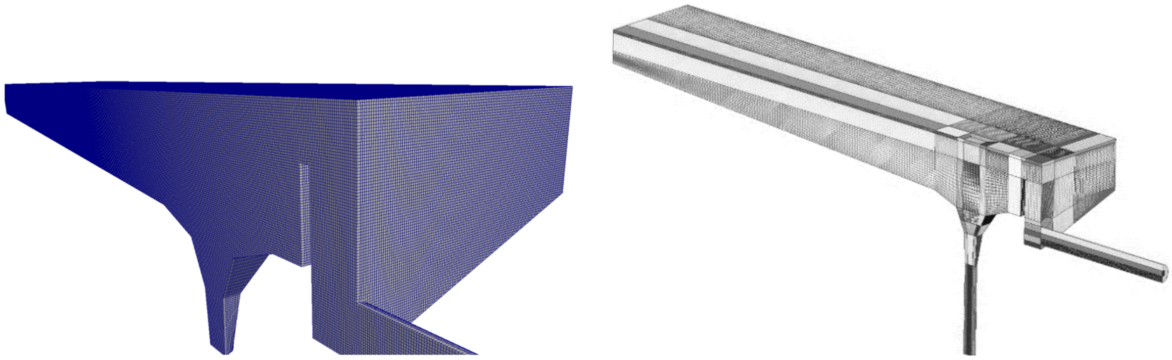
4.2.1 Rectangular Tank

Table 2: Mesh quality metrics reported by `checkMesh` for `snappyHexMesh` and Pointwise® meshes for the rectangular tank

Mesh Generation Software	Maximum Aspect Ratio	Maximum Non-Orthogonality ^{o}	Average Non-Orthogonality ^{o}	Maximum Skewness	Maximum Mesh/STL Difference	Total Cells
`snappyHexMesh`	5.29	42.8	6.3	2.4	$0.3mm$	$1,364,254$
Pointwise®	20.38	35.4	5.9	1.77	N/A	$629,466$

The final structured Pointwise® mesh used a 94 multi-block structure and took a total of 10 hours to construct. The Pointwise® mesh had a maximum centroid and equiangular skew of 0.408 and 0.58 respectively, with the interior angles of all quadrilaterals between 32° and 127°. Mesh quality metrics reported by `checkMesh` are shown in Table 2. It being structured meant there was a low maximum and average non-orthogonality and had half the total cells when compared to the unstructured, `snappyHexMesh` grid.

The `snappyHexMesh` took a total of 4 hours to pre-process and 64 seconds to generate. This makes its generation $\approx 60\%$ faster than the Pointwise® counterpart. It still had favourable mesh metrics with low non-orthogonality and a maximum snapping inaccuracy of $0.3mm$. The snappyHexMesh grid's maximum aspect ratio was a quarter of Pointwise®'s; this is because snappyHexMesh modifies a background mesh containing cells with aspect ratios of 1.



(a) **(b)**

Figure 3: Rectangular Tank meshes produced using (a) snappyHexMesh (b) Pointwise®

4.2.2 Swirl-Flo®

Table 3: Mesh quality metrics reported by checkMesh for snappyHexMesh and Pointwise® meshes for the Swirl-Flo®

Mesh Generation Software	Maximum Aspect Ratio	Maximum Non-Orthogonality ^{o}	Average Non-Orthogonality ^{o}	Maximum Skewness	Maximum Mesh/STL Difference	Total Cells
snappyHexMesh	7.81	64.5	7.5	2.4	$0.6mm$	$2,525,201$
Pointwise®	25.3	75.6	13.65	2.1	N/A	$4,686,638$

For the driftFluxFoam simulations, a mesh produced using snappyHexMesh was employed as it was discovered that the solver would diverge for the Swirl-Flo® mesh produced by Pointwise®. This was attributed to the Pointwise® mesh having 43/12,967,342 faces with a non-orthogonality greater than 70^o. While the mesh produced using snappyHexMesh had no severe non-orthogonal faces, creating a grid with boundary layers was found to be too difficult; this was not the case with the T-Rex, hybrid Pointwise® mesh. The mesh produced using snappyHexMesh took 6 hours to setup and 281 seconds to generate while the Pointwise® mesh took 15 hours to setup and 20 minutes to generate. However, the Pointwise® mesh was still considered to be good quality as it had a centroid skewness below 0.7, a benchmark set by Pointwise® webinars [14].

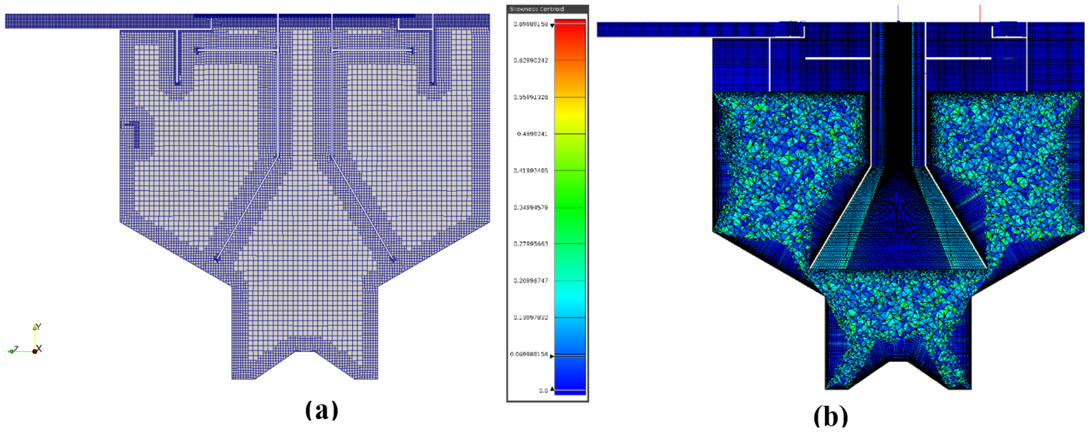


Figure 4: Swirl-Flo® meshes produced using (a) `snappyHexMesh` (b) Pointwise®

The *Top-Down* approach was found to be far quicker at generating meshes. Should unforeseen mesh metrics need to be changed, `snappyHexMesh` can complete this task an order of magnitude faster than Pointwise®: an advantage of flexible, automated meshing. However, this was at the expense of boundary layer control.

Conversely, the *Bottom-Up* approach excelled at structured mesh creation and was able to generate layers but took far longer. Because Pointwise® is not native to OpenFOAM®, non-orthogonality was not prioritised thus making it unsuitable for `driftFluxFoam`.

4.3 CFD Results and Validation

4.3.1 DriftFluxFoam Results

Methods for inversion of the pressure equation matrix were compared on the rectangular tank. Generalised Geometric-Algebraic Multi-Grid (GAMG) solver ran 12.8% faster than Preconditioned Conjugate Gradient (PCG). This is of little surprise, GAMG tends to be used for a faster solution, whereas PCG is utilised for stability. Due to negligible stability discrepancy between cases, the resolution of the mesh and time restraints, GAMG was used. Optimum tolerances for the pressure field were found to be: $tolerance = 1e-7$, $relTol = 0.01$. These conditions were then taken forward for the running of the Swirl-Flo® case.

4.3.1.1 Rectangular Tank Results

Figure 5 displays the dispersed-phase mass flow rates at the overflow and underflow for both the CFD simulation and empirical results for the rectangular tanks against time. These mass flowrates are proportionate to the concentrations at these times, and the time at which convergence occurs when steady-state concentration is achieved. Even after convergence, these results fluctuate; however, the converged mass-flow rate can be determined to 2 decimal places or one significant figure. From Figure 5, it can be observed that convergence occurs 8 minutes (or 480 seconds) into the experiment, with a mass flowrate of $0.005 \pm 0.0007 gs^{-1}$ for the underflow and a mass flow rate of $0.05 \pm 0.0025 gs^{-1}$ for the overflow. From the mass flowrates for the Swirl-Flo® displayed in [13], it can be observed that convergence occurs 5 minutes into the experiment with a mass flow rate of $0.02 \pm 0.008 gs^{-1}$ for the underflow and a mass flow rate of $0.06 \pm 0.018 gs^{-1}$ for the overflow.

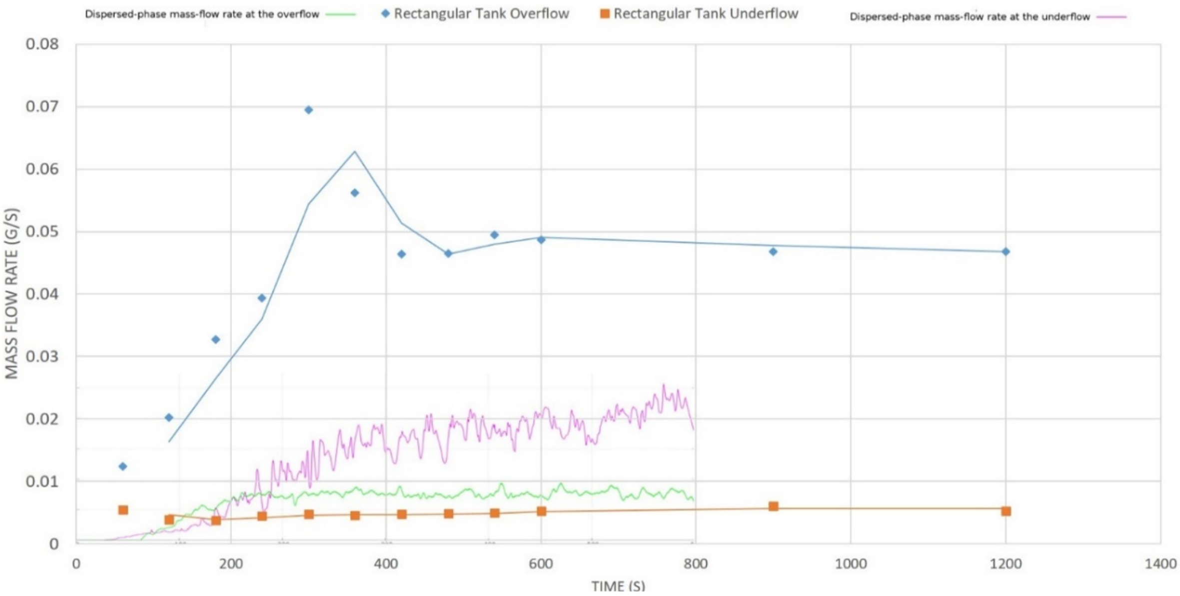


Figure 5: Overflow and underflow dispersed mass flow rates from empirical and CFD results (error bars for the experimental results are omitted for the sake of clarity)

From Figure 5, many differences can be observed between the CFD and experimental results. The key difference being that the CFD overflow result is closer in magnitude to the experimental underflow, while the experimental overflow result is over twice the size of the CFD underflow result. This is most likely due to the very small underflow flowrate meaning that despite the greater concentration of OSP present, the mass flowrate is smaller.

Following the running of the three driftFluxFoam simulations on the rectangular tank, the data was converted into a graphical format. For the rectangular tank models, the velocity (the component in the x direction of the tank) and phase fraction profiles were observed and compared at three points along the length of the tank. Figure 6 shows the velocity profiles and phase fraction profile observed for model 1 at the final timestep (1100s).

The shifting between positive and negative velocity indicates that there is some degree of recirculation in the tank. Also, as expected, the velocity is seen to be of greater magnitude nearer to the inlet, most likely due to the weir slowing the fluid for the rest of the tank.

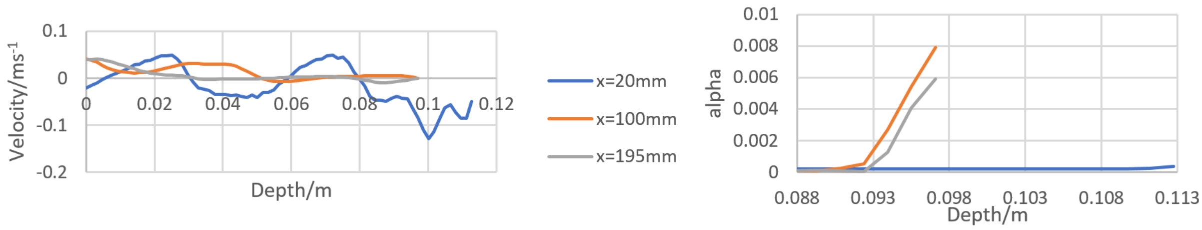
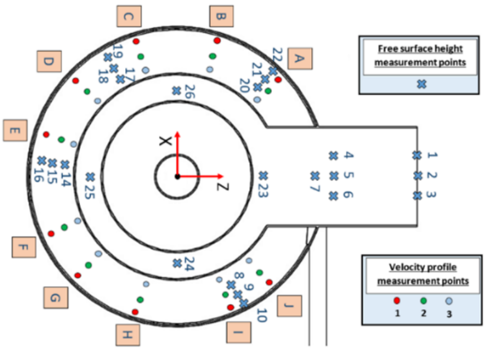


Figure 6: Graphs taken from the simulations using settling velocity Model 1. a) Velocity Profile. b) Plot of the phase fraction

4.3.1.2 Swirl-Flo® Results



Velocity Profile Measurement Points			Free Surface Height Measurement Points		
	X (mm)	Z (mm)		X (mm)	Z (mm)
A1	184.14	197.47	X2	0	480
A2	163.68	175.52	X5	0	330
B1	258.2	78.94	X8	-199.2	115
B2	229.51	70.17	X20	165.4	159.8
B3	200.82	61.4	X22	205	198
C1	256.79	-83.43	X23	0	179
C2	228.25	-74.16	X26	179	0

Figure 7: Image of the measurement points for the Swirl-Flo®

Figure 8 is a velocity profile at point C2 (shown in Figure 7) in the Swirl-Flo®. Displayed are the velocity results from the Acoustic Doppler, Propeller-meter and the simulations. The depth is the vertical distance from the origin which was the base of the jig and 71mm above the surface of the water. As can be seen in Figure 8, the flow for all profiles appear to decrease as the depth increases, however further plots from different measurement points are displayed in [15] and these show how the velocity profiles vary in different positions.

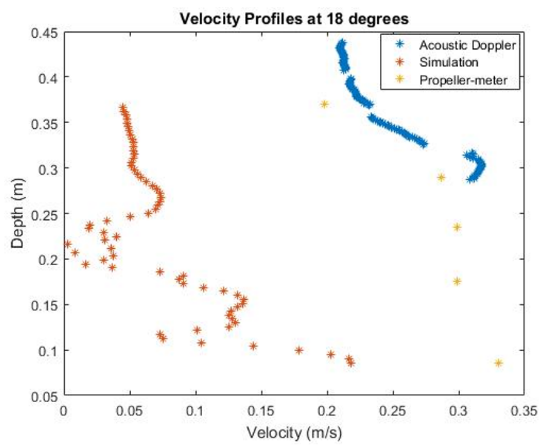


Figure 8: Graph of the velocity profile in the Swirl-Flo® at point C2

In comparison, there is a large difference between the measured velocities and the CFD velocities. This could be due to loss of simulation time as the simulations were not run to completion. The values obtained by the Acoustic Doppler and Propeller-meter are shown to be similar, validating these results. Although there is a large difference between the simulation and experimental results they can be seen to follow a similar trend, suggesting that the simulations are modelling similar behaviour even if the values are different.

4.3.2 `interFoam` Results

The experimental and `interFoam` simulation results for the Swirl-Flo® case are presented in Figure 9. For reference, an alpha value of 1 indicates water and a value of 0 denotes air. Values between 0 and 1 signify the interface region between the two fluids.

Both the experiment and simulation free surface elevation results indicate the rigid-lid assumption used in the `driftFluxFoam` simulation was not appropriate as this was set to 23 mm above the overflow tray. The average free surface height obtained from the experiments and simulation for points X1 to X26 was 23.3 mm and 24.8 mm respectively. However, the standard deviation of the experiment and simulation data was found to be 9.5 mm and 11.2 mm respectively, indicating a large spread around the mean. Thus, the free surface height for the Swirl-Flo® differs too greatly across the overflow tray to simply be modelled by a flat wall.

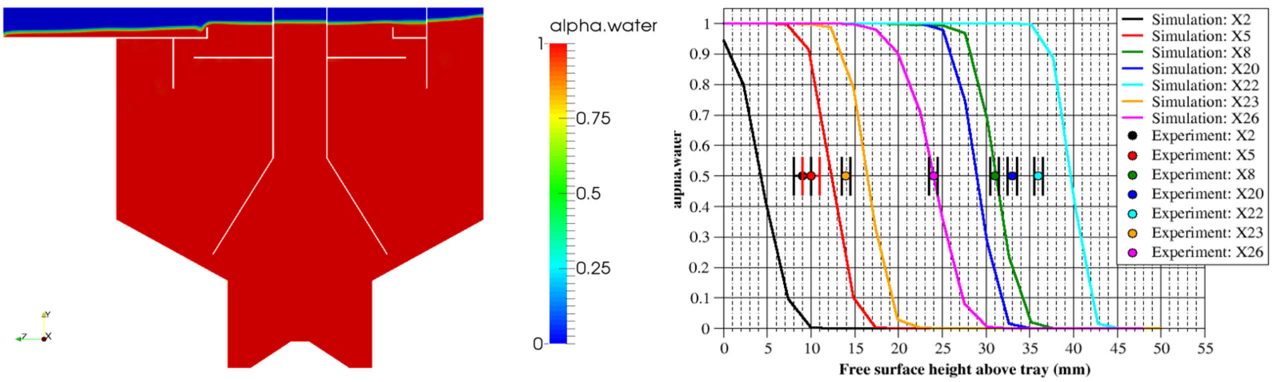


Figure 9: Left: alpha.water section-cut of the Swirl-Flo® normal to x-axis at $t = 300$ seconds. Right: Plot of experimental and free surface heights for the Swirl-Flo® at $t = 300$ seconds.

5 Critical Analysis

Overall, the group managed to successfully complete 5 of the 9 deliverables set for this project: the deliverables (listed in Section 1.2). Further to this, good progress was made towards 3 more with only 1 not completed. Deliverables (i), (iii), (iv), (v), and (vi) were fully completed and as such do not warrant extensive discussion.

Deliverable (ii) was half completed: a final rheology model was produced. However, the settling velocity models investigated were unsuccessful with simulation results being a factor of 10 away from the experimental results. This was potentially due to the limits on the accuracy of the experiments used to characterise the settling behaviour. However, the fourth model that was produced near the end as proof of concept, looks to be more promising from the first 50 seconds of simulated time. The underflow mass flowrate looks to be converging in the correct region and the overflow mass flowrate is still increasing towards the values seen in experiments.

Deliverable (vii) was largely completed; the CFD simulations were run and converged successfully on the rectangular tank. However, due to computational limitations, only 1 Swirl-Flo® simulation was run. This simulation produced 133 seconds of simulated time and took 19 days, meaning it would take up to 43 days to reach 5 minutes of simulated time. Computational time constraints were the only reason for not being able to produce converged Swirl-Flo® simulations to achieve this deliverable. As such, the group has provided Hydro International® with all of the case files required for them to complete this deliverable in their own time.

The other partially completed deliverable was (viii). This was mainly due to deliverable (ii) being only partially completed. Without an accurate settling model for the OSP a fully validated CFD model could not be produced. However, the experimental results are available, and a new settling model is in the process of being run for work on this to continue in the future.

The only incomplete deliverable from this project is deliverable (ix). This was the optimisation of the Swirl-Flo® which required the final time step from a converged simulation. The limit of computational time was the primary reason for being unable to complete this objective; all files were provided to Hydro International® so they can complete this.

6 Conclusions and Recommendations

The project produced experimental results for two sedimentation devices with validated velocity results and mass flowrates. Alongside this, CFD simulations on these devices were run using `driftFluxFoam` in OpenFOAM®. Successful results were gained for the rectangular tank. Due to computational time limitations, the Swirl-Flo® simulations did not reach steady state. It was not possible to validate the simulation results using the experimental results as the OSP models provided were unsuccessful. The basis of the work has been provided to continue running simulations and to validate them using the work that is ongoing for the OSP.

6.1 Recommendations for Further Work

Further to the work completed in this project, it would be recommended for the Swirl-Flo® simulations to be run until they reach a steady state. Combining this with further investigation into the OSP modelling would allow for the validation of the CFD simulations against the experimental data. Specifically, the OSP modelling would involve developing the Model 4 settling model and trialling a Newtonian suspension viscosity model. At this point, the optimisation of the Swirl-Flo® could be investigated.

It would also be of interest to investigate different meshing software and multi-phase solvers. The open source software `cfMesh` is of interest as it could potentially produce layers better than `snappyHexMesh`. Further to this, more investigation into T-Rex boundary extrusion would be useful in order to see if OpenFOAM® can integrate a mesh using this utility.

7 Project Management

A set management structure and chain of responsibility was implemented for this project. This structure defined three primary sub-groups with all group members being assigned individual responsibilities, listed in Table 4. The sub-groups were managed overall by a project manager.

Twice weekly meetings ensured efficient communication between the sub-groups. One meeting was formal with an agenda and minutes; this was with the project supervisor and industrial contact. The second was an informal progress meeting to discuss issues and arrange the formal agenda. Additionally, online messaging, small informal meetings and email chains ensured constant communication and swift resolution of issues.

Table 4: Table showing the structure of the group

Name	**Primary Sub-Group**	**Role**
Aaron Wye	Experimental	Project Manager
Abigail Baker	Experimental	Laboratory Manager/Safety Officer
Joshua Lowe	Meshing	*BlockMesh*, *SnappyHexMesh*, and *InterFoam* Lead
Michael Mendoza	Experimental	Rheology Lead
Rob Bentley	Simulation	Rectangular Tank Simulation Lead
Thomas Russell	Simulation	Swirl-Flo® Simulation Lead
Toby Scobell	Meshing	Finance Officer/PointWise® lead

7.1 Time Management

Two methods of time planning were employed in the project. These were a project workflow chart and Gantt charts used in parallel which were updated weekly. The flowchart, a simplified version displayed in Figure 10, provided a visual reference of the project plan. The Gantt chart provided a linear representation of the timings. Key project deadlines were contained in the group Gantt chart and all activities were planned with float time to mitigate for setbacks.

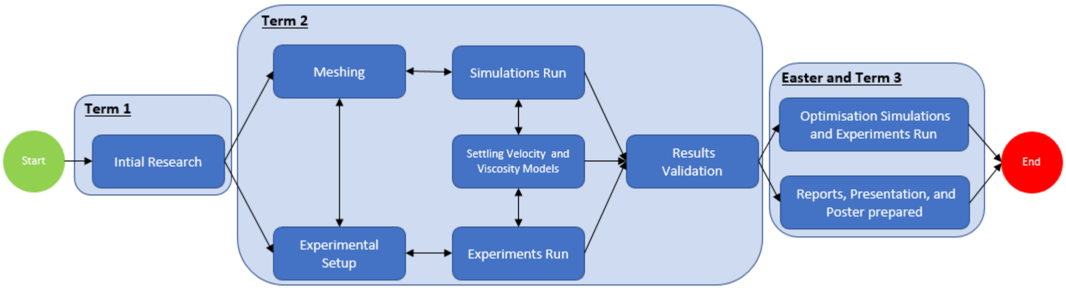


Figure 10: Simplified Flowchart showing the timings planned for the project

Several setbacks occurred in the project that had various impacts on its progress. One major setback was the need to remodel the rectangular tank which led to the nullification of previous work. This was mitigated for by utilising the float time of future activities. Other major setbacks included computational time and budget constraints which were mitigated for through use of coarser meshes and devising cheaper alternatives respectively.

7.2 Data Management

As requested in the IP agreement with Hydro International®, all group documents and data were stored within a SharePoint folder provided by the company. Regular backups of the documents were created to prevent full data loss. Logbooks were also kept by each member to record any information which was then digitised if necessary.

7.3 Financial Management

Careful management was needed to ensure the project was delivered within budget. The initial budget provided by the University was £595. All purchases were made through the treasurer to ensure consistency and compliance with university procedure: a Student Order Form was completed and placed with stores prior to any purchase. The total spend on the project was £423.07, leaving the group under-budget by £171.93.

The largest outgoing was the OSP, equating to 27.5% of the budget. There were multiple instances of lack of budget throughout the project meaning some specialist equipment could not be bought/rented to improve experimental results. In the case of plumbing in the Swirl-Flo®, large expense was unavoidable. The solution was to use a portion of Dr. Grossberg's post-doctoral budget totalling £1800.

7.4 *Health, Safety, and Sustainability*

The experiments carried out presented a variety of risks. These included flooding the building, electronic appliances encountering water and hazards associated with the OSP and glue. To mitigate these risks, risk assessments were completed and provided to the laboratory technicians before commencing the experiments. These assessments comprised of one broad assessment which covered all experiments in the laboratory and a further separate assessment required for the gluing of the pipework. Both risk assessments are available on request.

A major sustainability issue related to the project was the water usage. The experimental side of this project required a large volume of water. While this is initially unsustainable, the future potential from this completed project is that the company may be able to use simulations more confidently when developing new products and hence reduce the need of similar experiments. Thus, while the water use in this project may not have been sustainable, in the long-term this project could have far-reaching positive effects on water sustainability.

8 References

[1] R. Bolton and L. Klein, SEWAGE TREATMENT Basic Principles And Trends, London: Butterworths and Co, 1971.

[2] D. Ellis, "The Design of Storm Drainage Storage Tanks for Self-Cleansing Operation," University of Manchester, Manchester, 1991.

[3] V. Stovin and A. Saul, "Sedimentation in Storage Tank Structures," Water Science and Technology, vol. 29, no. 1-2, pp. 363-372, 1994.

[4] C. Greenshields, "OpenFOAM v5 User Guide: 5.4 Mesh generation with snappyHexMesh," CFD Direct: The Architects of OpenFOAM, 2 March 2017. [Online]. Available: https://cfd.direct/openfoam/user-guide/snappyhexmesh/. [Accessed 25 April 2018].

[5] D. Brennan, "The Numerical Simulaiton of Two-Phase Flows in Settling Tanks," Imperial College of Science, Technology and Medicine , 2001.

[6] I. Takacs, G. Paltry and D. Nolasco, "A Dynamic Model of the Clarification-Thickening Process," Water Research Journal, vol. 25, no. 10, pp. 1263-1271, 1991.

[7] Pointwise, "Pointwise YPlus Calculator," Pointwise, 2018. [Online]. Available: pointwise.com/yplus. [Accessed 25 04 2018].

[8] G. Tabor and B. Fabritius, "Improving the quality of finite volume meshes through genetic optimisation," Engineering with Computers, vol. 32, no. 3, pp. 425-440, 2016.

[9] ANSYS, "Modeling Turbulent Flows - Introductory FLUENT Training," December 2006. [Online]. Available: `http://www.southampton.ac.uk/~nwb/lectures/GoodPracticeCFD/Articles/Turbulence_Notes_Fluent-v6.3.06.pdf`. [Accessed 28 April 2018].

[10] G. Queguineur, D. Jarman, E. Paterson and G. Tabor, "Computational fluid dynamics of vortex flow controls at low flow rates," Proceedings of the Institution of Civil Engineers - Engineering and Computational Mechanics, vol. 166, no. 4, p. 211–221, 2015.

[11] S. Mueller, E. Llewellin and H. Mader, "The rheology of suspensions of solid particles," Proceedings of the Royal Society A, vol. 466, no. 2116, pp. 1201-1228, 2010.

[12] W. Herschel and R. Bulkley, "Konsistenzmessungen von Gummi-Benzollösungen," Kolloid-Zeitschrift, vol. 39, no. 4, p. 291–300, 1926.

[13] D. Thomas, "Transport Characteristics of Suspension: VIII. A Note on the Viscosity of Newtonian Suspensions of Uniform Spherical Particles," JOURNAL OF COLLOID SCIENCE, vol. 20, pp. 267-277, 1965.

[14] T. Carrigan and M. Landar, "Automotive Design Optimisation using Pointwise, Sculptor and OpenFOAM," Pointwise, 2015. [Online]. Available: http://info.pointwise.com/webinar-automotive-design-optimization. [Accessed 17 04 2018].

[15] A. Baker, "Validation of Sedimentation Tanks through Empirical Studies," University of Exeter, Exeter, 2018.