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Particle size distribution of suspended solids in a commercial recirculating aquaculture system

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ABSTRACT

For the understanding of solids characteristic in RAS, the particle size distribution (PSD) of the suspended solids (SS) is a valuable tool. This study evaluates the PSD of the SS in an industrial RAS smolt farm in Norway. Research has been done on the characteristics of the PSD throughout the different water treatment compartments of the RAS as well as the filter efficiency of micro screen drum filter equipped with different mesh sizes.

The laser based PSD analyses using the time-of-transition principle identified strong variations of the volumetric based PSD in the different water treatment units. The fish tank effluent contained particles in the full size range from 5 to >600 µm with strong dominance of particles in the upper size ranges. 55 - 81 % of the particles were bigger than 100 µm. After micro screening, whereby 85 % of the water flow passes 60 µm screens and a side stream of 15 % is filtrated on 30 µm, the PSD shifted towards a high content of fine particles smaller 60 µm (97 %). Downstream from the drum filters the water passes a two-chamber moving bed biofilm reactor (MBBR), in which the PSD changed towards a high content of particles in the range 203 – 300 µm (28 - 66 % of the total particle volume found in this range). This was most probably caused by biofilm release from the moving bed. Downstream the MBBR, the installed degaser (set up as a trickling filter) caused particle breakdown by the induced turbulences. Through the unit the amount of particles in the upper size ranges (>322 µm) decreased by about 50 %. The comparison of PSD previous to pumping to afterwards detected a decrease of particles bigger 256 µm by 68 %, most probably caused by pumping-related particle break down. Still, the samples from the inlet water of the fish tanks carried particles up to 300 µm with about 70 % bigger 100 µm. No evidence for fine particle accumulation in the system could be found. The load of particles smaller 20 µm in the fish tank influent was less than 3 % of the total particle volume.

The filter efficiency test of the installed microscreen drum filter units identified a strong mismatch between PSD and total suspended solid (TSS) based removal efficiencies. Although the PSD results illustrated a highly efficient removal of 97 % of all particles bigger than the filter screen of 60 µm, the TSS based efficiency proved a much smaller weight based TSS reduction of only 34 %. This difference indicates a particle-crushing impact of the drum filter on the particles bigger than the screen size. The particle breakdown caused a higher percentage of smaller particles after the filtration unit. The PSD of the filter effluent from a 10 and a 30 µm microscreen filter also exhibit low filter efficiencies. The PSD of the influent water contained 94 % respectively 87 % of the particles bigger than the filter mesh size. Assuming that the screen hinders all particles exceeding in diameter the mesh size, an equivalent high particle reduction should be expected. In contrast a PSD based removal of only 56 % respectively 48 % of the particles bigger than the filter mesh was found. The high content of particles exceeding in diameter the mesh size of the filter found in the filter effluent could be partly explained by construction failures of the filter screens.

The presented results about suspended solid characteristics and drum filter efficiencies can help to optimize particle removal in modern RAS system. The findings proved a highly dynamic, diversifying PSD affected by the different water treatment compartments. With the attained information about dominating particles sizes, removal strategies can be reviewed to achieve a better particle control and higher removal efficiencies. The optimization of particle removal in RAS is an important milestone for the future development of this innovative fish farming technology.

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AOT	Advanced Oxidation Technology
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DF	Drum Filter
DG	Degaser
DM	Dry Matter
FT	Fish Tank
MBBR	Moving Bed Biofilm Reactor
PS	Pumpsump
PSD	Particle Size Distribution
RAS	Recirculating Aquaculture System
SS	Suspended Solids
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Solids
UV	Ultra Violet

1. INTRODUCTION

1.1. RECIRCULATING AQUACULTURE SYSTEMS (RAS)

Intensive fish culture is receiving considerable attention from the public and private sector due to the constant growth within the last decades (FAO, 2012). Accompanied with the growth of the industry comes the concern about the environmental impact and how sustainable these intensive culture systems are. The spotlight can be put one three main areas which turned out to be of high importance in this context: (1) the use of fish meal and oil as feed ingredients (Naylor, 2000), (2.) escapees of farmed fish and (3.) discharges of waste into the environment (Buschmann et al., 2006, Boyd et al., 2005). Fish-farming effluent is rich on nutrients and the discharge into receiving waters can cause eutrophication, oxygen depletion, higher turbidity and increased total suspended solids (TSS) loads (Iwama, 1991a). The impact of escapees of farmed fish on wild stocks is under discussion and especially the possibility of so-called "genetic pollution" of the wild fish gene pole is alarming the science world and the public. By using closed culture systems, in which the water is recirculating (RAS), two of these three problems become controllable compared to open system, such as cage cultures.

Using RAS, it is possible to control what is going into and out of the system. This enables fish production in relative isolation from the surrounding environment. RAS provides opportunities to reduce water usage (Verdegem et al., 2006) and to improve waste management and nutrient recycling (Piedrahita, 2003). Additional RAS enables high control about the biological pollution risk by escapees of fish. That means that the production of seafood, on a highly intensive level, land based and isolated from the environment in a RAS, has big advantage compared to open systems such as flow through systems or sea cage cultures in terms of sustaining natural recourses. RAS makes intensive fish production compatible with environmental sustainability.

Besides the positive environmental aspects, there are many advantages of RAS on the production side as well. To name only the most important: (1.) nearly unlimited water resource throughout treatment and recirculating (=unlimited production), (2.) high savings on heating/ chilling costs, (3) climate independent year around production and (4.) protection from varying inlet water quality and incoming diseases and parasites.

Besides the advantages, new challenges come also with this technology. As soon as water is reused, metabolic waste products of fish, minerals, drug residues and hazardous feed compounds accumulate in the system (Martins et al., 2009a, Martins et al., 2009b). As far as not treated, these

substances effect, at certain levels, fish health, quality and safety. Because of that, water quality management is the key to a successful operating RAS, which can only be achieved by constant monitoring and control of all relevant quality parameter. Included should be temperature, dissolved oxygen, carbon dioxide, pH, ammonia, nitrite, nitrate, alkalinity, chloride and solids (Masser, 1992).

Firstly invented in the 1980's, RAS production increased significantly in volume and species diversity since then (Rosenthal, 1980). In Norway the smolt production is shifting from flow through to RAS. Important reasons for this development are limited freshwater resources, large seasonal variation in water temperature and low inlet water quality, including aluminium concentration (Kristensen et al., 2009). In Europe more than 10 species are actually produced in RAS and there is constantly research done on new culture species.

RAS is going to become more and more important in the Norwegian and global aquaculture sector as water sources are limited and environmental statutory requirements are being tightened. In the past, the Norwegian smolt production has been mainly run as flow-through systems, due to adequate freshwater bodies. But with increasing and intensifying production, many facilities reached the production limit set by the freshwater availability. Kittelsen (2006) predicted already, that an increase in smolt production would be hampered without the use of RAS by 2012. This trend is supported by many recently build RAS smolt farms in Norway. Besides water shortage as a reason for the change from flow-through to RAS, the industry sees further benefits of RAS for smolt production. Actual interest is the production of 1 kg plus fish, which has the benefit of (a) higher turnover due to higher temperature during grow out in RAS, (b) less exposure time to parasites in sea as well as (c) putative positive effect on smolt quality (growth, survival after sea transfer).

Even though RAS technology is well developed and technically mature, there is still work to do in future. According to Martins et al. (2010) many innovations will be needed in the future to enable the system performing well for a broader range of species, culture conditions and life stages. Research in the engineering sector is continuously looking for more energy and cost efficient systems, more closed systems, and/or for a cradle-to-cradle approaches in system development, whereby wastes are re-used for other purposes or product commodities. Martins et al. (2010) points out further, that the prioritised area of research should be the ecological sustainability of RAS, especially in terms of waste removal efficiency (solids, nitrogen, phosphate) in the system. In addition the reduction of water usages required for filter backwash-water is of interest. Martins et al. (2010) concludes, the bottleneck of RAS is the solid management of fine solid produced in the system. These particles are insufficiently removed from the water with the current available remove techniques (Chen, 1996; Chen, 1997; Losordo, 1999), which limits the system performance. A high

concentration of suspended solids has a negative influence on nitrification, water quality (Eding, 2006) and fish growth (Davidson et al., 2009).

Until today, there is no unambiguous and clear answer how to control and remove the different solids fractions in a cost effective and treatment efficient way. Hence, constant research is needed for technological implementation for more efficient fine-solid removal.

1.2. SUSPENDED SOLIDS IN AQUACULTURE WATER

Solid management becomes increasingly important as aquaculture systems intensify. In recirculating aquaculture systems, solid waste accumulation may become the first production limiting parameter as the recycle rate increases (Chen, 1991; Muir, 1982). Therefore the management and removal is a key process in a RAS. Two strategies can be used with the object of solid reduction: First, lowering the discharge by feed design and feeding management; second, filter technology for particle removal.

Ideally the particle waste removal is equal the particle waste production. If not, waste accumulates in the system and causes poor water quality. Problems caused by high suspended solid loads in RAS are gill damage, reduced growth rates, mortality, increased susceptibility to disease, clogging of biological filters, increased biochemical oxygen demand (BOD) and mineralization to produce ammonia (Chen, Malone 1991; Chen et al. 1993). To minimize stress level of the fish, the concentration of total suspended solids (TSS) should be kept below 10 mg/L when farming salmonids (Timmons, 2007).

Waste material in aquaculture water is mostly present in low concentrations, but the water flow rates are comparable high to other industries (Cripps, 1994). Solid waste in aquaculture systems mainly contain uneaten feed, fish faeces, algae, pathogens, and biofilter cell mass (Bergheim, 2007).The main components which are important to be removed in terms of water quality improvement, are nutrients, such as phosphorus (P) and nitrogen (N) components, biochemical oxygen demand (BOD), suspended solids (SS) and pathogens (Cripps, 1995).

The concentration of suspended solids (SS), total nitrogen (TN) and total phosphorus (TP) are commonly low in aquaculture effluent, respectively 14, 1.4 an 0.13 mg/l (Cripps, 1996). The majority of phosphorus from fish farms is particle bound, in comparison more than half of the Nitrogen compounds are present dissolved form (Ackerfors, 1994). Much of the biodegradable matter, which produces a BOD and reduces dissolved oxygen (DO) levels, is also present in the particulate fraction (Amirtharajah, 1990). About 7-32 % of the TN and 30-84 % of the TP is bound to particles (Bergheim,

1993a). The remainder is present in dissolved fraction. Kelly (1997) showed that 21 % of the BOD load remained after filtering the particle-rich effluent with a mechanical filter on a pore size of 60 micron.

Fish waste can be in organic or inorganic form and dissolved or suspended in the water. These suspended solids are mostly present in a broad particle size range with a low specific gravity (Chen, Malone 1991).

The removal of suspended solids from the process water should be done as soon and as close to the source, as possible (Lekang, 2007b). Nutrients leach out of the particles, which are intensified by increased surface area caused by particle brake down. Generally, the three physical properties that are most important for solids removal are particle specific gravity, particle size distribution and mechanical stability. When it comes to aquaculture use, the particle size is the decisive parameter for the efficiency of a given particle removal technique (Cripps, 1994). Particle sizes can be classified as followed: Particles smaller than 0,001 μm are classified as soluble, 0,001 – 1 μm as super-colloidal and larger than 100 as colloidal, $1 - 100$ µm as settle able (Lekang, 2007b).

The particle content is next to the particle size and important factor in terms of water quality. The amount of particles in the water can be defined as total suspended solids (TSS), Total solids (TS) or dry matter (DM). Herby TSS is defined as the amount of particles stopped by a fiberglass filter with a pore size of 0,45 μm. TS stands for the total amount of particles in the water, which is equal to the quantity of total DM. (Lekang, 2007b)

Many studies have been done on aquaculture effluent water properties. Nutrient contents, as BOD and SS, have been well quantified. The focus was hereby mostly the investigation of environmental load and effects (Bergheim, 1991, Enell, 1991), or the efficiency of treatment devices (Bergheim, 1993b; Bergheim, 1993a). Compared to that, little research has been done on the physical properties, such as particle characteristics.

One important characteristic is the particle size distribution (PSD). The PSD describes particle ranges and amounts of suspended solids present in the water. Further the PSD of the suspended load determines: (1) the duration of time that the particles remain in suspension for and (2) the depth-distribution of SS within the water column.

In general, smaller particles remain longer in suspension in the water column than larger particles (Schindl, 2005). That has the effect that SS loads with a fine particle-size distribution have for example more time to harm aquatic organism, than larger particles caused by the time of duration. The depth-distribution of SS describes the physical property, that in laminar flow or no flow

condition, smaller particles tent to be more present in the top layer of the water column, whilst the coarser particles tend to occupy the deeper zone of the water body (Bilotta and Brazier, 2008). The PSD can be influenced by many factors. Mechanical parts, like pumps, can break down suspended solids (Davidson, Summerfelt 2004), as well as destructive forces such as turbulence water flow pattern. Hereby shear forces break apart faecle matter, uneaten feed and feed fines soon after they are deposit. This allows them to disintegrate into much smaller and more soluble particles. For the particle removal it is important to avoid particle brakeage. With decreasing particle size, particularly below 60 – 100 μm, the removal becomes more difficult and costly (McMillan, 2003). That is why the brake-down of particles should be strongly avoided. Gentle handling of the particles by using low water velocity inside the system and having as few bends, valves etc. as possible to avoid creating extra turbulence, is the key to avoid particle brake down (Lekang, 2007b). McMillan describes the effect of pumping on the particle size to be significant when judged on differential volume. But pumping was found to affect significantly differential number. Not affected was the number of the sample dominating, very small particles (< 60 μm) (McMillan, 2003). Besides mechanical impact, biological degradation decreases particles size (Warrer-Hansen, 1981; Wong and Piedrahita, 1991). Important is especially the identification of particle-destroying units or processes within the RAS. By identifying and if possible, eliminating them, the particle removal can be optimized. Also for the optimization of filter pore size and hydraulic residence times for microscreens and sedimentation units, the data is useful.

Summarizing, the determination of the PSD in a RAS allows:

a) Identification of particle destroying units
b) Identification of optimal locations of particle separation treatment units in the process
c) Optimization of mechanical filter units (e.g. pore size) when it comes to cost-efficiency and/or treatment efficiency
d) Investigation of feed-derived effects on PSD
e) Monitoring of PSDs throughout the RAS and its different compartments

These listed possibilities for the use of PSD clearly show how highly valuable it is to gain deeper understanding about impact factors of the PSD in RAS. The knowledge can be used directly to improve water treatment and farm designs for higher removal efficiency.

1.3. PARTICLE REMOVING STRATEGIES AND PRINCIPLES

The removal of suspended solids from the water is a solid-liquid separation process. This treatment step is highly important and generally the first step of the recirculating water treatment process in a RAS. Besides in recirculation aquaculture systems, particle separation finds also place in flow through fish farms. Here it can be used to treat inlet water to protect the fish in the system from incoming miner water quality as well as on the outlet water to protect the recipient water from high nutrient loads, escaping fish and parasites.

The removal techniques of SS can be classified as sedimentation, mechanical filtration and depth filtration. Mechanical filtration can be straining or micro screens. Depth filtration is also called sand filtration. Alternative methods are flotation, membrane filtration and ozonation, which are suitable methods particularly for the removal of smaller particles but therefore more costly.(Lekang, 2007b)

Mechanical filters

Mechanical filtration is accomplished with screens or bar racks (Chen, 1994; Lekang, 2007b). The principle of a mechanical filter is the collection of particles and larger objects out of a water flow. Particles bigger than the aperture/ mesh of the filter screen are blocked and can be removed. To avoid increasing head loss up to total blockage of the filter material, continuous particle removal from the rack/ screen has to be accomplished. The removal can be done manually, which is very labour-intensive, or automatically, also called “self-cleaning” (e.g. back flush system, scraper, vacuuming or mechanical vibration). There are two types of screens in use, static and rotary. Rotary screens can be classified into axial rotating screen, radial rotating screen, rotating belt and horizontally rotating disc. (Lekang, 2007b)

Most commonly used are drum filters. The function principle can be described as followed. The water enters the filter from one side into a turning drum, which is stringed with a microscreen. Passing the screen, the filtered water leaves the drum filter and flows over an overflow out of the filter unit. The captured particles remain on the microscreen. As the particles are retained and accumulate in filter cloth, the water level rises inside the drum and a level alarm activates the back washing system. Spray nozzles blow water from the outside onto the screen. The particles are washed into a channel and the sludge is sent out of the filter unit.

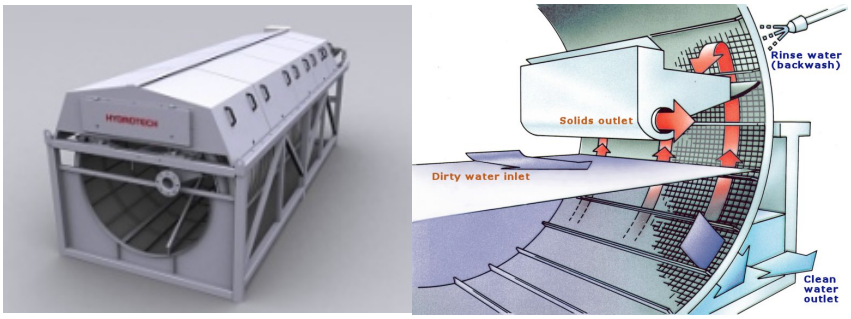

FIGURE 1: FILTER PRINCIPAL OF A ROTATING DRUM FILTER. WATER ENTERS THE DRUM AND PASSES THROUGH THE FILTER SCREEN. THE CONTINUOUS CLOGGING OF THE FILTER LET THE WATER LEVEL RISE INSIDE THE DRUM. A LEVEL ALARM ACTIVATES THE HIGH-PRESSURE JETS FOR BACKWASHING THE FILTER. THE SOLIDS ARE RINSED INTO AN INTERNAL COLLECTOR FROM WHERE THEY ARE TRANSPORTED TO THE SLUDGE STORRIGE.(HYDROTECH)

Depth Filtration

Depth Filtration describes the removal of particles from a flow of water by forcing it to flow through a layer of material (granular filter medium) of various sizes and depths. Commonly used filter materials are sand or other granular material. The filter material traps particles, which are bigger then a certain size. Mechanism involved in this removal process may be straining, settling (unaltered, due to flocculation and adhesion) and absorption. The filter medium grain size determines the maximum particle size, which can pass the filter. The grain size and the particle characteristics in water, decide maximal flow rates through the filter and how fast the filter will clog. The same as with mechanical filter, depth filter have to be back flushed to keep their purification efficiency and to avoid clogging. (Lekang, 2007b)

Settling or gravity filter

For sedimentation, settling tanks, settling tubes or hydro cyclones (swirl separators) are commonly used. Sedimentation or settling is dependent on the density differences between particle and water. Particles have a higher relative density than water (1.005 – 1.2 compared to 1 freshwater)(Wong and Piedrahita, 2000), but due to the small difference in density, only particles larger than about 100 – 150 μm can be easily removed by sedimentation. For finer particles, filtration is necessary (Couturier, 2009). The higher the density of a particle, the easier it is removed by settling or gravity.

Settling basins are a simple way to utilize the gravitational force for separation. As long as the sinking velocity of the particle created by the gravitational force does not exceed the horizontal velocity component created by the water flow through the basin (Lekang, 2007b). Besides horizontal flow

pattern, a separation against a horizontal flow pattern is possible as well. The settled particles have to be removed manually or for example with a vacuum pump to avoid nutrient leaching and re

resuspensions. Figure 2 shows the principle of a settling basing, where the gravitational force is utilized for the separation of particles from the water.

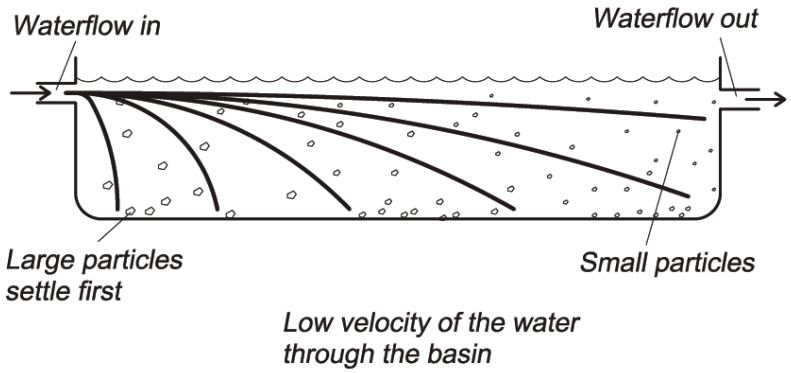

FIGURE 2: PRINCIPAL OF A SETTLING BASIN, WHERE THE GRAVITATIONAL FORCE IS UTILIZED FOR THE SEPARATION OF PARTICLES FROM THE WATER. LARGE PARTICLES SETTLE FASTER, DUE TO THE HIGHER SINKING VELOCITY, THEN SMALL PARTICLES. (LEKANG, 2007B)

In swirl separator or hydrocyclones the higher density of particles is used in combination with an introduced centrifugal force. While the purified water is pressed into the centre of the swirl separator and is drained out, the particles sink to the bottom. Due to the fact, that the centrifugal forces are greater than the gravitational force, a smaller area is needed than for a settling basin. (Lekang, 2007b)

To achieve best possible water purification throughout the suspended solid removal, it is important to select the appropriate process or even a combination of processes. Figure 3 schematically presents an overview over the available removal techniques for suspended solid removal in recirculating aquaculture systems with its individual optimal particle size work range. Different removal efficiencies can be achieved by the combination of several techniques to match different water quality requirements.

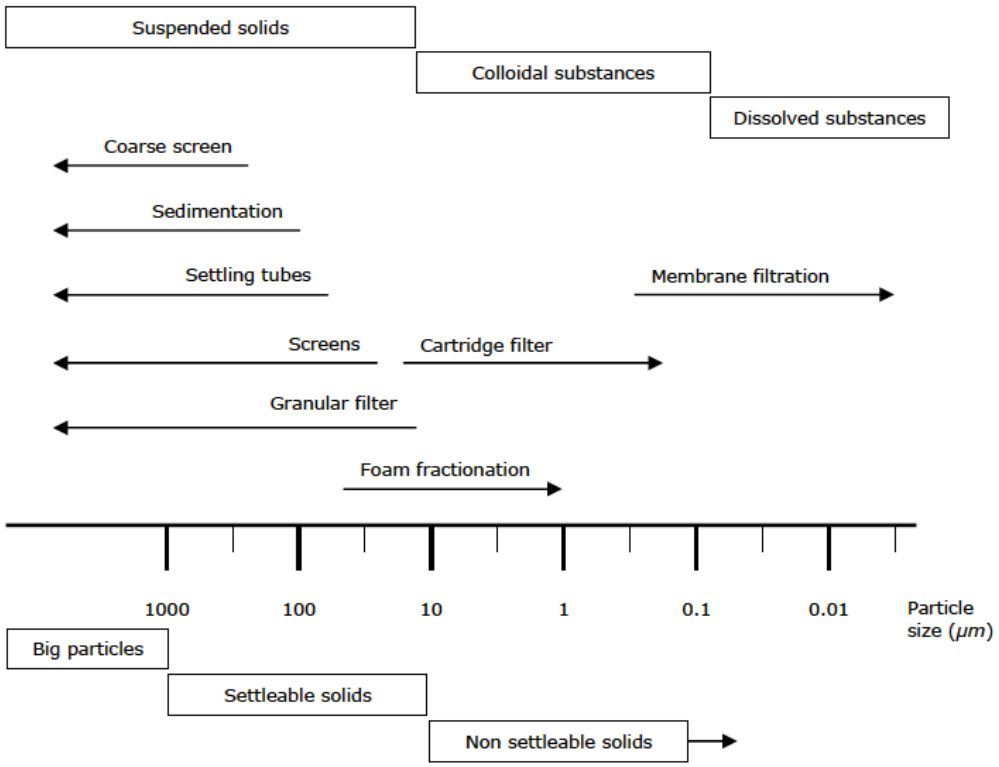

FIGURE 3:SOLID REMOVAL MECHANISMS AVAILABLE FOR OPERATION IN RECIRCULATION AQUACULTURE SYSTEMS (RAS) IN RELATION TO THE PARTICLE SIZE RANGE OVER WHICH THE REMOVAL PROCESS WORKS (ORELLANA, 2006)

To evaluate the removing efficiency of a filter technique, the purification efficiency can be used. It gives a percentage value of suspended solids removed from a flow. It can be defined as followed (Lekang, 2007b):

$$C_e = (\frac{C_{in} - C_{out}}{C_{in}}) * 100$$

C_e= efficiency (%)

C_{in}= concentration of the actual substance entering the filter

C_{out}= concentration of the actual substance existing the filter

The percentage removal of TSS is normally used for evaluating the removal efficiency in aquaculture. Furthermore it can be used to estimate the removal of other substances such as nutrients (total phosphorus (TP) or total nitrogen (TN)) as well as biological oxygen demand (BOD5) or chemical oxygen demand (COD).

1.4. METHODS FOR PARTICLE SIZING IN AQUACULTURE WATER

In the past, several methods have been adopted for measuring particle size distribution of suspended solids in aquaculture facilities. For these studies mainly four different principles/methods have been used: Sieving, resistance pulse counter, laser light-scattering (laser diffraction) and time-of-transition particle sizer. The marked for particle-sizer offers many kinds of instruments, which were original invented for other purposes than aquaculture, such as the pharma- or food industries, heavy industry, such as oil, as well as for life science and biotechnology. Since not made for analyses of particles from aquaculture, the functionality and accuracy of each particle sizer has to be questioned and tested before usage.

In general following properties describe suspended solids in aquaculture water: Aquaculture particles are distributed extremely patchily in time and space (Bergheim et al., 1984, Summerfelt, 1999). The solids are often transient and vary in shape, colour and density (Summerfelt, 1999). The upper particle size (max) is generally unknown, because the texture can be described as dynamic (Influenced by flocculation or biological degradation) (Brinker, 2005).

These particles are generally present in a wide size range from less than a micron up to several mm. Available particle sizer offer only small size ranges to measure the particle size distribution with a rather low upper particle size limit. Due to that most analyses of particles from aquaculture were restricted to particles ≤240 μm, which represent only a small fraction of the total suspended solids (Cripps, 1995).

Besides a small size range of measurable particles sizes, many methods expose the particles to forces (e.g. shear forces), which adulterates the particle size distribution of the sample. Therefore selecting the right method and instrument is the key for a correct PSD measurement.

The ideal method for determine particle size distribution in fish culture water should combine following attributes (Brinker, 2005):

- No sample treatment necessary
- No limit on sample volume
- No concentration dependency of particle size measurements
- No mechanical interaction with the particles
- Recording of the complete range of particle sizes
- Measurement that are independent of the optical properties of the particles or their chemical composition
- Rapid processing (< 1h per sample)

- High resolution in the particle size domain
- Open architecture (water can be sampled directly)
- Mobile technology (direct field surveys)

Since there is no instrument combining all the above named attributes yet, the best available method has to be chosen. Table 1 reviews the most commonly used methods for PSD analyses in the aquaculture section pinpointing pros (+) and cons (-).

TABLE 1: OVERVIEW OVER THE MOST COMMONLY USED METHODS FÜR PSD ANALYSES IN THE FIELD OF AQUACULTURE INCLUDING THE USED PRINCIPLE, THE INSTRUMENT SUPLLIER AND THE THEORY/ METHOD WITH IST PROS AND CONS. (BRINKER, 2005)

Principle	Instrument supplier	Theory/ Method
Sieving		Sieving of particles through a series of sieves with a decreasing mesh size fractionates into different size ranges, which are weighed as dry mass (DM) + Method is comparable with mechanical effluent treatment – Rough method – Time consuming; labour-intense – Clogging of pores may result in retention of particles smaller then mesh size (Patterson and Watts, 2003) – Mechanical impact of sieve brakes particles and changes PSD
Resistance pulse counter	Coulter; Elzone; Fritsch	Resistance pulse counter determine the volume of particles suspended in an electrolyte by pumping the suspension through an aperture with an electric field. The displacement of electrolyte due to a particle induces a change in resistance across the aperture, which can be correlated to the particle volume. + Fast & precise + Broad size range from 0.5 to 1200 µm with high resolution (Milligan, 1991) – Addition of electrolyte to freshwater samples may alter the original PSD by inducing flocculation or de-flocculation of particles (Milligan, 1991, Iwama, 1991b) – High velocity and strong shear forces at the aperture may destroy fragile particles – Electrolyte may infiltrate the particles and conduct the current, resulting in an underestimation of the real particle volume – Measurement of a wider size range requires the application of different apertures
Laser diffraction	Light-scattering particle sizer	Laser diffraction sizes particles by using the diffraction patterns generated by the interaction of a laser beam with a particle. For particles larger 10 times the wavelength of the laser beam the Fraunehofer approach is valid, while for smaller particles Mie's theory applies (McCave, 1991). Mie requires the refractive index of samples to be known, which is not usually the case in fish farms. + Fast + High resolution + Non-intrusive – Diffraction patterns depend on the refractive indices of the particles and the liquid they are in, their chemical composition, and their

		density (Jonasz, 1991) – The resolution of polymodal distributions is unsatisfactory (Agrawal, 1991) – Significant inaccuracies occur when a critical amount of material is close to or beyond the extremes of the measurable size range (Bale and Morris, 1991) – Results depend in particle concentration (Loizeau, 1994)
Time-of-transition	Galai CIS1/ CIS50/ CIS100 EyeTech	A laser beam passes through a rotating wedge prism and a focusing lens. This causes the beam to deviate from the optical axis. The wedge prism rotates and produces a rotating laser, which scans the circular measuring area within the center of the flow cell. A photo diode detector registers the light intensity. When the laser beam interacts with a particle, the duration of the temporary blockage of the laser beam by the particle is detected. The generated pulse signals have a proportional width to the particle size. Since the laser scans at a known speed, the particle size can be computed from the pulse signal. + Reliable method with high-resolution + Method suitable for aquaculture water analyses with a high reliability for optimization of mechanical effluent treatment + Transportable technology – Slow analyses (2-4h/sample) – Only the old model CIS1 is able to measure accurately, the newer models overestimate PSD. The actual laser sizer EyeTech has not been tested yet.(Brinker, 2005)

In Brinker (2005), the author reviews in table 1 named methods and concludes, that the most suitable for aquaculture, is the time of transmission principle. He claims, that the laser-based high resolution determination of PSDs using the time of transmission principle combined with a sieve-based determination of out-of-range particles is the most reliable way to determine PSDs of aquaculture water.

Problematic is, that only the old model of the Galai CIS particle laser sizer, the CIS-1, was found to be suitable. Trials with the newer model Galai CIS-100 resulted in highly inaccurate results (Brinker, 2005). Since the GALAI CIS-1 is not produced anymore, the availability of the instrument for analyses is extremely limited.

Several authors have investigated research on particle size distribution in aquaculture water. Measurements have been done in fresh and saltwater, different species, flow through as well as RAS systems with different methods (compare table 2). Many studies done on RAS consistently reported, that fine particles (<20 µm) were the dominant based on number, whereby volume based bigger particles (>100) represented the major part. It is important to clearly separate between number based and volume/weight based PSDs. Even though, fine particles might be carried in high numbers in the water, the total volume is nevertheless often less than 10 % of the total particle volume (compare table 2). One extreme case was reported by Chen (1993). The author published results

from three RAS about specific gravity and particle size distribution. He found out, that more than 95 % (based on number) of the suspended particles in the investigated systems had a diameter less than 20 microns. By weight these particles represented still 40 – 70 % of the total suspended solids. However, many authors report that fine particles smaller 20 µm represent only a small portion of the total particle volume.

TABLE 2: OVERVIEW OF LITERATURE AND THEIR RESULTS ON PARTICLE SIZE DISTRIBUTION (PSD) FOUND IN RECIRCULATING AQUACULTURE SYSTEMS (RAS) AND FLOW THROUGH (FT) RACE WAYS (RW) USING DIFFERENT DETERMINATION METHODS; RPC = RESISTANCE PULSE COUNTERS (E.G. COULTER COUNTER, ELZONE, FRITSCH, COULTER® MULTISIZER; LLS = LASER LIGHT-SCATTERING PARTICLE SIZER

Method	Environment	Species	Weight (g)	PSD (μm)	%of fine solids (<20 μm)	Reference
RPC	Fresh water (RAS)	Rainbow trout *(Oncorhynchus mykiss)*	500	4-130	95 (by number) 10-48 (by volume)	(Chen, 1993)
RPC	Fresh water (RAS)	Rainbow trout *(Oncorhynchus mykiss)*	500	7-50	>95 (by number)	(Chen et al., 1993)
Sieving	Fresh water (FT RW)	Atlantic salmon (*Salmo salar) and sea trout (S. trutta)*	12-25	0.45->200	<10 (by volume)	(Cripps, 1995)
RPC	Fresh water (FT RW)	Atlantic salmon (*Salmo salar) and sea trout (S. trutta)*	12-25	8-240	>50 (by number)	(Cripps, 1995)
Sieves	Brackish water (RAS)	European eel *(Anguilla Anguilla)*	15-20	0.45->100	56 (by volume)	(Langer et al., 1996)
RPC	Salt water (RAS)	*Striped bass (Morone saxatilis)*	270-560	0.4-100	50 (by volume)	(Krumins, 2001)
RPC	Salt water (RAS)	Hybrid striped bass (*Morone saxatilis x M.chrysops*)	400	0.4-900	<10 (by volume)	(McMillan, 2003)

LLS	Fresh water (FT RW)	Rainbow trout (*Oncorhynchus mykiss*)	64-700	0.2->600	<5 (by volume)	(Brinker and Rosch, 2004)
LLS	Fresh water (FT RW)	Rainbow trout (*Oncorhynchus mykiss)*	-	0.2->600	<10 (by volume)	(Brinker, 2005)
Sieving	Fresh water (RAS)	Tilapia (*Oreochromis niloticus)*	100	<23 - >500	< 10 (by volume)	(Pfeiffer, 2008)
LLS	Fresh water (RAS)	Rainbow trout (*Oncorhynchus mykiss)*	10-500	5->600	10 (by volume)	(Sindilariu et al., 2009)

Table shows clearly the predominance of small particles <20 (μm) in number, which results from limited solid removal techniques in terms of fine particles. May the mass of the small particles compared to the bigger particles be negligible small, so is the total surface area related to the total mass extremely high. This high surface area offers excessive space for nutrient leaching and attachment of free-floating bacteria. Both affect negatively the water quality and is therefore of high concern and shows clearly the high need of research in the field of fine solid removal. The accumulation of small particle sizes in the RAS can become a problem especially with high recirculation rates. The most important tool to detect accumulation of fine particles is the measurement of the particle size distribution of the suspended solids in RAS.

1.5. OBJECTIVES

Current RAS systems are reasonably well designed to manage nitrogenous wastes and gaseous exchange, but there is still improvement necessary in terms of solid removal. In (Martins et al., 2010) the authors points out, the main bottleneck of RAS systems is the insufficient fine solid removal with the currently removal techniques. To improve the suspended solid capture, there is a need in appropriate technology development and implementation. Hence, more detailed knowledge about the attitudes of particles in RAS systems, especially with increasing intensification and higher water reuse factors needs to be investigated. Since particles are preferentially removed as quickly as possible after being released into the process water and any kind of particle brake down has to be avoided, the system design is key factor for particle control optimization. Due to that, there is a present importance in gaining more information on what kind of particle sizes are released into a

modern RAS system and how the PSD changes trough out the different units in the system influenced by the impact of different forces impacting on the particles. Especially important is the localization of particle-destroying units in the system since the knowledge can be directly used for optimized design solutions. Further use of PSD analyses are the improvements of removal strategies in terms of choosing the best removal techniques and identifying the ideal placing of the particle treatment units. On the other hand, the efficiency of particle removal by the filters itself need to be tested to find out possible weak spots and most sufficient filter mesh sizes to be used on the present particle size distribution. More efficient particle removal directly leads to an increase of water quality and by that to a higher productivity of land based fish farms.

Based on the present state of the art and the apparent need for more knowledge about particle size distribution, impact factors and more efficient removal techniques, the objectives of this study are as followed:

- To identify a detailed picture of the particle size distribution of the suspended solids in the fish tank effluent water of an industrial RAS system.
- The examination of the possible impact of the different water treatment compartments of a RAS system on the particle size distribution of the suspended solids in the process water. Tested compartments:
    - Drum filter
    - Biofilter (MBBR)
    - Degaser (CO^2-stripper)
    - Pumping and deepshaft oxygenation

- To evaluate the filter efficiency of Hydrotech drum filters equipped with 60 μm, 30 μm or 10 μm filter mesh.

2. MATERIAL AND METHODS

2.1. EXPERIMENT

The experiment was conducted in Mai/June 2013 at the Marine Harvest Smolt Farm in Dalsfjord, Norway. An express company delivered the particle laser sizer (Galai CIS 1), owned by the Fischereiforschungstelle Langenargen (LAZBW), to the facility in Dalsfjord. The laser was installed in a small machinery room on top of the RAS unit, which guarantied short distances between sample spots and laser. The duration of the experiment was 14 days. An overview of the analyses done during that time can be seen in table 3.

As listed in table 3 the 14 days were used as followed. After setting up the laser, adjusting it and doing some test runs, the first PSD analyses were extensive measurements of the fish tank effluent, sampled at the drum filter inlets. This was done over a full day on the size range 5-600 µm of the laser, as well as, with the smaller range 2-300 µm. On day 3 to 6 and day 11, the comparison of the different water treatment units were conducted. Therefore samples were taken before and after each unit. To approach a correct comparison of the two samples, the sample after the unit was taken according to the retention time of the unit. For example: The retention time of the MBBR was estimated with 8 min based on the size in m^3 and the total water flow. That means the sample after the MBBR was taken 8 minutes after sampling at inlet of the unit.

On day 7 and 8, PSD analyses were conducted to test the filter efficiency of the Hydrotech filter in the system, which is installed for fine filtration of a side stream. This filter is equipped with 30 µm mesh. On day 9, an experiment for testing the effect of a 10 µm microscreen filtrating a side stream of the total water flow was prepared. Plan was to test the effect of the finer filtration onthe PSD of the water in the RAS. Therefore water samples were taken prior to the filter mesh change, after 24 h and after 1 week of filter operation. The results of this test series are not published in this study due to problems regarding the data evaluation. On day 10 and 11 filter efficiency test were run on newly installed 10 µm filer panels. For that experiment, the filter panels of the 30 µm filter were changed to 10 µm panels.

In parallel to the tests of the efficiency of the 10 µm filter, a trial on the impact of the newly installed 10 µm filter on the water quality in the total system was arranged. Therefore samples were taken in the pump sump before the change to 10 µm panels, after 24 h as well as 1 week after the change. This experiment was set up to investigate, if the amount of fine particles in the system can be further decreased by a 10 µm mesh compared to a 30 µm mesh. As mentioned previously, the results from this test series are not published in this thesis.

Each sample in the different experiments was taken as double sample, to minimize the influence of human error, as described previously in literature (Brinker, 2005). Two samples were taken at the same sample spot and the PSD results were taken as a mean value.

According to the applied method for PSD analyses (Brinker, 2005), all water samples were filtered over a gaze filter as well as over a 0.45 µm cellulose acetate filter. Both, gaze and cellulose acetate filters were deep-frozen after the filtration and transported collective to the laboratory of the University of Life Science (UMB). There, the filters were analysed for the total dry weight of particles (TSS/DM) on the filter material according to German standards (DIN 1987).

After all particle size analyses were finished, the equipment was packed and sent back to Germany (day 14).

TABLE 3: OVERVIEW OVER THE EXPERIMENT PERIODE OF 14 DAYS INCLUDING INFROORAMTION OVER THE CONDUCTED EXPERIMENT PER DAY AND THE USED SAMPLE SPOT. EXPERIMENTS MARKED WITH * = RESULTS NOT PUBLISHED

Day	Experiment	Sample Spots
0	Laser installation & test run	-
1	PSD in the fish tank effluent	Mixed sample (according to %-flow into filter units) from before the drum filters
2	PSD in the fish tank effluent	Compare day 1
3	Comparison - PSD before and after **drum filter**	Mixed sample from before the drum filters & mixed sample from after the drum filters (according to %-flow into and out of filter units)
4	Comparison - PSD before and after **MBBR**	Mixed sample from after the drum filters (according to %-flow out of filter units) & mixed sample from both overflows of the biofilter (50/50)
5	Comparison - PSD before and after **MBBR** Comparison - PSD before and after **degaser**	(Compare day 4) Mixed sample from both overflows of the biofilter (50/50) & mixed sample from the outlets of the two degasing units (50/50)
6	Comparison - PSD before and after **degaser**	(compare day 5)
7	Filter efficiency of 30 µm drum filter	Comparison of sample before and after filter
8	Filter efficiency of 30 µm drum filter	(compare day 6)
9	Effect of changing drum filter mesh from 30 to 10 µm *	Sampling in pump sump centre (before change of filter panels). Later: Change of 30 µm filter panels to new 10 µm ones

10	Effect of changing drum filter mesh from 30 to 10 µm (after 24h) *	Sampling in pump sump
	Filter efficiency of 10 µm drum filter	Comparison of sample before and after 10 µm filter
11	Filter efficiency of 10 µm drum filter	Comparison of sample before and after 10 µm filter
12	Comparison - PSD **after degasing** and **before fish tank**	Sampling in pump sump (after degaser) and from inlet pipe into fish tank (before fish tank)
13	Effect of changing drum filter mesh from 30 to 10 µm (after 1 week) *	Sampling in pump sump
14	Filter panel change back to 30 µm and packing of equipment	-

2.2. EQUIPMENT

2.2.1. *Particle Lazer Sizer Galai CIS 1*

FIGURE 4: GALAI CIS-1 LASER SIZER SET UP INCLUDING FLOWMETER, PC AND PRINTER

Galai CIS-1 (Galai CIS-1 Production Ltd., Midgal Haemak, Israel) is a laser-based particle inspection system, which uses the time of transition operating principles for particle size determination. This method sizes the diameter of the individual particles. The laser is equipped in addition with a flow controller (Galai: LFC-100) and a flow-through cell (Galai: GM-7) (compare figure 4).

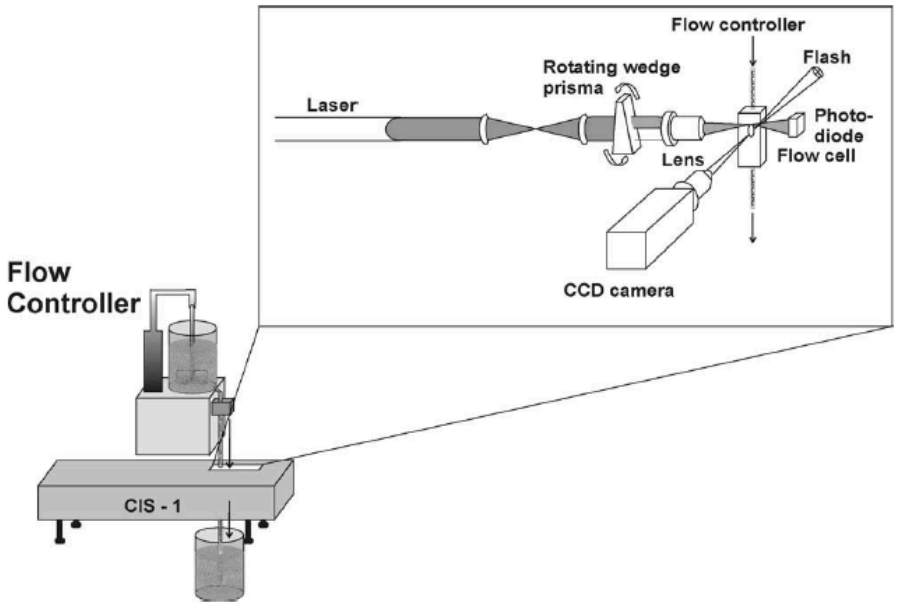

FIGURE 5: BASIC CONFIGURATION OF THE LASER SIZER (GALAI CIS-1) AND THE FLOW CONTROLLER (GALAI: LFC-100) INCLUDING SKETCH OF TIME-OF-TRANSITION PRINCIPLE WITH BASIC OPTICS, CCD CAMERA AND FLASH FOR DETECTION OF AIR BUBBLE OR AGGREGATES (BRINKER, 2005).

The measurement principle was previously described by (Brinker, 2005): A combined helium/neon-laser beam with a wavelength of 632,8 nm passes through a rotating wedge prism and a focusing lens. This causes the beam to deviate from the optical axis by a deflection angle of 1°. The wedge prism rotates on 80 Hz and produces a rotating laser, which scans the circular measuring area of approximately 1.13 mm^2 within the center of the flow cell. Focused is the laser by a lens on 1.2 μm. A photo diode detector located at the end of the light path registers the light intensity. When the laser beam interacts with a particle in his path, a photo diode detects the duration of the temporary blockage of the laser beam by the particle. The generated pulse signals have a proportional width to the particle size. Since the laser scans at a known speed, the particle size can be computed from the pulse signal. During each analysis the laser beam has millions of interactions with the particles. To measure particle size correctly the pulse shape and height are used to discriminate, if a particle is out-of-focus or in-focus, as well as to identify off-centre particles. Only pulses with narrow derivatives - the characteristic of a particle that is hit straight on its diameter - are accepted as valid on-center interactions, and subsequently added to the particle size distribution. The resolution is 0,3 % of the selected size range with a lower boundary of 0.2 μm.

Three measurement size ranges can be chosen. With the first optic, the range 0.2 to 150 μm can be analyzed. The second optic allows two size ranges, 2 to 300 μm and 5 to 600 μm.

A computer is controlling the measurement and calculates the size data. (Brinker, 2005, Tsai, 1996)

The lazer sizer Galai CIS-1 was detached by the newer model CIS-50, followed by CIS-100. According to (Brinker and Rosch, 2004), both followers are not suitable for aquaculture purposes. The laser overestimates evidently the particle sizes of suspended solids in aquaculture water. The author assumes, that the overestimation is due to a higher laser beam deflection angle of 4°. (Brinker, 2005)

The technology of the Galai CIS has been sold and a new version, produced under the name EyeTech Particle Sizer by Ambivalue based in the Netherlands, is actual available on the market. According to the producer, the EyeTech laser is suitable for PSD analyses of suspended solids from aquaculture, but an independent third party has not approved this yet.

FIGURE 6: (LEFT) LASER SET UP WITH FLOWMETER GALAI CIS 1; (MIDDLE) FLOWCONTROLLER; (RIGHT) GAZE FILTER FOR CATCHING OUT-OF-RANGE PARTICLES

2.2.2. SAMPLING AND ANALYSE EQUIPMENT

Filtration unit for TSS analyses

To filter the water sample through a 0,45 µm cellulose-acetat filter (d: 50 mm, Sartorius 11106-50-N), a low negative pressure of about 0,001 MPa (KNF Neuberger, model PJ 2209-026) was used. The equipment can be seen on figure 7. The red tube is connected to the pump. The water is filled into the beaker on top and is sucked through the filter, which is placed on top of poriferous plate. The filtration is finished, when all water has passed the filter.

FIGURE 7: FILTRATION UNIT FOR TSS ANALYSES

Sampling equipment

1. 4 ball bottles (V=10l)
2. 1 pit
3. 2 x 25 l Millipore water
4. Bar water sampler
5. Automatic vertical water sampler
6. Several bins and canisters

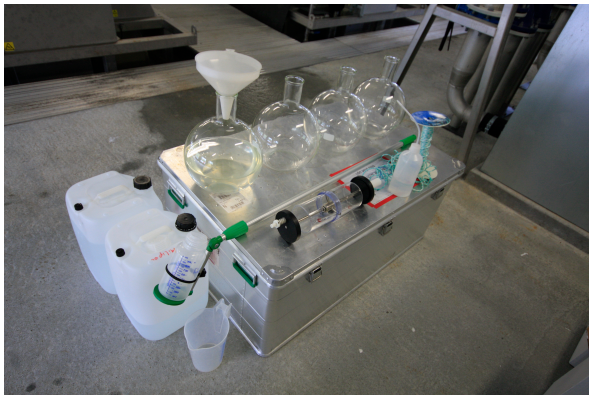

FIGURE 8: SAMPLING EQUIPMENT

Equipment for paper and gaze filter analyses (TSS and DM)

1. Drying cabinet
2. Scale (Mettler AT 200 Fact)

   Capacity: 205g

   Readability: 0.1mg

   Repeatability: for full load, 0.07mg mg and for 0-50g range, 0.04mg, linearity: +- 0.15mg.

FIGURE 9: SCALE METTLER AT 200 FACT

2.3. RAS

The Marine Harvest Hatchery and Smoltfarm Dalsfjord is located close to Volda in Romsedal. The facility has been built as a recirculating aquaculture system (RAS) in 2010.

The RAS, is a Kaldnes®RAS unit, designed and build by Krüger Kaldnes. Figure 10 shows the treatment unit looking from the fish tanks onto the RAS.

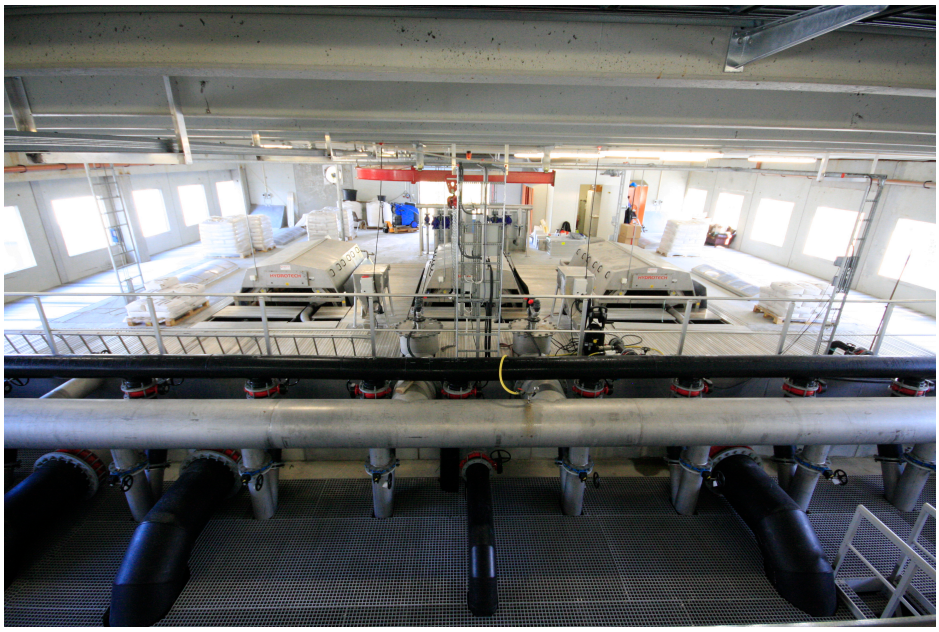

FIGURE 10: VIEW FROM THE FISH TANKS ONTO THE RAS OF THE MARINE HARVEST SMOLT FARM IN DALSFJORD

2.3.1. Dimensioning Values

The water treatment system is designed according to the general set-up of a RAS. Starting, after the fish tanks, with particle separation by mechanical filtration, biological filtration in the MBBR, degasing and oxygenation before entering the fish tanks. For particle removal, the system is equipped with three drum filters, two units filter 85 % of the flow on 60 μm and the remaining 15 % are treated by one filter of 30 μm.

The Moving Bed Biofilm Reactor (MBBR) is divided in two reactors. Reactor 1 has a volume of 210 m^3 and is filled with 87,5 m3 of biomedia. Reactor 2 has a volume of 250 m3 and 87,5 m3 biomedia.

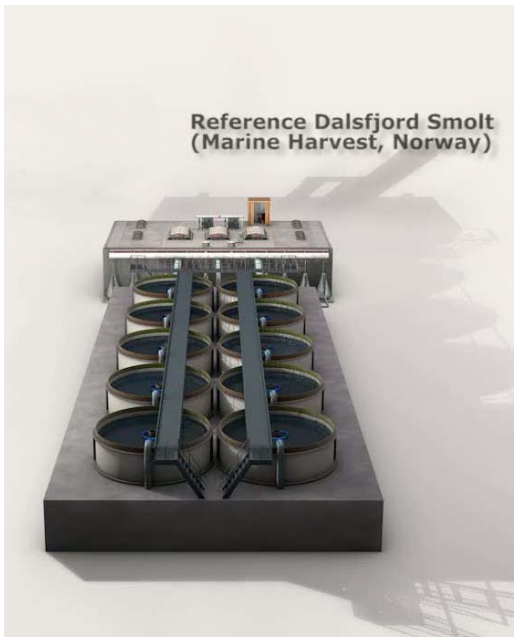

FIGURE 11: SKETCH OF THE MARINE HARVEST RAS DALSFJORD

This gives a total reactor volume of 460 m3 (compare table 4). Air blower installed on the bottom of the MBBR keep the moving bed in motion. On top of reactor 1 are two pH control units installed. The pH is adjusted by lime addition to the water.

TABLE 4: DIMENSIONING SPECIFICATION OF MBBR

Reactor 1 Biomedia (BFC-P/M)	Reactor 1 Water volume	Reactor 2 Biomedia (BFC-P/M)	Reactor 2 Water volume	Total Reactor Water vo	Total Reactor Airflow
87,5 m^3	210 m^3	87,5 m^3	250 m^3	460 m^3	1600 Nm^3/h

The installed CO2 strippers are placed after the MBBR and consist out of two channels. They have a total trickle area of 47 m2. Fans suck air through the units, 4000 Nm3/h per degaser.

After the CO2 stripper the water is collected in the pump sump from where it is pumped by propeller pumps to the fish tanks. The pumps have a capacity of 1200 m3/h at 7.5 mWc. Two pumps running at full engine speed give a retention time of approx. 35 minutes in the fish tanks. The make-up water is added into the pump sump. It can be assumed, that the approximately 300 l of water are added per kg of feed per day used. That gives roughly 25 m3/h at maximum feeding.

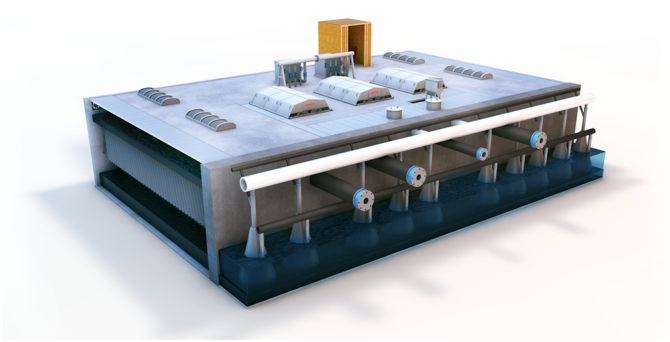

FIGURE 12: SKETCH OF THE RAS UNIT WITH THE MAIN MANIFOLD DISTRIBUTING THE WATER AFTER PUMPING TO THE 10 DEEPSHAFT CONES

The water temperature in the RAS is controlled by the amount of hot water circulating between the heat pump and the exchanger. The system is designed for an average water temperature of 14 °C.

Before entering the fish tanks, the entire flow is oxygenated by deep shaft oxygen cones. One oxygenation unit is supplying each fish tank. The amount of oxygen added in the cones is regulated by valves and is individually adjusted according to O2 level in the fish tanks.

An overview of the dimensioning base values for the RAS in Dalsfjord can be seen in the table below.

TABLE 5: MAIN DIMENSIONING VALUES FOR THE SMOLT FARM DALSFJORD

Parameter	Value	Unit
Tank size	140	m^3
Total prod. volume	1400	m^3
Max stocking density	50	kg fish/ m^3
Max biomass	70000	kg
Max feed	2000	kg/ day
Max oxygen requirement	300	g/ kg feed

The table below shows general water quality parameter, for which the system is designed for.

TABLE 6: MAIN WATERQUALITY PARAMETER THE RAS IS DESIGNED FOR

Parameter	Concentration	Unit
Temperature	14	°C
TAN production	32	g/kg feed
Salinity	0	%
Water flow	2400	m^3/h
Makeup water	300	l/kg feed
TAN	1,5	mg/l
NH3	0,02	mg/l
CO2	15	mg/l

Figure 13 illustrates the set-up of a Kaldnes®RAS unit. It shows the water flow from the fish tanks through the different treatment units, collected in the pump sump and pumped back via deep shaft oxygenation cones to the fish tanks. The whole process is controlled via SCADA.

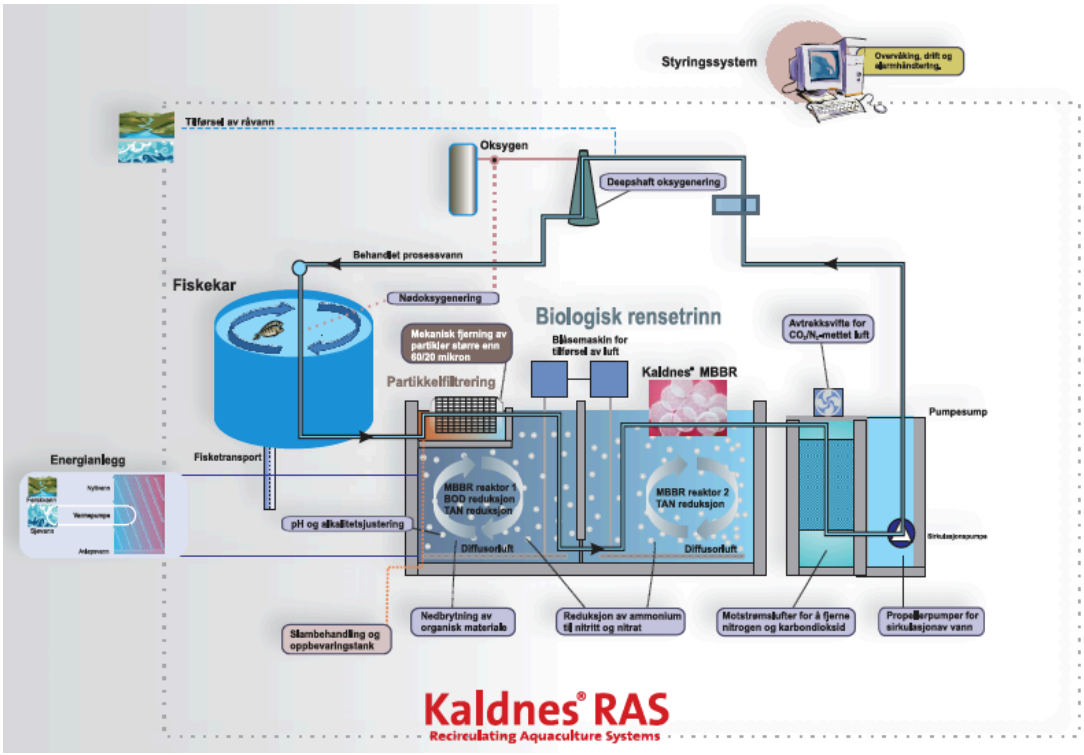

FIGURE 13: SCHEMATICAL FLOWDIAGRAM OF KALDNES RAS

2.3.2. *FILTER UNITS*

The RAS is equipped with 3 Hydrotech drum filters type HDF 2006. All three filters are submerged into reactor 1 (biofilter) on top of the RAS unit. The Hydrotech drum filters are mechanical, self-cleaning filter specially designed for high performance in systems where it is essential to prevent particles from fragmenting. The total flow of the process water coming from the fish tanks is divided into three parts. Two times 42,5 % passes one 60 µm filter each and the remaining 15 % are filtrated by a 30 µm filter. Figure 14 shows a sketch of a Hydrotech filter visualizing the working function.

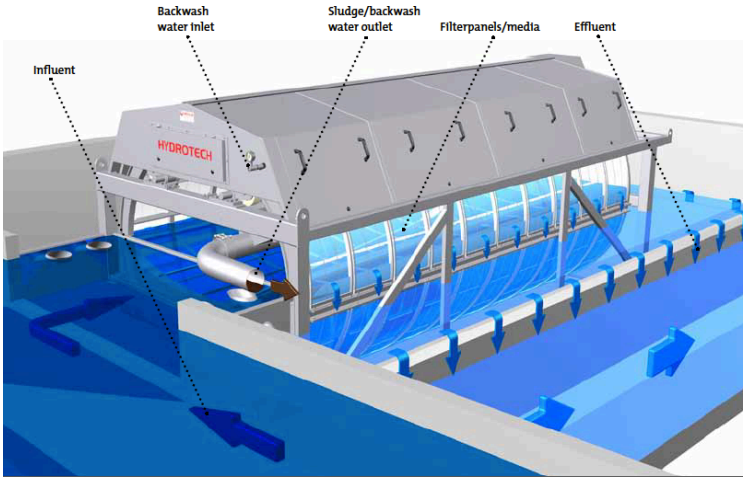

FIGURE 14: SCHEMATICAL WORKING PRINCIPLE OF HYDROTECH DRUM FILTER. WATER ENTERS THE DRUM IN THE FRONT AND LEAVES IT OVER THE SIDES THROUGH THE FILTERPANELS. THE SLUDGE, REMAINIG ON THE FILTER SCREEN IS WASHED OFF BY BACKWASH SYSTEMAND SEND OUT VIA SLUDGE OUTLET.

2.3.3. *Farm utilization during experiment*

During the experiment time, the Smoltfarm in Dalsfjord was operating on a high biomass between 44 and 50 t (compare table 7). The RAS system is designed for a max biomass of 70 t, which means that it was operating on 70 % biomass capacity utilization. 9 of 10 tanks were stocked with fish during the experiment period. The tanks were stocked with average fish sizes from 3,9 up to 56 g.

TABLE 7: FARM DESIGN VALUES FOR MAXIMAL BIOMASS AND MAXIMAL FEEDING COMPARED TO UTILIZATION DURING EXPERIMENT.

Parameter	Max. design values	Max. values during experiment
Biomass	70 000 kg	50 000 kg
Feed	2 000 kg/day	934 kg/day

The water temperature in the tanks varied between 11 and 14 °C and a pH around 7.

The feeding and light regime was set continuously 24 h/day. The automatic feeder supplies one tank at a time with pellets. The amount of feed fed in total in the RAS system during the time of the PSD analyses is summarized in figure 14. It can be seen, that the amount varied between round 400 kg up to 900 kg.

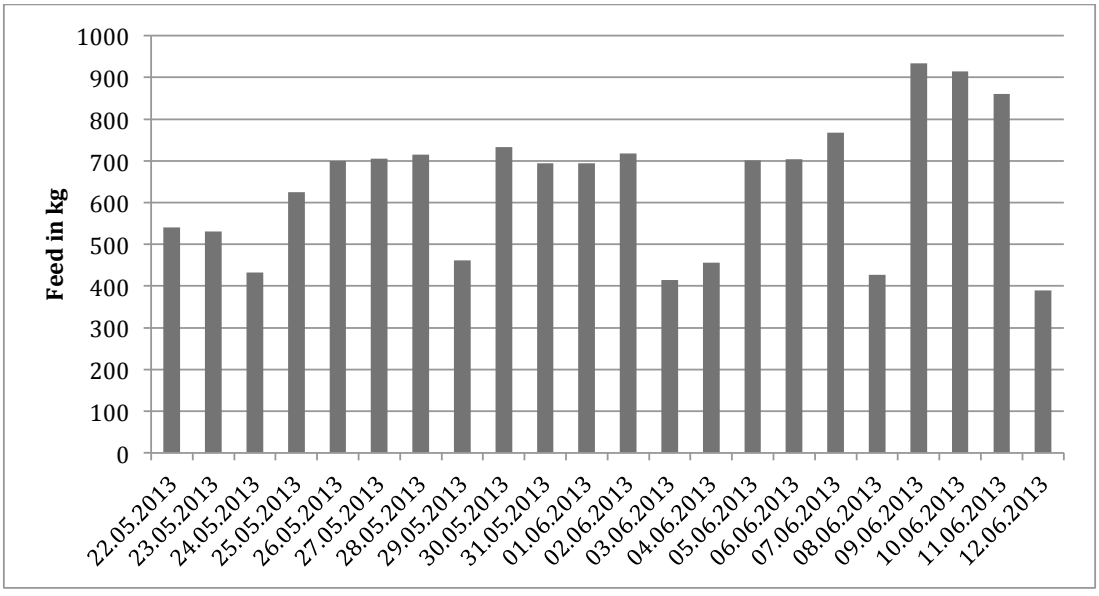

FIGURE 15: TOTAL FEEDING PER DAY IN FARM DURING THE TIME OF THE EXPERIMENT. DAY 1 OF EXPERIMENT WAS 23.05.; DAY 2=24.05; DAY 3=26.05.; DAY 4=27.05.; DAY 5=28.05.; DAY 6=29.05.; DAY 7=30.05.; DAY 8=31.05.; DAY 9=03.06.; DAY 10=04.06.; DAY 11= 05.06.; DAY 12=06.06.; DAY 13=11.06.; DAY 14=12.06.

2.4. SAMPLE SPOTS

The sample spots were chosen according to the objectives of the PSD analyses. Since the compact design of the Kaldnes® RAS unit limits the excess points to the water, the water samples needed to be taken, were the water flow was accessible. An overview of the different sample spots is shown in figure 16.

All water samples were taken as carefully as possible, avoiding any kind of shaking or high turbulences during sampling and transport, which could lead to a change of particle sizes. In addition to that, the time in between sampling and laser analysis was kept at its possible minimum. In case sampling was done in open basins, the sample was always taken out of the water column and not from the surface.

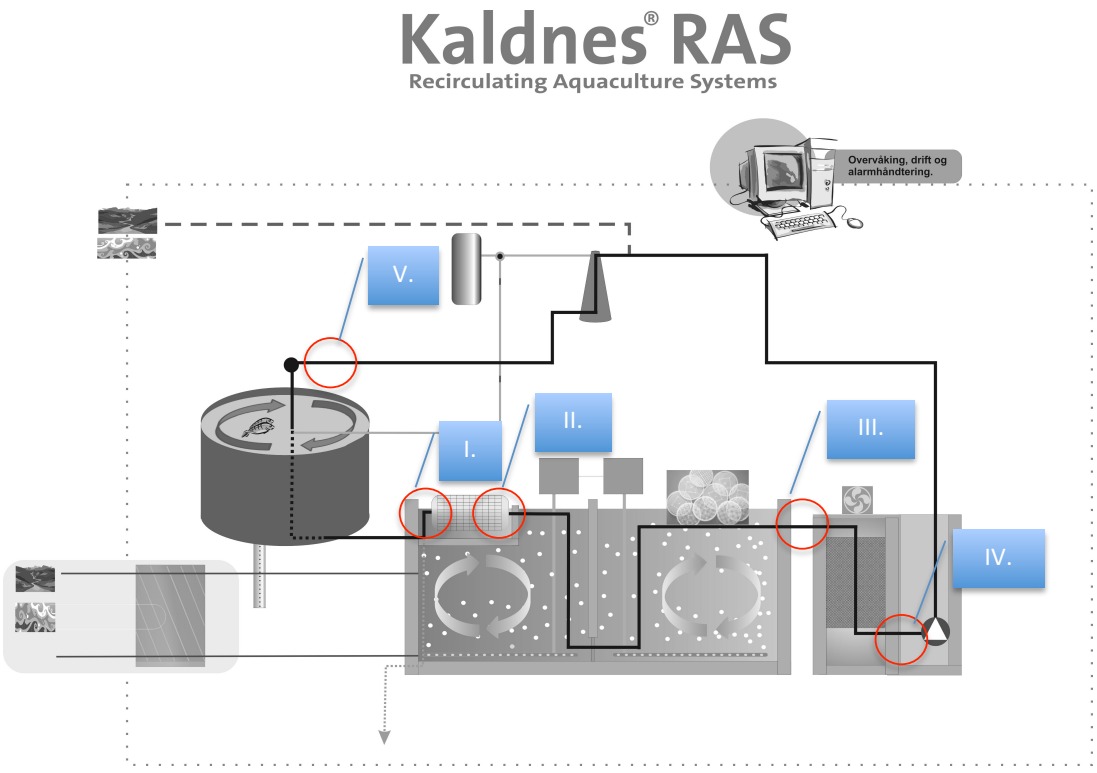

FIGURE 16: OVERVIEW OF SAMPLE SPOTS USED FOR PSD ANALYSES. I. BEFORE DRUM FILTER; II. AFTER DRUM FILTER; III. AFTER MBBR; IV. AFTER DEGASER; V. FISH TANK INLET

I. Before drum filter (*sample spot I.)*

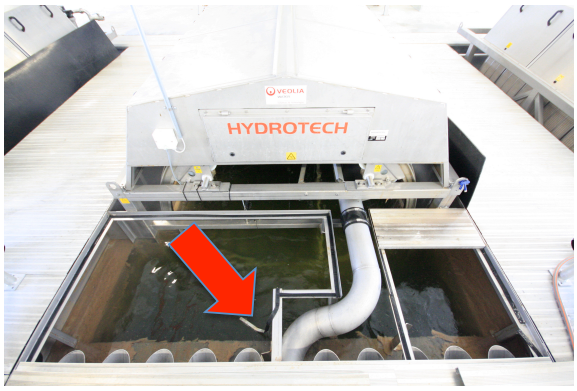

FIGURE 17: SAMPLE SPOT – DRUM FILTER INLET. THE RED ARROW MARKS THE SPOT, WHERE THE WATER SAMPLES WERE TAKEN

This sample spot was located in water flow direction after the fish tanks and is the first treatment step of the RAS unit. The water from the fish tanks is drained over the fish tank outlets and collected after piping in one big manifold. From that manifold three pipes distribute the water to the three drum filters. The two 60 µm filter are supplied with 42.5 % of the total flow and the remaining 15 % is sent into the 30 µm filter. The inlet-pipe into each drum filter ends submerged in an open channel, which ends at the drum inlet.

The objective of this sample was to gather accurate data of the particle size range and the PSD in the water coming from the fish tanks. To know what kind of particle sizes in what kind of amounts is entering the filter units is important knowledge for correct dimensioning of particle filtration units and as well for choosing the most efficient mesh sizes of the filter material. Further use of this sample spot was the comparison from influent and effluent water from the filter units. That could test the PSD based filter efficiency of the different mesh seizes as well as the overall effect of the set of drum filter on the PSD of the solids in the process water.

Water sampling

FIGURE 18: WATER SAMPLER. BOTTLE VOLUME: 1L

According to the sample volume going to be analysed, water samples were taken directly at the outlet of the pipes, which delivered the water from the manifold towards the three drum filters. By taking the sample from the incoming flow, a representative sample from the incoming water could have been taken. A water sampler (compare figure 18) with a sample volume of 1 litre was used. For sampling, the sample bin was submerged with the opening upside down, so that the air inside was not released before turning the bin upwards. This way a sample from the middle point of the incoming flow could have been taken. For a water sample, which was supposed to represent the total water flow of the system, a mixed sample according to the

percentage flow into the drum filters (42,5 % into each 60 µm and 15 % into the 30 µm filter) was prepared for the laser analyse.

II. After drum filter (*sample spot II.)*

After entering the drum from one end (compare figure 17), the water is filtered through the filter cloth and leaves the drum over the side into a box, in which the drum filter is placed. The drum filter and the box are submerged into reactor 1 of the MBBR. Over the long sides of the box, the water overflows into the MBBR reactor.

FIGURE 19: SAMPLE SPOT – DRUM FILTER INLET. THE RED ARROW MARKS THE SPOT, WHERE THE WATER SAMPLES WERE TAKEN

Objective of this sample spot was to examine the effect of the particle filtration units on the full water flow in the RAS as well as the test of the filter efficiency of different filter mesh sizes. For both experiments, the PSD data from the water after filtration was compared to the PSD of the inlet water (sample spot I). The sample spot II is simultaneously the spot were samples for the MBBR comparison (before the unit) were taken.

Water Sampling

Samples after drum filter were taken at the side of the drum (compare figure 19). The water sampler (compare figure 18) was used for sampling. Samples were taken ca. 15 cm under the water surface. For representative samples of the total water flow in the system, sample volume according to the percentage flow into the drum filters, were taken.

III. After MBBR *(sample spot III.)*

The water filtered from the drum filters overflows into reactor one of the MBBR. It continuous through the aerated biomedia, passes a sieve to enter into reactor 2 and leaves the biofilter over two on both sides of the reactor over overflows.

Objective of this sample spot was to examine the impact of the MBBR on the PSD of the process water. Therefore samples were taken before and after the MBBR and the results of the PSD analyses were compared (sample spot II and III). In addition, sample spot III is simultaneously the inlet to the degaser. Yet, influent-samples for the comparison of in-and effluent of the degaser were taken here as well.

FIGURE 20: SAMPLE SPOT – AFTER MBBR. THE RED ARROW MARKS THE SPOT, WHERE THE WATER SAMPLES WERE TAKEN.

Water Sampling

Samples after the biofilter unit were taken with the water sampler (compare picture 18) directly from the overflowing water from both sides out of the MBBR. According to required sample volume, the sample procedure was repeated and the water was collected in a ball bottle. By supposing an equal division of the flow into the two outlet channels on each side of reactor 2 of the MBBR, samples were taken in a ratio of 50 % to 50 %.

IV. After degasing (*sample spot IV.)*

The water leaving the biofilter over the overflows is sent into two open channel located at the side of the Kaldnes®RAS unit. The bottom of the channel is a distribution plate through which the water trickles onto the media of the degaser. The degaser are placed along the side of the MBBR and the pump sump (compare figure 21). The degasing units are supplied with water over a distribution plate. From there, water trickles by gravity through trickling filter blocks and flows collected to the pump sump. Under the use of the counter current principle and negative pressure, air is sucked through the degaser by fans to have sufficient gas exchange.

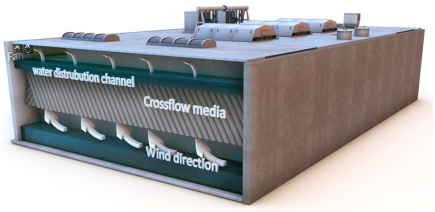

FIGURE 21: SKETCH OF ONE DEGASER CHAMBER PLACED AT THE SIDE OF THE KALDNES®RAS UNIT VISUALLIZING THE WORKING PRINCIPLE. WATER AND AIR ARE EXCHANGED BY COUNTER.CURRENT PRINCIPLE FOR MAXIMUN GAS EXCHANGE.

The sample spots seen on figure 22 are the outlets from both degaser into the pump sump. Objective of this sample spot was to examine the impact of the degaser on the PSD of the process water of the RAS (PSD of sample spot III compared to sample spot IV).

FIGURE 22: (LEFT) RED ARROW MARKS THE SMAPLE SPOT WHERE SAMPLES WERE TAKEN FROM THE EFFLUENT OF ONE OF THE TWO DEGASER; (MIDDLE) RED ARROW MARKS THE SMAPLE SPOT OF THE SECOND DEGASER; (RIGHT) WATER SAMPLER USED TO TAKE SAMPLES OUT OF THE WATER COLUMF FROM INFLWOING WATER OF THE DEGASER INTO THE PUMP SUMP.

Water sampling

The samples from the water coming out of the degaser were taken as close as possible to the outlet. For water sampling, an automatic water sampler (compare figure 22) was used. This sampler enabled sampling water in the water column of the pump sump (about 50 cm below the surface. Each time a mixed sample from both degaser, meaning from each side of the pump sump, was taken (50 % - 50 % ratio).

For the comparison of the PSD in the water of the pump sump to the PSD in the water entering the fish tank, the pump sump water was sampled in the centre of the pump sump, next to the propeller pumps.

V. Inlet fish tank (*sample spot V.)*

From the pump sump, in which the water is collected, propeller pumps deliver the water back to the fish tanks. After being pumped, the water is distributed over a manifold into 10 pipelines (one for each tank). Each pipeline enters a deepshaft oxygenation unit (cone), in which the water is supersaturated with oxygen. The oxygenated water is then supplied over inlet nozzles into the fish tanks. The water from sample spot V was taken from a valve placed at the inlet pipe of one of the fish tanks. By taking samples over the valve, samples from the inlet pipe could be taken without having the risk of contamination with water from inside the fish tank.

Objective of this sample spot was to compare PSD data of the water in the pump sump to the PSD of the inlet water of the fish tank. Possible impact factors are: pumping, oxygenation and piping.

FIGURE 23: THE RED ARROW MARKS THE VALVE, FROM WHICH SAMPLES FROM THE FISH TANK INLET PIPE WERE TAKEN.

Water Sampling

Water samples from sample spot V were taken directly from the inlet pipe, which is supplying one of the fish tanks with water from the RAS unit. Therefore a valve, which was mounted to the inlet pipe for sampling, was fully opened and the attached tube was flushed for about 30 seconds. Afterwards a ball bottle was carefully filled with the required sample volume.

2.5. ANALYSE PROCEDURES

2.5.1. MEASURING PROCEDURE WITH THE GALAI CIS 1

The particle size distribution of the suspended solids in the water of the smolt farm was analysed with the Galai CIS-1 (compare chapter 3.2.1).

The analyse-procedure can be described as followed: After sampling, the water is filled into a beaker on top of the flow controller. A stirrer is keeping the particles in suspension. The steering speed is adjustable and was set for this experiment on 40 turns per minute. The sample volume as well as the time required for each analyse depends on the particle load of the water. The higher the particle amount of the sample is, the shorter is the time and by that smaller is the sample volume, which needs to pass the laser, to achieve accurate measurements. Usually the required volume varies between 0,5 – 5 l and the duration between 20 – 80 minutes. The beaker has to be refilled continuously to secure a constant flow, until the analyses is finished.

Controlled by the flow meter, the water runs from the beaker through a tube and passes the laser through a cuvette. After being analysed by the laser, the water is send onto a polyester screen with a mesh size of 600 µm / 300 µm / 150 µm (according to the used particle range of the laser) to capture the out of range particles. After that, the filtrated water flows into a recipient. The captured water is filtered afterwards by 0,45 µm cellulose-acetate filter (d: 50 mm, Sartorius 11106-50-N) using a low

negative pressure of about 0,001 MPa (KNF Neuberger, model PJ 2209-026) to capture the TSS (total suspended solids). This TSS analyse is further described in chapter 3.5.3.

The laser-determined PSDs were corrected for out-of-range particles (those > 600 µm or >300 µm) by dividing their weight by the total weight of particles.

The raw data from the laser is arranged into size classes ($d_{i+1} = 1.26 * d_i$; where d= the upper diameter of the class) according to (Patterson et al., 1999). All data was then converted into cumulative volume and relative volume data assuming a sphere as the basic shape.

The CIS-1 provides a statistical routine which must be >99 % to achieve robust PSD data. Meaning, that with further measurements the mean of the determined PSD will not change by more than +/- 2,5 %

2.5.2. TOTAL SUSPENDED SOLIDS (TSS)

Prior to the TSS analyses all filter were prepared according to German standard method (DIN 1987) and labelled individually. Each cellulose-acetate filter was boiled in millipore water, dried in a drying cabinet (103 °C/ 24h), stored in an exicator for temperature adaption and finally weight (0.1 mg). The dry weight of each labelled filter was noted and the filters were packed for the analyses on side.

For the TSS measurements, the water sample, which was collected after the laser PSD analyse (compare 3.5.1.), was filtered by the 0,45 µm cellulose-acetate filter. Since the water volume, which passes the 0,45 µm filter, is limited by the amount of solids in the water (filter clogs), a representative TSS sample of the water from the laser was taken. Therefore the PSD water sample was well mixed and according the filterable volume, a water sample for the TSS filtration was extracted. After the vacuum pump was started, the sample was filled into the top beaker of the TSS filtration unit. After all water had passed the filter, the beaker was rinsed with a small amount millipore water to flush particles attached to the beaker onto the filter.After the TSS filtration, the filter with the filter cake on top was packed and stored in a freezer until being further analysed in the lab.

In the lab, all TSS filter were dried (103 °C/ 24h) and stored in an exicator for temperature adaption before the dry weight of the TSS including the filter was measured (according to German standard method DIN 1987).

The same analyse-procedure was conducted as well with the 300 µm and 600 µm gaze filter for the DM weight analyse. All filter weight analyses were repeated once for accuracy. This included a repetition of drying cabinet, exicator and weight analyse.

The TSS in mg/l and the dry matter (DM) on the gaze filter are used to calculate the correction factor for the out of range particles of the laser counter. Hence, the weight of the particles above 300 µm or 600 µm (dependent on used size range in laser) divided by the total particle weight gives the correction factor for the laser-determined PSD for the out-of-range particles larger than 300 µm or 600 µm.

2.5.3. STATISTICS

For statistic reliability of a hyperbolic distribution, the PSD data were arranged in size classes according to Patterson et al. (1999). Data analyses were performed with JMP (SAS Institute Inc.) and Microsoft Excel. For each data set from one sample spot, the standard deviation was determined and included in the graphical diagrams in the result chapter.

Besides that, no further statistical investigations were performed on the PSD data. It was found to be not relevant in terms accuracy and general conclusion of the results.

3. RESULTS

3.1. PSD OF FISH TANK EFFLUENT

3.1.1. PSD MEASURED ON 5-600 µM RANGE

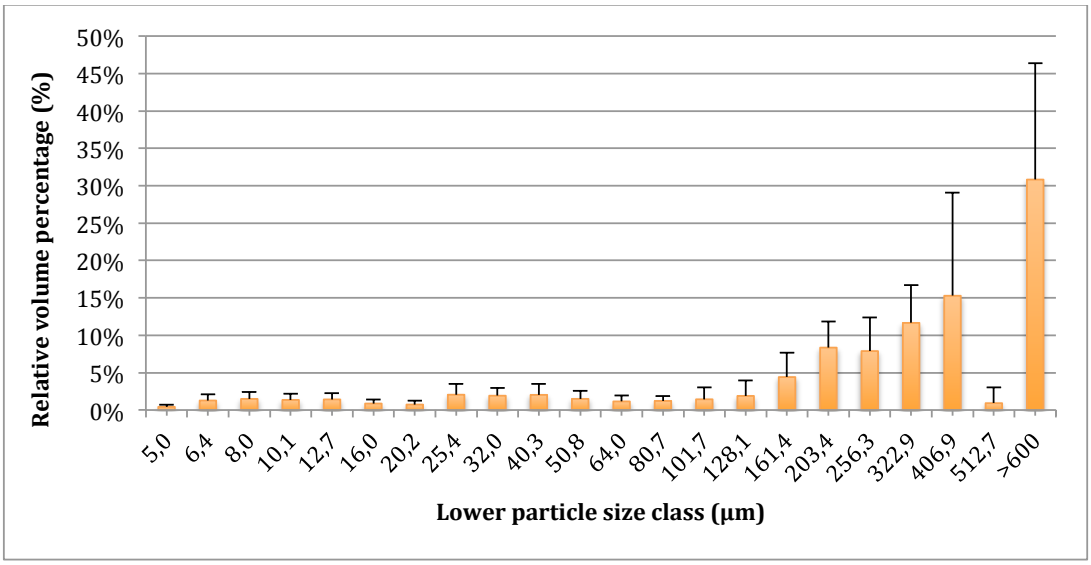

FIGURE 24: DISTRIBUTION OF PSD (RELATIVE VOLUME PERCENTAGE) IN THE WATER FROM THE FISH TANK OUTLETS. SAMPLE SPOT WAS AT THE DRUM FILTER INLET. DIAGRAM SHOWS SUMMARIZED DATA OF CONTINUOUSLY MEASUREMENTS OVER A 7 H PERIOD (N = 9).

In this experiment, the PSD was measured over a full day (7h) to get a good overview of the particle loads in the effluent water from the fish tanks. The laser was set up to measure on the biggest possible size range of the CIS 1, from 5-600 µm, to get the most complete picture of the size distribution of suspended solids released in the fish tank and entering the water treatment unit. Figure 24 summarizes the results of the particle size distribution measurements from samples taken in front of the filter units. It becomes apparent, that the main particle volume is present in the size group > 600 µm. The particles bigger than 600 µm represent around 30,8 % of the total particle volume. The next four biggest size groups are 406 - 512 µm with 15.3 %, 322 – 406 with 11.6 %, 203 - 256 µm with 8.3 % and 256 - 322 with 7.9 %. Particles in the range from 517 – 600 µm, were nearly negligible present. The remaining round 25 % particle volume is relatively evenly distributed over the range from 5 to 203 µm, whereby marginal higher volume percentages where measured in the size groups 6.4 to 16 µm and 25,4 to 64 µm.

The results presented are the mean PSD values of 9 analyses. The single analyses vary in between each other, visualized in the diagram by the standard deviation. The volume percentage in the particle range > 600 µm together with the range from 406 – 512 µm show the highest standard

deviation equivalent of 15.6 % and 13.8 %. This illustrates a high variation of the amount of particles > 600 coming from the fish tank. The remaining size ranges exhibit only small variation represented by standard deviation in the range from 0.4 and 7 %.

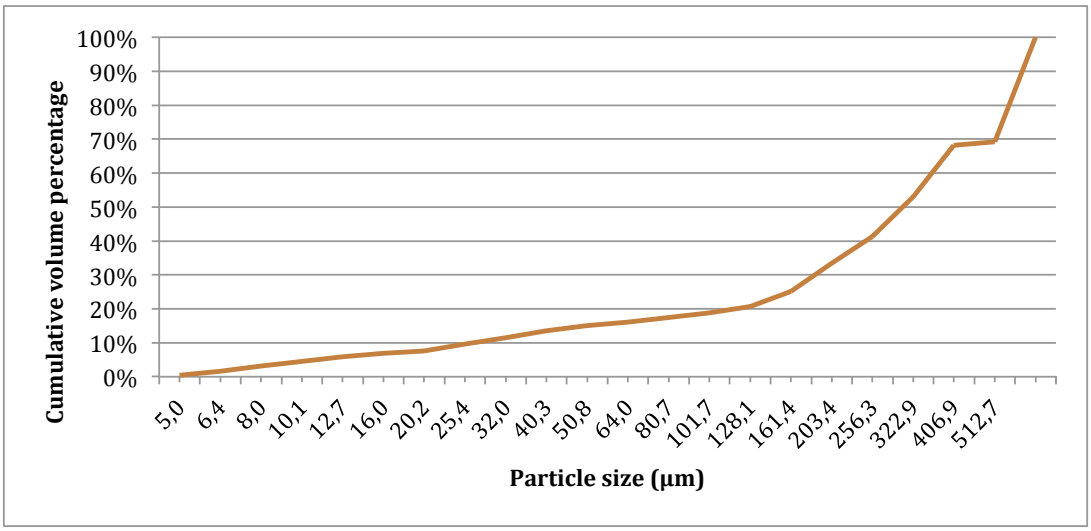

FIGURE 25: DISTRIBUTION OF PSD (CUMULATIVE VOLUME PERCENT) IN THE WATER FROM THE FISH TANK OUTLETS. SAMPLE SPOT WAS AT THE DRUM FILTER INLET. DIAGRAM SHOWS SUMMARIZED DATA OF CONTINUOUSLY MEASUREMENTS OVER A 7 H PERIOD (N = 9).

Figure 25 illustrates the PSD results in cumulative form. As displayed, only a small volume percentage is represented by the fine particles smaller 20 µm (<10 %). Big particles are clearly dominating in the water. Over 80 % of the total particle volume is present in the range > 60 µm.

4.1.2. PSD MEASURED ON 2-300 µM RANGE

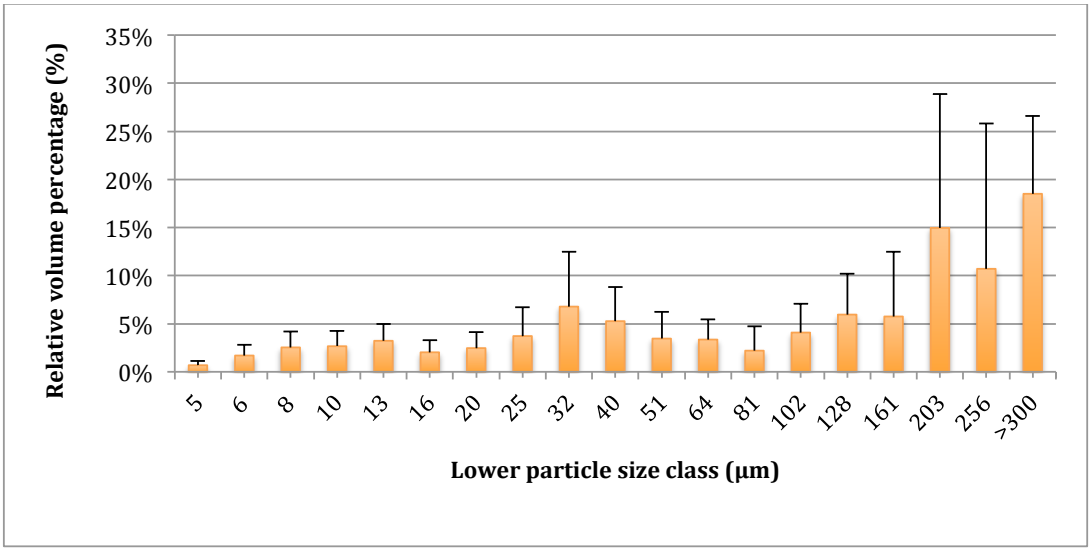

FIGURE 26: DISTRIBUTION OF PSD (RELATIVE VOLUME PERCENTAGE) IN THE WATER FROM THE FISH TANK OUTLETS. SAMPLE SPOT WAS AT THE DRUM FILTER INLET. DIAGRAM SHOWS SUMMARIZED DATA OF CONTINUOUSLY MEASUREMENTS OVER A 7 H PERIOD (N = 10).

The second experiment was a repetition of day one with the difference, that a smaller measurement range of the laser sizer was used. In this run, the particle range from 2-300 µm mas measured. The used optic allows measuring the PSD on the smaller particle range, which decreases the analyse-time required per sample. In addition, the laser is separating the measured particles in finer grouped particle size ranges, which allows a more detailed data analyse. For this data examination, the same particle size groups according to (Patterson et al., 1999) for both optics (2-300 µm and 5-600 µm)have been used. By that, the comparison of the different analyses is more unmistakeable.

Figure 26 summarizes the results of the PSD measurements of the water sampled in front of the filter units (representing the total flow coming from the fish tanks). The diagram shows, that the dominating particle sizes are in the range from 203 up to > 300, whereby the highest volume percentage is present in the size group > 300 µm. This size group represents around 18.5 % of the total particle volume. The next two biggest size groups are 203 – 256 µm with 15.0 % and 256 - 300 µm with 10.7 %. It stands out, that the volume percentage is more even distributed in figure 26 than on the first day (figure 24). As already visual in figure (day 1), dominating in the smaller particle range were particles around 8 to 16 µm as well particles in the range from 25 to 51 µm. These clear peaks in the beam diagram are present in the results of both days.

At day 2, particles covered the full size range. All particles bigger than the measurement range are summarized in the size group >300.

The single analyses vary in between each other, visualized in the diagram by the standard deviation. The volume percentages in the particle range 203 - 256 µm and 256 - 300 µm show the highest standard deviation from the mean (14.0 and 15.1 %).

In the particle groups of the fine particles the most outstanding standard deviation is the size range from 32 - 40 µm with 5.7 %

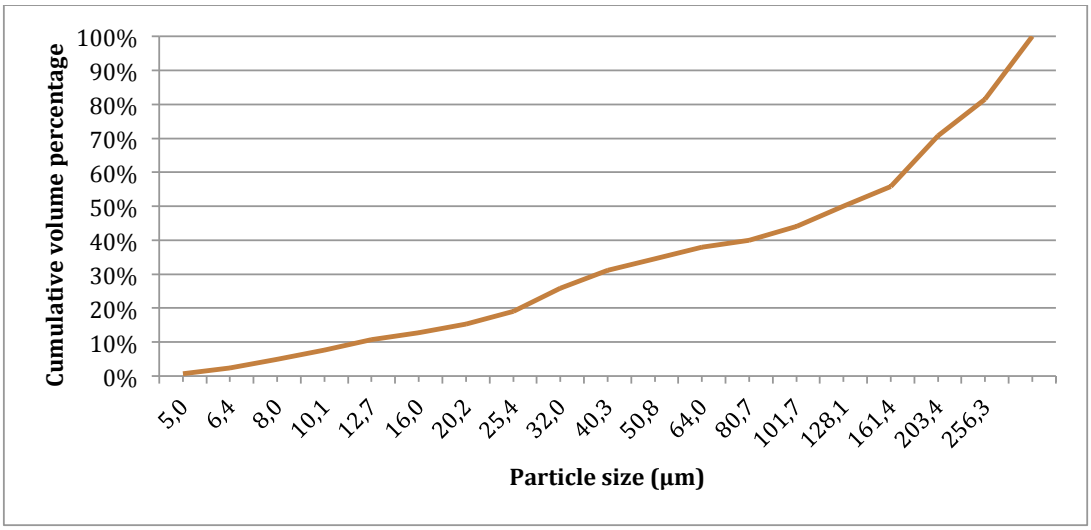

FIGURE 27: DISTRIBUTION OF PSD (CUMULATIVE VOLUME PERCENT) IN THE WATER FROM THE FISH TANK OUTLETS. SAMPLE SPOT WAS AT THE DRUM FILTER INLET. DIAGRAM SHOWS SUMMARIZED DATA OF CONTINUOUSLY MEASUREMENTS OVER A 7 H PERIOD (N = 9).

Diagram 27 illustrates the PSD results in cumulative form. As displayed, a higher volume percentage is represented by the fine particles than at day one. In average over 35 % of the total particle volume is below 60 µm, whereby it was less than 20 % at the same sample spot on day one. Big particles are still clearly dominating in the water.

4.2. IMPACT OF THE DIFFERENT WATER TREATMENT UNITS

4.2.1. IMPACT OF THE DRUM FILTERS

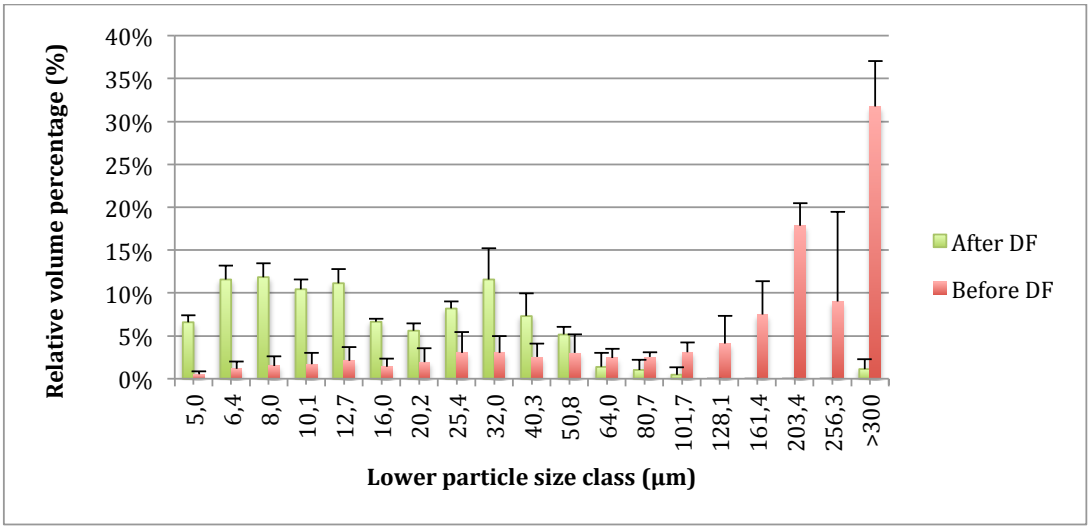

FIGURE 28: DISTRIBUTION OF PSDS (RELATIVE VOLUME PERCENTAGE) BEFORE AND AFTER DRUM FILTRATION. WATER SAMPLES ANALYZED WERE MIXED SAMPLES FROM BEFORE (N=4)/ AFTER (N=4) THE 3 HYDROTECH DRUM FILTER WITH 2 X 60 µM (85 % OF FLOW) AND 1 X 30 (15 % OF FLOW) µM FILTER GAZE.

This experiment was conducted to test the filter efficiency of the particle treatment unit of the RAS and to illustrate the effect of the filters on the PSD. The HDF 2006 Hydrotech drum filters are set up in the Marine Harvest smoltfarm (Dalsfjord) as followed: Two filters are running with 60 µm screens and one, for fine filtration, with a 30 µm screen. The results of the particle size analyses from before and after filtration are summarized in figure 28 and 29. The comparison of the results from the influent und effluent water of the drum filters show a clear effect of the filter on the distribution of the particle volume per cent. The distribution of the total particle volume measured in the influent water to the drum filters covered the full particle size range, as previously measured on day 1 (figure 24) and day 2 (figure 26). Clearly dominating were again particles bigger 300 µm. By comparing the results of the PSD of the water leaving the filter units, a clear reduction of upper particle ranges in the drum filter's effluent can be seen. Hardly any particles bigger 128 µm were detected in the water, which had passed the filter unit. Within the complete detected particle size range, the particles were relatively even distributed over the single size classes. No clearly dominating particle size can be seen. The leading classes 6-8; 8-10; 10-13; 13-16 and 32 - 40 µm share the highest volume percentage of around 11 %.

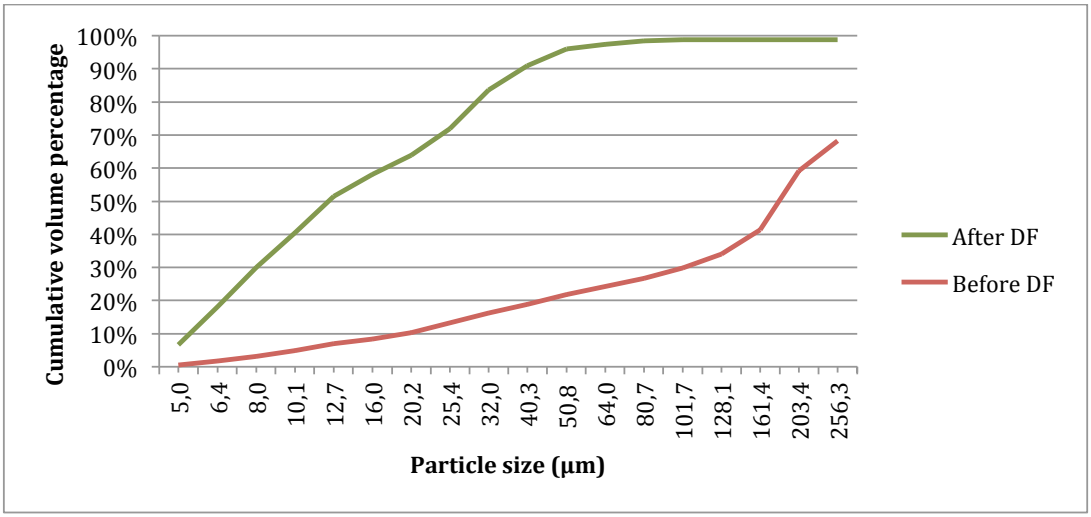

FIGURE 29: DISTRIBUTION OF PSDS (CUMULATIVE VOLUME PERCENTAGE) BEFORE AND AFTER DRUM FILTRATION. WATER SAMPLES ANALYZED WERE MIXED SAMPLES FROM BEFORE (N=4)/ AFTER (N=4) THE 3 HYDROTECH DRUM FILTER WITH 2 X 60 µM (85 % OF FLOW) AND 1 X 30 (15 % OF FLOW) µM FILTER GAZE.

Figure 29 exemplifies the PSD results from before and after the filter units in cumulative form. The red graph, displaying the results from the water sampled before the filters, shows, that the water contained a small volume percentage of fine particles, around 10 % smaller 20 with bigger particles over 100 µm being dominant with around 70 %. Based on the PSD of the influent water, the theoretical removal potential of a 60 µm mesh would be over 75 % and the removal of a 30 µm screen over 80 % of the total particle volume in the water (compare figure 29). The water samples taken after the filter units show a clear change in the PSD throughout the treatment unit. From the cumulative mean of the samples, displayed by the blue line in figure 29, it can be seen, that hardly any particles were measured in the range >60 µm. Less than 4 % of the total particle volume was detected to be bigger than the filter mesh size. The PSD was changed from dominant big particles (over 75 % >60 µm) to dominant small particles (around 97 % <60 µm) throughout the filter units. The particles, smaller than the filter cloth of the fine filtration unit, meaning smaller than 30 µm, are present in a high volume per cent of over 85 % after the water was sent through the filter.

The variation of the single particle size analyses, visualized in form of the standard deviation (figure 28), show noticeable variations in the different particle size groups of both sample spots. The influent water shows stable values up to 256 µm with standard deviations of 0.4 to 3.8 %. Only in the biggest particle classes the variation is higher and reaches maximal 10.5 % (256 -300 µm).

The summarized PSD analyses of the effluent water have had only negligible variations. The peak value is 3.7 % in the size class 32 - 40 µm.

4.2.1. IMPACT OF THE MBBR

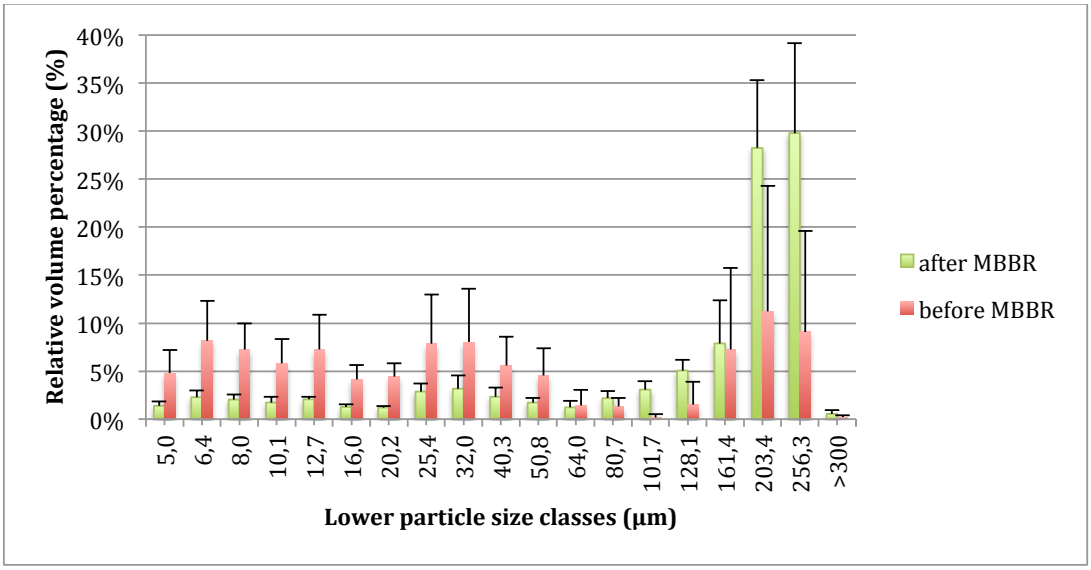

FIGURE 30: DISTRIBUTION OF PSDS (RELATIVE VOLUME PERCENTAGE) BEFORE (N=4) AND AFTER (N=4) BIOFILTRATION (MBBR).

This experiment was done to investigate the impact of the two-chamber MBBR on the particle size distribution in the process water. The comparison between the particle size distribution of the influent and effluent water of the MBBR showed clear differences in the distribution of the particle volume per cent (compare figure 30). The influent water, which is equal to the effluent water of the three drum filter units in the system, contained relative high percentage of small particles (<64 µm). Around 70 % of the total particle volume was smaller than 64 µm. In the particle size groups from 64 µm up to 128 µm are only 1,6 % of the total particle volume present. The remaining 28 % of particles were bigger then128 µm. The maximum particle size detected by the laser in the influent water into the MBBR was in the range 256 to 300 µm. The dominating particle sizes of the influent water of the MBBR were distributed over three size ranges, visualized in the beam-diagram as peaks. Particles of 5 to 16 µm, 25 to 50 µm and 161 to 300 µm where leading the water samples entering the MBBR. The most particle in terms of volume percentage were found in the range from 203 - 256 µm with 11.2 %.

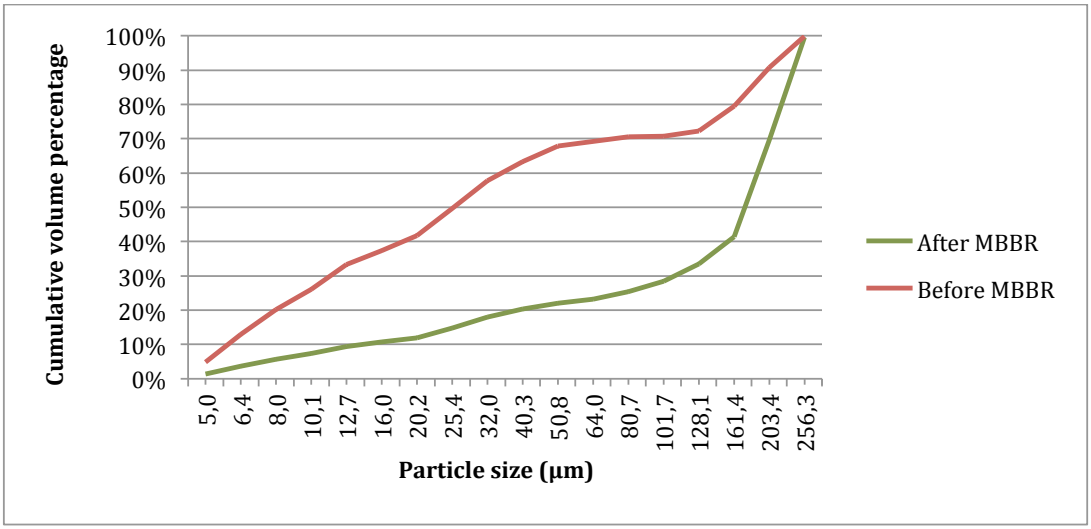

FIGURE 31: DISTRIBUTION OF PSDS (CUMULATIVE VOLUME PERCENTAGE) BEFORE (N=4) AND AFTER (N=4) BIOFILTRATION (MBBR).

By passing the two reactor of the biofilter, the particle size distribution of the particles in the water changed distinctly (compare figure 31). The effluent water out of the MBBR showed comparable lower percentage of small particles (<64 µm) and a clearly higher percentage of particles bigger then 161 µm to the influent water. Only 23 % of the total particle volume was found to be smaller then 64 µm in the effluent, whereby this size group represented around 70 % of the total particle volume in the influent water into the MBBR. Clearly dominating in the effluent, were particles in the sizes from 203 up to the detected maximum of 300 µm (around 60 %). Equally in influent and effluent is, that hardly any particles bigger than 300 µm where detected.

In the water flowing into the MBBR, the volume percentage was relatively evenly distributed over the complete size spectrum with four peaks (compare figure 30). Still, the particle size distribution in the water after the MBBR showed highly dominating particle volume per cent in the two biggest detected size groups (203 – 256 and 256 - 300 µm). These two groups represent nearly 60 % of the total particle volume, while before in the influent water only around 20 % of the particles were detected in these size classes. That indicates, that by passing the MBBR, the PSD changed distinctly a clear dominance of big particles.

The variation of the single particle size analyses, visualized in form of the standard deviation (figure 30), show noticeable differences in the different particle size groups. The highest standard deviations of the influent water into the MBBR were measured in the two particle size groups 203 - 256 µm and 265 - 300 µm with 13.1 % and 10.5 %. In the effluent water, the two highest standard deviations remained in these two size groups, whereby the values decreased to 7.1 % (203 - 256 µm) and 9.4 % (265 - 300 µm). Below 161 µm, the variations were comparable small throughout the particle sizes, both for the influent as well as for the effluent.

4.2.2. IMPACT OF THE DEGASER

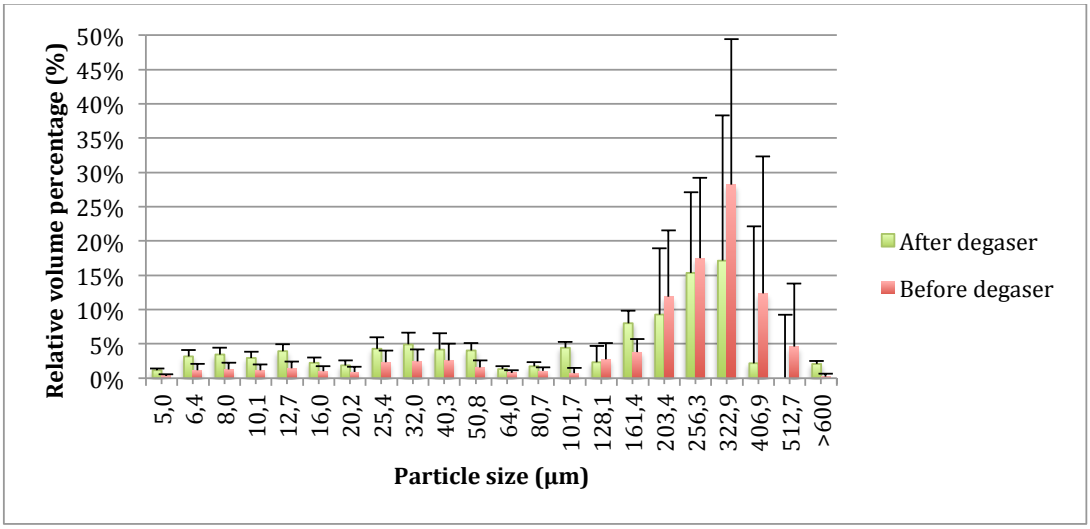

FIGURE 32: DISTRIBUTION OF PSDS (RELATIVE VOLUME PERCENTAGE) BEFORE (N=4) AND AFTER (N=4) CO2 STRIPPER (DEGASER).

The PSD analyses before and after the degasing were made to investigate the effect of this water treatment unit on the PSD of the RAS process water. The PSD-test of the influent and effluent water of the degaser showed only minor differences in the average particle size distribution.

Both water streams, influent and effluent, showed a high fraction of particles in the upper size ranges. Dominating were at the sample spots particles in the size classes 256 - 300 µm and 300 – 322 µm. The highest volume percentages at both sample spots were measured in the size range from 322 - 406 µm. 28.2 % in the influent water and 17,1 % in the effluent. Remarkable is a distinctly higher percentage of particles bigger 322 up to 600 µm in the water flowing into the degaser compared to in the effluent. Whereby around 50 % of the total particle volume was detected in that upper size range (> 128 µm) in the water flowing in, only around 23 % were found in the water leaving the degaser (compare figure 33). Particles bigger 406 µm were hardly found in the effluent water (only 4.2 %), whereby before the water had passed the degaser 16.7 % were present in that size.

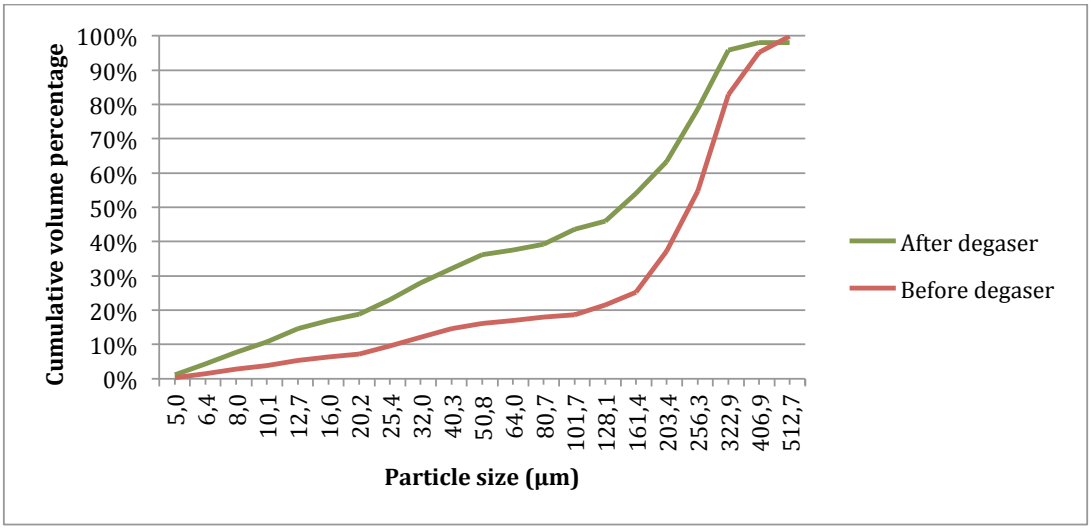

FIGURE 33: DISTRIBUTION OF PSDS (CUMULATIVE VOLUME PERCENTAGE) BEFORE (N=4) AND AFTER (N=4) CO2 STRIPPER (DEGASER).

Consequently the amount of particles bigger than 203 µm decreased substantially throughout the degaser from about 50 % to about 25 %.

The variation of the single particle size analyses, visualized in form of the standard deviation (figure 32), show noticeable differences in particularly in the upper particle size groups. The highest standard deviations of the PSD, measured in the inlet water, were 13.1 % and 10.5 % for the ranges 322 – 406 µm and 406 – 512 µm. In the degaser effluent, the highest standard deviation appeared within the particle sizes from 322 – 406 µm and 406 – 512 with 13.8 % and 20.0 %. It can be clearly seen, that the standard deviation was particularly higher in the upper particle size ranges. In the smaller ranges (<203 µm), the standard deviation never exceeded 3.9 % in the effluent and 2.4 % in the influent water stream.

4.2.3. *Impact of pumping and deepshaft oxygenation*

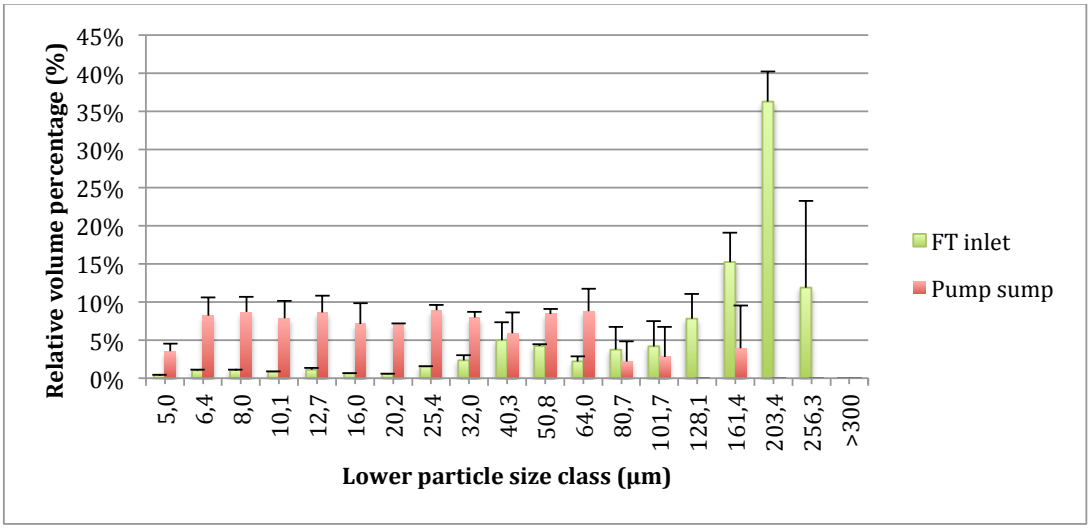

FIGURE 34: DISTRIBUTION OF PSDS (RELATIVE VOLUME PERCENTAGE) FROM SAMPLES TAKEN AT THE PUMP SUMP (N=4) AND AT ONE FISH TANK INLET PIPE (N=4).

This experiment was done to compare the PSD of the water in the pump sump (after leaving the degaser) to the PSD of the water entering the fish tank. The goal herby was to test, if pumping by centrifugal pumps and oxygenation by deepshaft cones has an effect on the PSD of the SS in the water.

Figure 34 and 35 summarizes the results of the PSD analyses at the two sample spots. The comparison between the particle size distribution of the water in the pump sump and the water taken at the fish tank inlet, shows clear differences in the distribution of the particle volume per cent (compare figure 34 and 35). The water sampled in the pump sump, contained a high percentage of small particles (<80 µm). Around 92 % of the total particle volume was smaller than 80 µm. This majority of particles were quite homogenous distributed over the lower size range. Only few particles (8 %) were found to be bigger than 80 µm with the maximum particle size detected in the range from 161 – 203 µm.

The water sampled at the fish tank inlet pipe, contained a clear differing PSD. Whereby in the sample taken in the pump sump, the majority of particles were found in the lower size range, at the fish tank inlet over 75 % of the total particle volume was measured to be larger than 80 µm. Clearly dominating were particles from 203 to 256 µm. 36.3 % of the total particle volume was measured in this group. Only very little particles were found smaller than 25 µm (5.6 %) and the remaining 19.4 % distributed over the range from 25 – 80 µm with a peak in the size group from 40 – 50 µm.

At both sample spots, the laser instrument detected no particles larger 300 µm.

The variation within the PSD size ranges of the single analyses of both sample spots (displayed as the standard deviation in figure 34) show only small variations in the range smaller 203 µm. The standard deviation within the size ranges was measured to be maximum 3.9 % (101-128 µm) at the pump sump. The highest variation of the PSD analyses of the water in the pump sump was found in the biggest detected size range from 161 – 203 µm with 5.9 %. In the water of the fish tank inlet, the highest standard deviation with 11.4 % was also found in the biggest detected size range (256 - 300 µm). At both sample spots, the biggest variations were found in the upper particle size class.

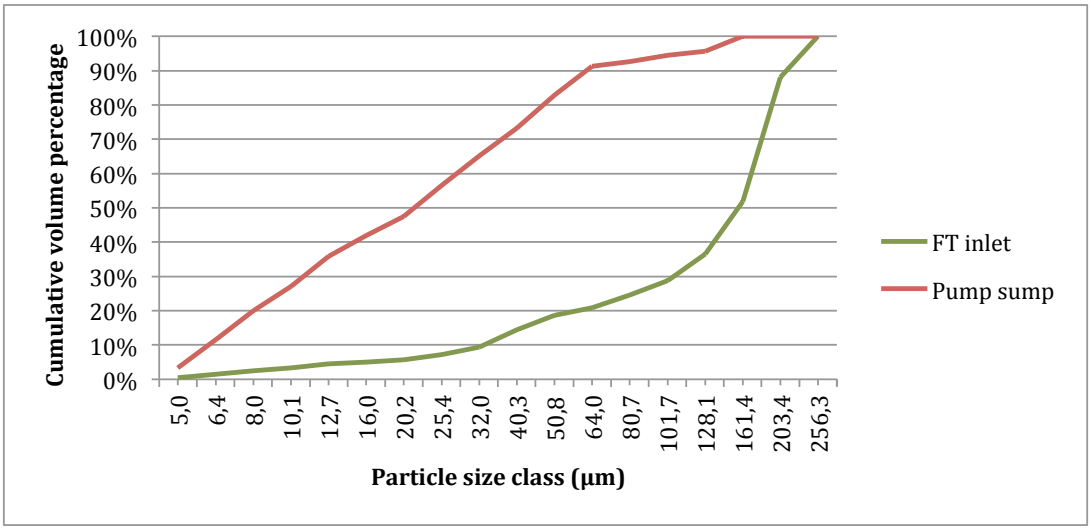

FIGURE 35: DISTRIBUTION OF PSDS (CUMULATIVE VOLUME PERCENTAGE) FROM SAMPLES TAKEN AT THE PUMP SUMP (N=4) AND AT ONE FISH TANK INLET PIPE (N=4).

4.3. FILTER EFFICIENCY TEST

4.3.1. 10 µM DRUM FILTER

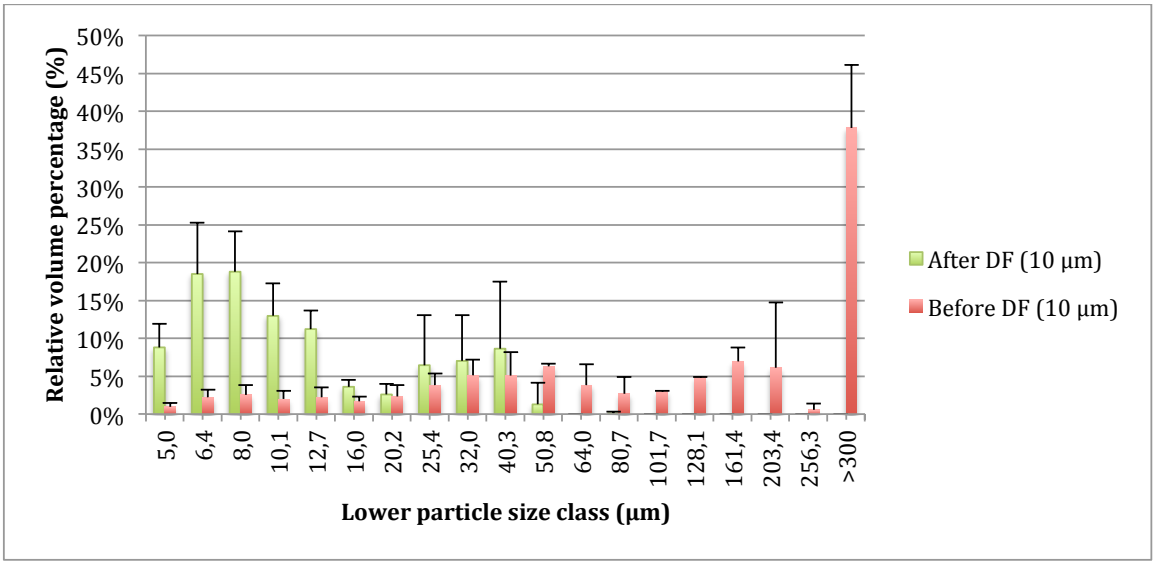

FIGURE 36: DISTRIBUTION OF PSDS (RELATIVE VOLUME PERCENTAGE) BEFORE AND AFTER DRUM FILTRATION. WATER SAMPLES ANALYZED WERE SAMPLES FROM BEFORE (N=2) AND AFTER (N=6) ONE HYDROTECH DRUM FILTER SET UP WITH 10 µM FILTER GAZE.

This experiment was set up to test the filter efficiency of the HDF 2006 model equipped with a 10 µm screen.

The comparison of the particle size distribution of the influent and effluent water of the drum filters shows clear differences in the distribution of the particle volume per cent. The PSD in the water coming from the fish tanks covered the whole size range (compare figure 36), with a high percentage of particles in the upper size range. About 94 % of the particles were bigger than 10 µm and over 51 % bigger than 162 µm (figure 37). Based on that the theoretical removal potential of a 10 µm mesh would be around 94 % of the total particle volume in the water entering the drum filter. When the results are compared to the PSD of the water leaving the filter units, a clear reduction of upper particle ranges in the drum filter effluent water can be seen. No particles bigger 64 µm were detected in the water, which had passed the filter unit. The majority (60 %) of the particle volume was smaller than 10 µm. 70 % was below 13 µm. Above 10 µm, the dominating particle size was in the size class from 40 to 50 µm (8.6 %). Only a very small percentage of the particle volume was found to be bigger than 50 µm. 1.2 % were detected in the size from 50 to 64 µm. Over the complete particle range, particles in the size from 8 to 10 µm were leading in the volume percentage. 18. 8 % were found in this range, closely followed by particles from 6 to 8 µm (18.5 %).

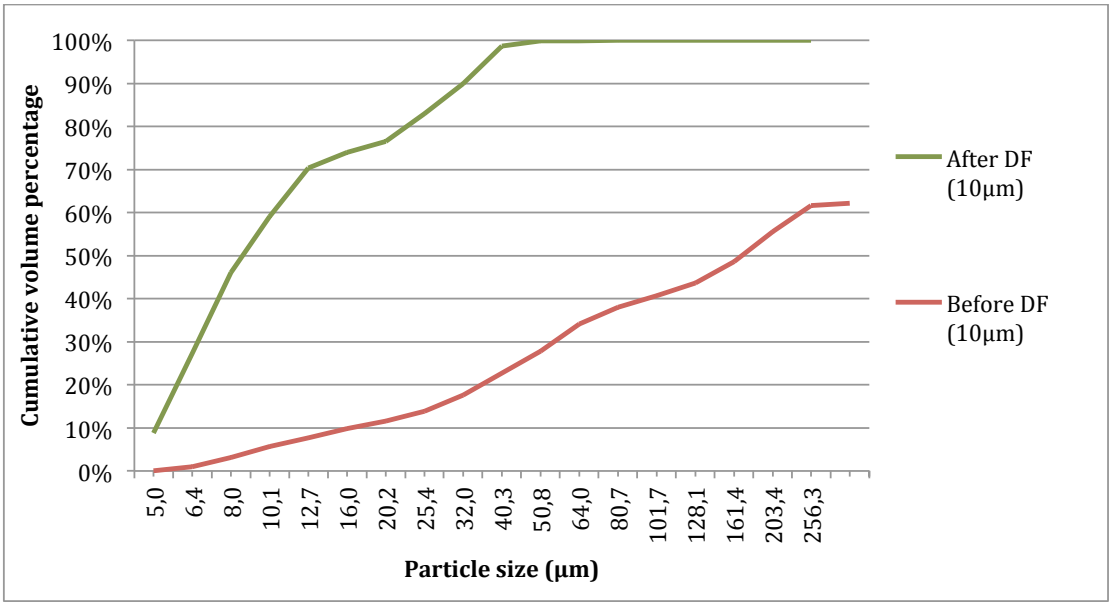

FIGURE 37: DISTRIBUTION OF PSDS (CUMULATIVE VOLUME PERCENTAGE) BEFORE AND AFTER DRUM FILTRATION. WATER SAMPLES ANALYZED WERE SAMPLES FROM BEFORE (N=2) AND AFTER (N=6) ONE HYDROTECH DRUM FILTER SET UP WITH 10 µM FILTER GAZE.

The variation of the single particle size analyses, visualized in form of the standard deviation (figure 36), shows noticeable differences in the various particle size groups. In the water samples taken before the drum filter, a clear trend of the standard deviation can be seen. The overall trend of the standard deviation can be described as followed: With increasing particle size the variation grow accordingly, meaning in the smallest particle size range from 5 to 6 µm the standard deviation was small with 0.5 %. In the middle range from 40 - 50 µm, it was 3.1 % and 16.0 % from 203 to 256 µm. 16.0 % is simultaneously the highest standard deviation in the influent to the drum filter. Evidently, the biggest variations of PSD are found in the biggest particle size ranges.

In the effluent water, the variations within the different PSD measurements were differently distributed compared to the PSD of the influent water. In the detected size range up to 64 µm, two particle volume peaks, spread over several size ranges, were measured, shown in figure 36. The highest standard deviation occurred in the ranges from5 to 12 µm and 25 to 50 µm accordingly of up to 6.8 % and 8.9 %. In between these peaks, the variations were not as considerably, with values from 1 to 3 %.

4.3.2. 30 µM DRUM FILTER

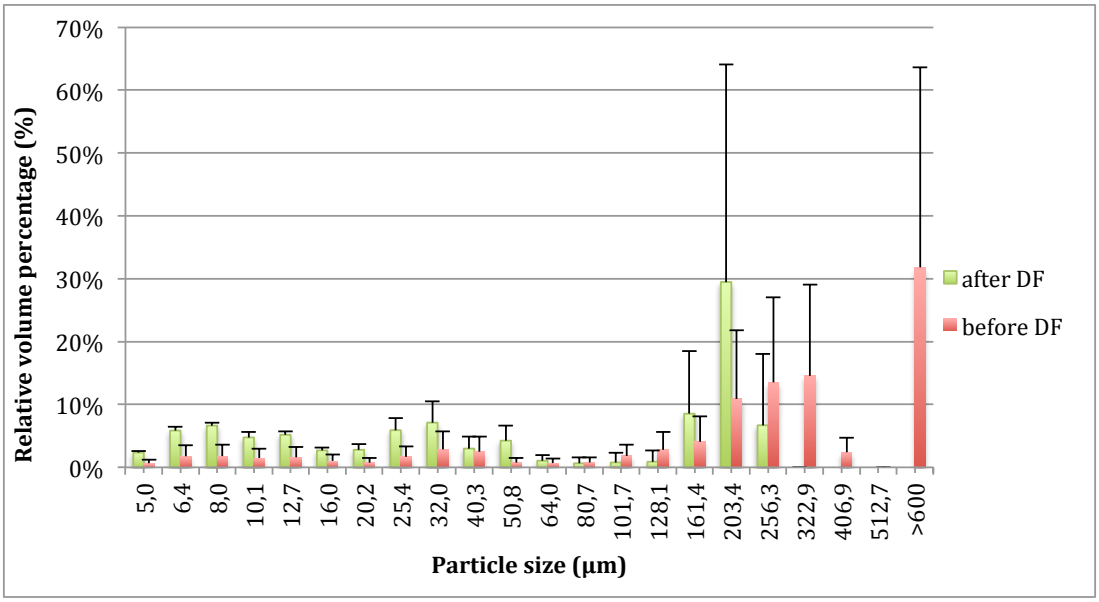

FIGURE 38: DISTRIBUTION OF PSDS (RELATIVE VOLUME PERCENTAGE) BEFORE AND AFTER DRUM FILTRATION. WATER SAMPLES ANALYZED WERE SAMPLES FROM BEFORE (N=2) AND AFTER (N=6) ONE HYDROTECH DRUM FILTER SET UP WITH 30 µM FILTER GAZE.

This experiment was set up to test the filter efficiency of the HDF 2006 model equipped with a 30 µm screen.

Figure 38 and 39 summarize the PSD measured in the influent and effluent water of the filter unit. The comparison of both particle size distributions shows clear differences in the distribution of the particle size groups. The PSD in the water coming from the fish tanks covered the whole size range (compare figure 38), with a high percentage of particles in the upper size range. Clearly dominating were particles bigger than 600 µm. They represent about 32 % of the total particle volume. About 86 % of the particles were bigger than 30 µm and over 73 % bigger than 162 µm (figure 39). Based on that, the theoretical removal potential of a 30 µm mesh would be around 86 % of the total particle volume in the water entering the drum filter.

After filtration, the PSD of the water leaving the unit shows a clear reduction of upper particle ranges. No particles bigger 322 µm were detected in the filtrated water. But even though the water was filtrated, over 45 % of the particles were still found to be bigger than the mesh size. Clearly dominating were particles in the range from 203 to 256 µm (with 29 %).

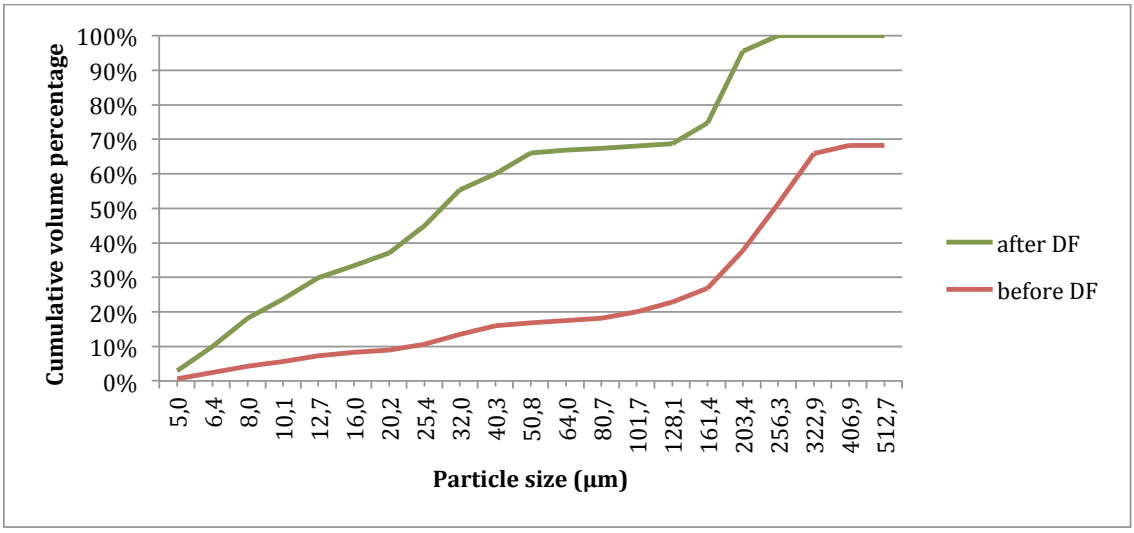

FIGURE 39: DISTRIBUTION OF PSDS (CUMULATIVE VOLUME PERCENTAGE) BEFORE AND AFTER DRUM FILTRATION. WATER SAMPLES ANALYZED WERE SAMPLES FROM BEFORE (N=2) AND AFTER (N=6) ONE HYDROTECH DRUM FILTER SET UP WITH 30 µM FILTER GAZE.

The standard deviation visualizes the variation of the single particle size analyses (figure 38). The standard deviation shows noticeable differences in the different particle size groups of both, influent and effluent water.

In the influent water, the variations within the different PSD measurements were found in the upper size ranges. The highest standard deviation with about 31 % occurred in the size group representing the out of range particles >600 µm. All size groups bigger 161 µm, except 406 – 512 µm, showed high standard deviation with over 10 %. In the lower size ranges smaller 161 µm, the variations were not as considerably, with values up to 3 %.

In the water samples taken after the drum filter (effluent), the standard deviations for the size groups up to 161 are negligible with maximal 2.6 % in the group from 32 to 40 µm. The particle load measured in the size groups bigger 161 µm show comparable strong variations up to 35 % (203 – 256 µm). Evidently, the biggest variations of PSD are found in the three biggest particle size ranges.

4.3. TOTAL SUSPENDED SOLIDS (TSS)

For all PSD laser analyses, TSS samples were taken from the analysed water to evaluate the out-of-range particles together with DM retained on the out-of-range filter gaze (compare method chapter). Table 8 summarizes the mean, maximal and minimal TSS values as well as the standard deviation for all measurements, which were carried out. Within the result chapter, the TSS at the different sample spots will not be further described. The TSS results will be described and discussed in detail in the discussion chapter.

TABLE 8: TSS RESULTS FOR EACH PSD SAMPLE SPOT INCLUDING NUMBER OF ANALYSES (N), MEAN TSS (MG/L), MAXIMAL TSS (MG/L), MINIMUM TSS (MG/L) AND THE STANDARD DEVIATION OF THE SUMMARIZED RESULTS.

EXPERIMENT	Sample Spot	n	Mean TSS (mg/l)	Max. TSS (mg/l)	Min. TSS (mg/l)
4.1.1 detailed PSD test (day1)	Before DF	9	**21,0** ±3,3	26,3	16,0
4.1.2 detailed PSD test (day2)	Before DF	10	**12,1** ±1,6	14,4	9,0
4.2.1 impact of DF on PSD	Before DF	4	**15,0** ±1,5	13,5	16,7
4.2.1 impact of DF on PSD	After DF	4	**9,9** ±0,2	10,2	9,7
4.2.2 impact of MBBR on PSD	Before MBBR	4	**10,0** ±0,7	10,8	9,0
4.2.2 impact of MBBR on PSD	After MBBR	4	**10,1** ±1,4	11,9	8,6
4.2.3 impact of DG on PSD	Before DG	4	**10,2** ±0,4	10,8	10,0
4.2.3 impact of DG on PSD	After DG	4	**10,7** ±0,6	11,7	10,3
4.2.4 comparison PS to FT inlet	PS	4	**5,4** ±0,4	6,0	4,9
4.2.4 comparison PS to FT inlet	FT inlet	3	**5,9** ±0,4	6,5	5,5
4.3.1 filter efficiency 10 µm	Before DF	2	**10,2** ±0,7	10,9	9,5
4.3.1 filter efficiency 10 µm	After DF	6	**4,8** ±1,3	7,5	3,7
4.3.2 filter efficiency 30 µm	Before DF	2	**13,4** ±2,5	15,9	10,9
4.3.2 filter efficiency 30 µm	After DF	4	**4,2** ±0,3	4,5	3,9

5. DISCUSSION

Waste from fish farms can be defined as all materials produced in the system, which are not removed through harvesting. A high percentage of that is present in the water in particulate form as suspended solids. The solids consist mainly out of three sources: uneaten feed, excreta and detached bacterial flocks (Timmons, 2007). In recirculating aquaculture systems (RAS) particle accumulate, if not efficiently removed, and can cause problems. Too many suspended solids result in water turbidity and increased oxygen consumption as a reason of bacterial decomposition. Further particles can plug system components in the RAS and cause higher stress levels at the fish. Particularly fine particles can affect directly fish health by irritating their gills (Chen, 1993). Hence the systematic particle removal is an elementary treatment step as water is recirculated. To attack the suspended solids with the right technology, detailed knowledge about their characteristics within the RAS is required. Besides the amount of particles on a weight base (TSS) and the specific gravity, the particle size distribution (PSD) is an important parameter for correct sizing and placing the particle treatment equipment in the process.

Brinker (2005) summarized, that solid particles from aquaculture have complex characteristics such as wide size ranges, a non-spherical form and a non-homogenous composition. Therefore he developed a laser-based, non-invasive technique to size particles. By comparing this high resolution method, which uses the 'time-of-transition' theory, against other particle sizing methods, the author points out, that this principle allows reliable PSD measurements with a high reproducibility. A comparison of laser data with the results of a subsequent serial sieving gave on average only small differences, indicating that this method is highly suitable for predicting the efficiency of effluent micro screening. Until today, this method has been used several times in the research field of aquaculture to determine PSD in different fish farms (Brinker, 2005, Brinker et al., 2005, Brinker and Rosch, 2004, Sindilariu et al., 2009). Nevertheless, no scientific paper has been published yet, where this PSD-method has been used to investigate the particle size distribution in a commercial, state of the art recirculating aquaculture system (RAS). Particularly for optimizing the RAS design in terms of particle control, PSD data is crucial. As Brinker (2005) points out, important applications for the laser sizer are the identification of particle-destroying units or processes within fish farm facilities and the optimization of filter pore sizes and hydraulic residence times for microscreens and sedimentation.

In order to investigate PSD data for this thesis, intensive measurements have been conducted in a Norwegian recirculation smolt farm. The facility has been designed and build by Krüger Kaldnes, who planed included in the quality control for the customer, to gain knowledge about the amount of particles and their distribution in their patented RAS (Kaldnes® RAS). Since many particle sizing

methods, such as residence pulse counter, laser light-scattering particle sizer and sieving are not suitable for fish farm particles analyses (Brinker, 2005), the only method, which has been tested with satisfaction within its limitation, has been used for these PSD analyses. The laser sizing method using the 'time-of-transition' theory has main advantages compared to other laser techniques. It is independent from the optical properties of the particles, it is non-invasive, fast and allows on-site measurements of PSD within the fish farm (Brinker, 2005).

Summarized, the laser particle sizer Galai CIS-1 performed well throughout the analyses. The PSD measurements took place at different sample spots through the RAS process followed by detailed tests of drum filter efficiencies.

Only in the end of the experiment, the PC connected to the lazer broke down several times at the end of some PSD analyses. This computer problem caused the loss of several data sets.

5.3. THE PSD CHARACTERISTICS THROUGHOUT THE WATER TREATMENT PROCESS

5.3.1. FISH TANK EFFLUENT

The results of the PSD analyses in the RAS system show distinct variation at the different sample spots. By comparing the size distributions in flow direction of the water, starting with the first sample spot after the water leaves the fish tanks (before drum filter), it can be noticed that big particles > 160 µm were dominating the samples on day one with around 77 % (compare 4.1.1). On day two, the average amount of particles >160 decreased to around 47 %. The fine particle fraction smaller 20 µm was present with 7.5 % on day one and 15.2 % on day two.

FIGURE 40: (LEFT) 5 LITER WATER SAMPLE TAKEN AT THE DRUM FILTER INLET. (MIDDLE) SEDIMENTED SOLIDS IN SAMPLE. (RIGHT) OUT-OF-RANGE PARTICLES AFTER LASER ANALYZE COLLECTED ON 600 µM GAZE.

Overall, the PSD results correspond with the outcome of other PSD measurements in the effluent of fish culture units, such as tanks or raceways (J.D. McMillan, 2002, Pfeiffer, 2008, Brinker et al., 2005, Brinker and Rosch, 2004, Sindilariu et al., 2009).

Pfeiffer (2008) measured the PSD by sieve analyses. He found the dominating particle size in a RAS measured in the outlet water from the tanks to be in the range 105-500 µm. The size ranges 105-250 µm, 250-500 and >500 µm carried respectively 26, 28 and 17 % of the total particle weight. Fine particles smaller 23 µm represented less than 1 % of the total particle weight in the water. Brinker (2005) compared influent and effluent water from a 40 µm Hydrotech drum filter at a German trout farm. The outlet water from the fish culture systems contained high amounts of particles bigger than the screen size. Clearly dominant were particles in range >600 µm (about 18 % of the total particle volume). About 70 % was bigger than the filter screen of 40 µm. McMillan (2003) measured the particle size distribution in a RAS to examine the effect of pumping. Herby he analysed the PSD based on differential volume after the fish tanks and found around 75 % of the particles to be bigger than 100 µm. In the smaller range, about 6 % was found to be below 20 µm. In Sindilariu et al. (2009) the author measured the PSD in a partially recirculating trout farm. He reports as well that big particles (>100 µm) dominated the water with over 60 % coming from the fish units. Particles smaller 20 µm were present with about 10 % of the total particle volume.

The extensive analyses of the fish tank effluent entering the water treatment plant from this experiment illustrate similar low amounts of fine particles below 20 µm. Even though fine particles are claimed to accumulate in RAS, since they only excess the plant over the make-up water exchange (Couturier, 2009), no evidence for that was found. Chen (1993) investigated the PSD in a RAS and found more than 95 % of the suspended particles to be smaller in diameter then 20 µm. By volume, these particles accounted for 40-70 % of the total suspended solids. The PSD results of this investigation do not confirm Chen's observation. On average 8 % (day one) to 15 % (day 2) of the total particle volume was found to be smaller 20 µm, indicating a much lower presents of fine particles, based on volume, in the tested RAS unit. Since no particle numbers were investigated, it can only be assumed that on a number base the fine particles most likely dominated the water samples as well. Just by comparing for example a particle of 5 µm in diameter to one of 150 µm, it becomes clear, that the 150 µm particle may have a volume, which is greater than several thousands of 5- µm-diameter particles. Cripps (1995) confirms, that in the outlet water of fish tanks from a RAS, particle numbers are greatest at the lower end of the size range whereby total particle volume is usually greatest at the upper size range. Such high percentage of fine particle in the water, as presented in Chen (1993), seem to be rather uncommon in the tank effluent.

In this experiment the detected bigger particles are presumably of organic nature in form of fish faeces and feed remains released in the fish tanks. After sampling, sedimentation of particles in the sample bottles occurred, which can be seen in figure 40. Here, fish faeces are clearly visible.

In between the analyses, the amount of particles in the upper size range varied clearly noticeable. Unstable particle loads released in the fish tank can explain this phenomenon. Varies factors, such as feeding regime, particle accumulation being released caused by hydraulics or fish stress, can effect the amount of particles in the outlet water. Further, the sampling method has an influence on the particles sampled from the water. In figure 40, it can be seen that water samples taken before the drum filter contained a few clearly visible big particles. Since the PSD analyses are volume based, a few big particles influence strongly the PSD result. Meaning, if the PSD measurements were based on number, they would have a comparatively negligible impact on the total PSD. Based on that, catching a few big particles more or less in the water sample, influences strongly the volumetric PSD. These strong particle load variations are also illustrated by the TSS values of the analyses water samples. On the first day the TSS values ranged from 16.0mg/l to 26.3mg/l with an average TSS of 21.0 (+/- 3.3) mg/l. On the second day, the average TSS value decreased by around 40 % to 12.1 (+/- 1.6) mg/l. The peak value was 14.4 mg/l and the lowest 9.0mg/l. By comparing the TSS results with the daily feeding of the smolts on the specific days, no direct correlation between the amounts feed fed and the average TSS released can be seen (compare figure 15). Hence, it is questionable, what caused the big differences in TSS amounts found in the water coming from the fish tanks on day one compared to day two. An explanation might be a cleaning operation of the fish tank outlet grids by the farm staff during the first day. Because of problems with clogging of some grids, the staff changed them in each tank to a different typ. This operation has probably caused a higher release of particles (accumulated on the grid) into the water. Followed by that, it can be assumed, that during normal farm operation, the average TSS of the outlet water from the fish tanks is more in the range of 12 mg/l (day 2) than 21 mg/l (day 1). This cleaning, and by that the intensive release of big particles, might have caused the differences in the detected PSD between day one and two. The out-of-range particles were much more present on day one then they were on day two.

5.3.2. MICROSCREEN DRUM FILTER

The next sample spot, following the water flow, was the effluent side of the drum filter. The comparison of the analyses before and after the filter units, illustrates the removal efficiency of the installed filter screens and the change in PSD through the unit. The results of the PSD measured in the mixed effluent water flow from all three filter units shows that only around 3 % of the particle volume was measured to be bigger than the installed 60 µm mesh and around 17 % was bigger than

the 30 µm filter mesh. On a weight base a reduction in TSS of 5.1 mg/l, from 15.0 down to 9.9mg/l was measured. This is equal a particle removal of 34 %.

Before filtration the water contained 75 % particles, which were bigger than the filter mesh of 60 µm, meaning, the theoretical removal potential of the two 60 µm filter would be according to that over 70 %. By taking in consideration that a side stream of 15 % of the total water flow is send through a finer filtration down to 30 µm, the removal potential is even higher (77 %). In fact, the filter removed efficiently (according to the PSD analyses) around 97 % of all particles bigger than the mesh size. Yet on a mass base (TSS), a much lower removal of only 34 % is found. Since the differences in particle density of aquaculture origin are relatively small (heavier particles around 1.152 kg/m3 and lighter particles around 1.050 kg/m3 (Patterson and Watts, 2003), the disequilibrium between theoretical removal potential based on the volumetric PSD and the actual particle removal based on weight, cannot be explained by high specific weight differences of small and big particles. More likely, particles bigger than the filter mesh size were broken down to smaller particles in the filter units. This would explain the high removal efficiency in size of 97 %, but the comparable low removal in particle weight of only a third of that. This hypothesis is further discussed in the section 4.2.1.

5.3.3. MBBR

After the water has passed the drum filter, it overflows into the biofilter (MBBR). The results of the investigation of the PSD in the water before and after the MBBR show that the PSD changed distinctly by passing the biofilter. Particles in the range from 203 to 300 µm strongly dominated the water sample after the MBBR with about 60 %. Before they were only present with about 20 %. Presumably these particles were biofilm flakes released from the biomedia in the MBBR. The so-called Kaldnes™Moving-Bed-Bio-Reactor Process generated biomass, which is constantly released into the water as particles. The main objective of the MBBR use in aquaculture is the nitrification of highly toxic nitrite to less toxic nitrate. Secondly, mainly for wastewater treatment applications, the MBBR process is used to trap particles, to remove organic matter from the process. In order to secure an efficient nitrification (aquaculture purpose), a low organic load into the MBBR has to be maintained, so that the heterotrophic bacteria that removes organic matter, does not out-compete the nitrifying bacteria (Rusten et al., 2006, Minett, 1995). Since effective nitrification for MBBR installation in aquaculture facilities has always been the priority, the solid removal has not been investigated in detail. It is known, that MBBR absorbs organic loads in fish farm installation. (Rusten et al., 2006) Yet, the measured TSS level, which represent the undissolved fraction of solids going in and out of the MBBR showed equivalent constant values of 10.0 (+/- 0.7) and 10.1 (+/- 1.4) mg/l. These results illustrate, that on a mass balance, the solids load remained equal throughout the MBBR

process. Nevertheless, the PSD changed to a higher content of particles bigger than 100 µm. This hypothesizes, that a replacement of smaller to bigger particles occurs in the MBBR. Most likely, smaller particles (<50 µm) hydrolyse and get trapped in the biofilm and in exchange, biofilm in form of bigger particles is released into the water. Bouwer (1987) described already the effectiveness of biofilter for removing submicron particles. In Yang et al. (2001) the author explains the suspended solids removal by biofilm through hydrolysis. He summarizes, that the bacteria *consortia* utilize the captured organic suspended matter as an alternative substrate indirectly through hydrolyses first by extracellular hydrolysis enzymes secreted by the bacteria. By assuming a reduction of fine particles by hydrolyses and trapping in the MBBR plus the release of bacteria flakes/ biofilm, the change in the PSD can be explained.

Additionally, similar PSD results have been found before by Nofima within the framework of PSD measurements to test the effectiveness of ultrafiltration (Kolarevic, 2009). The authors report a decrease of fine particles, smaller 60 µm, combined with an increase of particles bigger 100 µm throughout the MBBR process. This corresponds well with the results from this experiment.

The separation of bigger particles in the MBBR process can be explained as followed: The bacteria film, which grows on the surface of the media, is maintained as a thin layer for good surface diffusion of nutrients by the constant movement of the media. The turbulences create shaering forces, which scrapes of biofilm layer from the media (Rusten et al., 2006). Secondly, in addition to biofilm release, agglomeration of finer particles to bigger flocks might have supported the monitored change of the PSD. The assumption of agglomeration of particles has been described previously by Brinker and Rosch (2004). Flocculation of particles can occur naturally by collision or attraction (Cripps and Bergheim, 2000).

The visual observation of the 300 µm filter gaze, which was used to capture out-of–range particles during laser analyses, is strengthening the assumption that biofilm particles were in the effluent water of the MBBR. The mucus like substance of light brown colour had not been observed in the influent water to the MBBR (figure 41). The biofilm colour of low load filter has been described by Tal et al. (2003) previously as brown to yellow coloured,

FIGURE 41: 300 µM FILTER GAZE FOR CAPTURING OUT.OF-RANGE PARTICLES. THE PRESENTED FILTRATE IS THE RESULTS OF A PSD ANALYZE OF THE EFFLUENT WATER FROM THE MBBR.

which matches the filtrate found after the water after the MBBR.

Basically, it is known from previous research that biofilm particles are generated in the MBBR and constantly added as particles to the water (Timmons, 2007, Pfeiffer, 2008). A new aspect is the combination of PSD and TSS results, which showed a shift from small to bigger particles in the MBBR while remaining a constant TSS level.

FIGURE 42: TOP VIEW INTO MBBR WITH MOVING BIO-MEDIA (KALDNES®BIOCHIP-P)

5.3.4. DEGASER

The PSD analyses of the water samples taken before and after the degaser illustrate no strong changes in the size distribution. The PSD of both sample spot is similar distributed in the lower size range (<80 µm), whereby the remarkable difference is the decrease of particles in the upper particle classes from before to after degaser.

FIGURE 43: (LEFT) SKETCH OF DEAGSER WITH ARROWS SHOWING AIRFLOW DIRECTION THROUGH THE UNIT - COUNTER CURRENT PRINCIPAL. (RIGHT) PICTURE OF MBBR OVERFLOW ONTO DEAGSER DISTRIBUTION PLATE.

Particles bigger 161 µm were present in higher amounts (volume percentage) in the influent compared to the effluent. The water entering the degaser contained particles from which 75 % were bigger than 161 µm. The water leaving the unit contained in contrast only 46 % in that upper size range. An explanation for this can be found in the functional principle and design of the degaser. In this unit the water enters on top to trickle through a distribution plate onto a crossflow media. From there it falls further through the media and drops afterwards ca. 50 cm onto the water surface on the bottom level of the unit. As described in literature (Brinker and Rosch, 2004) waterfalls are claimed to have a significant effect on the PSD by destroying particles. The drop onto the surface exposes the particles to shear forces, which breaks apart fragile particles into smaller ones. Since the water drops three times within the unit construction wise, an effect on the PSD cannot be excluded. The introduced destructive turbulences probably broke down the high percentage of the particles bigger 203 µm and particularly in the range from 322 to 512 µm. The nature of the broken down particles needs to be taken in consideration as well. Before entering the degaser, the water had passed the MBBR in which particles in the upper size range were released. These particles are most likely pieces of biofilm generated within the MBBR (compare above). It can be assumed that these biofilm flakes are not solid in structure and brake down to smaller pieces by the impact of the waterfalls.

The comparison of the TSS levels measured from the in- and effluent water of the degaser shows constantly similar particle loads around 10 mg/l (compare table 8). The outcome of this is that the degaser is not changing the particle load on a mass base but crushes particle to smaller size.

5.3.5. PUMPING AND OXYGENATION

After CO^2 stripping in the degaser, the water is collected in the pump sump from where it is distributed by propeller pumps via deepshaft oxygenation cones back to the fish tanks. For comparison a series of PSD analyses were performed with water sampled in the pump sump and from a fish tank inlet pipe. The goal herby was to test, if the PSD changes from the pump sump to the fish tank inlets, by e.g. impact of pumping or oxygenation. Even though, it would have been more accurate to divide these units into several PSD check points by collecting samples before and after the pumps as well as the deepshaft cones, but unfortunately the only accessible sample points were the pump sump and the fish tank inlet pipe.

The PSD results from the water in the pump sump differed extremely to the PSD sampled at the fish tank inlet. The water taken from the fish tank inlet, contained high amounts of big particles. Over 75 % of the total particle volume was found to be larger than 80 µm. In contrast in the water taken from the pump sump only about 17 % were found above this size. Since for the previous examination (impact of the degaser on PSD), water samples were also taken and analysed from the pump sump, a

comparison of both sets of PSD data can be done. Whereby for the degaser test, samples were taken at the sides of the pump sump next to the outlet from the degaser (sample spot 1 on figure 44), for the pumping effect test the water was sampled in the center of the pump sump (sample spot 2). Figure 44 visualizes the different sample spots in the pump sump.

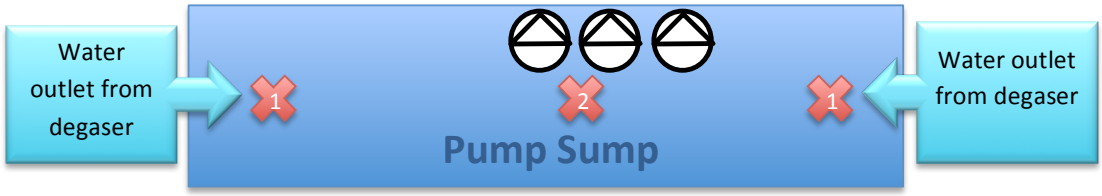

FIGURE 44: SCHEMATICALLY ILLUSTRATION OF THE DIFFERENT SAMPLE SPOTS WITHIN THE PUMP SUMP. SAMPLE SPOT 1 ARE THE TWO DEGASER OUTLETS. SAMPLE SPOT 2 IS THE CENTER OF THE PUMP SUMP.

As graphically illustrated in diagram 45 a distinct difference between the two sample spots can be seen. Even though, the measurements presented as cumulative volume percentage curves were not taken simultaneously, it gives an indication that the two sample spots result in highly differing PSD results. An assumption for a reason is that the water flow patterns at the two spots have a strong impact on the captured particles in the water samples. The water enters the pump sump with turbulent flow out of the degaser at both short sides. The pump sump has been designed for a retention time of around 50 seconds, giving a water speed of around 10 cm/s. Based on that, a laminar flow pattern towards the pumps can be assumed. A laminar flow causes settling of particles within the water phase. The settling velocity is controlled by the viscosity of the fluid and the diameter of the particle (if the particle is assumed spherical) as cited in Cripps and Bergheim (2000).

The low velocity in the pump sump presumably caused particle settlement within the water flow, since the water speed is below 0,3m/s, which is the required minimum flow to avoid particle settlement (Lekang, 2007a). While the sample taken right at the outflow of the degaser contained a well-mixed particle load, the PSD of the water in the pump sump centre differed strongly. Figure 45 displays that over 90 % of the total particle volume in the pump sump centre was found to be smaller 64 µm whereby at the sides, only 37 % were below 64 µm. Since the water samples were always taken in the first meter below the water surface, the assumption can be made that within the time the water flow takes from the sides to the centre, a particle separation process occurred. Bigger particles settled in the water column and were therefore not captured in the samples taken in the upper part of the flow in the pump sump centre. Since the pump sump has similar hydraulics as a raceway, following research supports the hypothesis. Brinker and Rosch (2004) studied the effect of distance from raceway bottom and of sampling site in the course of the fish farm on the PSD. They found out, that the particle size decreases with increasing distance from the raceway bottom. The effect can be explained by the different settling characteristics of differently sized aggregates. Large,

fast sinking particles are mainly flowing in the near bottom region whereas smaller ones tend to become homogenously distributed in the water column (Wong and Piedrahita, 2003). In addition, the hypothesis is strengthened by the PSD of the SS in the water sampled from the fish tank inlet pipe. As figure 45 shows, the PSD measurements after pumping contained again nearly the full particle spectrum, as measured before at the inlet of the pump sump. From the centre the propeller pumps lift up the water to a main distribution manifold, which divides the flow into the deepshaft cones. The propeller pumps suck the water from the bottom of the pump sump and by that probably capture again the complete particle spectrum (compare figure 45).

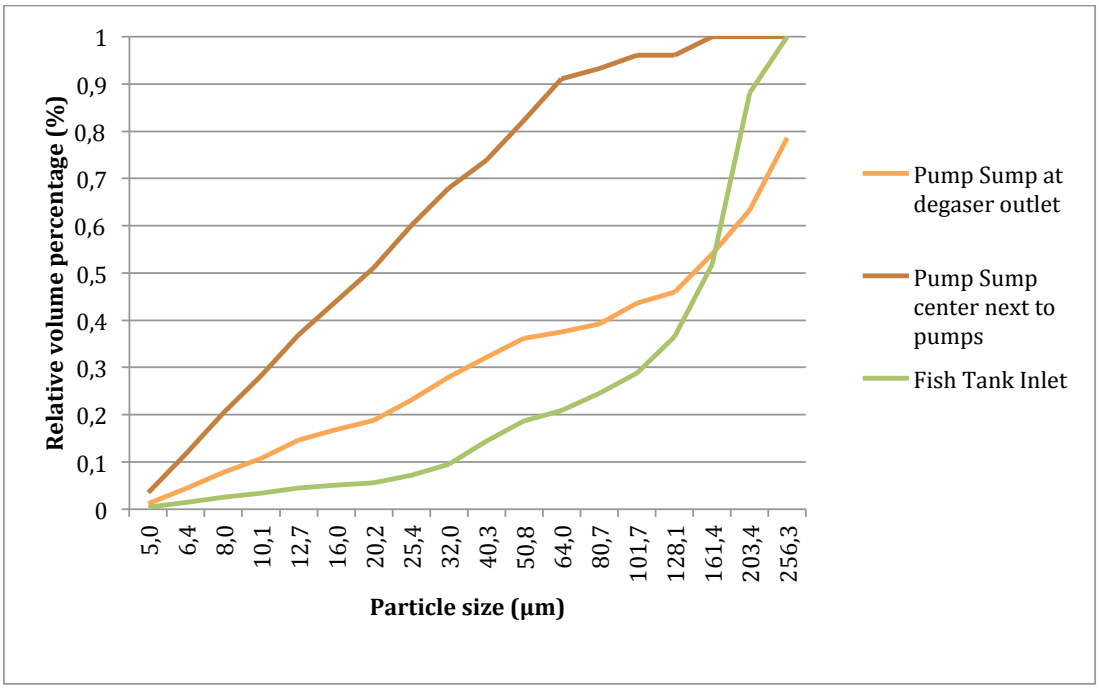

FIGURE 45: DISTRIBUTION OF PSDS (CUMULATIVE VOLUME PERCENTAGE) MEASURED AT PUMP SUMP (DEGASER INLET/ SAMPLE SPOT 1 (N=4)) AND PUMP SUMP (CENTER/ SAMPLE SPOT 2 (N=4) COMPARED TO PSD AT THE FISH TANK INLET (N=3).

Due to previously named reason, the planned comparison of the PSD in the water sampled in the pump sump centre (sample spot 2) to the PSD in the water at the fish tank inlet seems to be not sufficient. The results indicate that the comparison of the PSD measured at the pump sump inlet (sample spot 1) to the fish tank inlet is more meaningful. This comparison has been graphically displayed in figure 45 and 46.

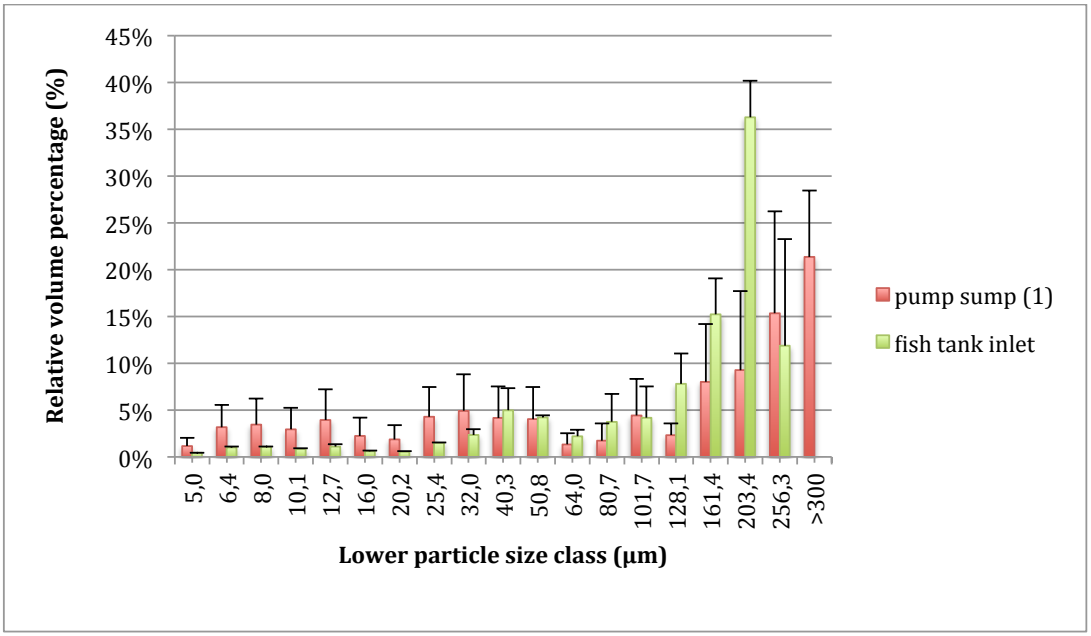

FIGURE 46: DISTRIBUTION OF PSDS (RELATIVE VOLUME PERCENTAGE) MEASURED AT PUMP SUMP (DEGASER OUTLET/ SAMPLE SPOT 1) COMPARED TO PSD AT THE FISH TANK INLET.

Still, this comparison has to be taken under conditional acceptance, since the two sample spots have been tested at two different days. For all other PSD comparisons the time the water takes to pass the unit was taken in consideration for sampling the effluent after the influent sample. This was done as an approach to sample out of the "same" water flow into the unit as well as out of the unit.

The comparison of the results in figure 45 and 46 show similar characteristics of the PSDs at the two sample spots with a dominance of particles bigger 60 µm, although in the range from 203 to 256 µm clear differences can be seen. Whereby the water in the pump sump (degaser outlet/ sample spot 2) carried 19.6 % of the total particle volume in that range, 71.0 % was found here in the water sampled at the fish tank inlet. Expressed as cumulative volume per cent, 44 % of the particles in the pump sump were smaller than 102 µm and only 29 % at the fish tank inlet. Summarized, the water in the pump sump carried a higher amount (in volume) of smaller particles then the water entering the fish tank but therefore a lower amount of particles bigger 100 µm. Even though, the water from the fish tank inlet carried more particles in the upper size range, the maximal size was limited to 300 µm, while the water in the pump sump contained about 21 % of the particles in the range bigger 300 µm.

Previous research has shown that pumps break particles (McMillan, 2003, Brinker et al., 2005). McMillan (2003) found pumping to have a significant negative effect on particle size ($P<0.05$) based on differential volume. The actual PSD results of this experiment indicate a reduction of the upper size range. Figure 46 shows an increase in particle size from before to after pumping in the range 203

– 300 with a 100 % reduction of particles bigger 300 µm. The increase of particles from 203 – 300 µm might have been caused by the break-down of particle bigger than 300 µm.

For the comparison of the results to the previous studies it is important, to take the installed pump type into consideration. As mentioned before, in the examined RAS system the impact of three vertical propeller pumps was tested, whereby in McMillan (2003) and Brinker et al. (2005) the effect of impeller pumps were investigated. The construction differences of the pumps seem to be crucial for the impact on the PSD. Impeller pumps seem to expose particles to higher shear forces, which causes the particle break down. In the contrary, Sindilariu et al. (2009) tested the effect of propeller pumps on the PSD. The author found no particle destroying impact of propeller pumps on the PSD in the water, which had already passed the particle treatment. The impact changed on the other hand, when the drum filter was bypassed. Without the particle removal, the propeller pump had a significant effect on the PSD, leading to a higher fraction of small particles. The author explains the results with the higher shear stress on bigger particles compared to smaller, due to the decreased surface and minimized mechanical inertia. The results of this study support Sindilariu's observations. No particle brake-down on particles below 256 was detected, while a 100 %reduction of particle bigger 300 µm (out-or-range) was found.

Nevertheless, the reliability of this comparison is questionable, since the compared PSDs were measured independently from each other at different times. Because of that, an influence caused by a change in the PSD in the process water over the time cannot be excluded.

On a mass base, the particle load has been measured as TSS at both sample spots (the pump sump centre and the fish tank inlet). The TSS level measured at the pump sump centre (sample spot 2) was on average 5.4 mg/l and at the fish tank inlet 5.9 mg/l. The measured TSS level show a slightly higher suspended solid load entering the fish tank. This fact could support the theory that the sample spot in the pump sump was not adequate to sample a representative sample. Nevertheless, the differences in weight are not distinct enough to support the PSD results. According to the PSD results 50 % of the particles, which were detected in the water entering the fish tank (50 % > 203 µm), were not detected in the water taken upstream in the pump sump. The water samples taken from the pump sump centre contained no particle bigger 203 µm. Due to the fact that downstream from the pump sump (FT inlet), particles bigger 203 were found in high number in the samples, they must have bypassed the sample spot. Possible is also an interaction of several PSD influencing factors which might have caused the strong particle size increase from pump sump to fish tank inlet. Flocculation might have caused the creation of bigger particle flocks. The similar TSS levels at both sample spots support this phenomenon. Further, biofouling in pipes and the release of bioflocs out of that might be a reason as well. Anyhow, based on the presented analyses, it cannot be clearly

identified, how these results came about. To identify the PSD changes caused by impacts of the RAS units from pump sump to the fish tanks, as for example pumps, deepshaft oxygenation cones and piping, more detailed analyses need to be done. A larger timeframe would be necessary for this experiment.

5.4. FILTER EFFICIENCY

For this study different filter mesh sizes for Hydrotech Filter have been tested for their efficiency in particle removal. In- and effluent water from 10, 30 and 60 µm screens have been tested for PSD as well as TSS, whereby the 60 µm filter screen was only tested in combination with a 15 % side stream through a 30 µm screen (original farm set up).

The PSD results from the measurements of the fish tank effluents (compare result chapter 4.1) give an overview of the contained PSD of SS. The results illustrate the PSD in the effluent as an average over one day. They show further, how the SS are composed in size which enter further downstream the filter units. With the help of the cumulative volume per cent of the measured PSD, the theoretical removal potential of a certain filter screen size can be calculated. Based on the construction principle of microscreens, all particles bigger than the filter mesh should be blocked on the screen and then removed from the water (Cripps and Bergheim, 2000, Brinker and Rosch, 2004, Chen, 1994). Table 9 gives an overview of the theoretical removal potential of four different screen sizes on the average PSD measured in the inflow to the filter units. As a base for the calculation the average PSD measured on day two has been used (compare chapter 4.1) because the values on day one might have been higher in TSS as usual due to the outlet cleaning operation of the farm staff mentioned earlier. As illustrated, a 10 µm filter screen could remove in theory over 90 % of the particles in the water coming from the fish tank, whereby a 60 µm screen still removes theoretically over 60 % (compare as well figure 27).

TABLE 9: THEORETICAL FILTER REMOVAL POTENTIAL FOR 4 DIFFERENT FILTER MESH SIZES BASED ON PSD MEASURED IN THE INFLUENT WATER TO THE FILTER UNITS (FIGURE 27).

DF mesh size	Theoretical filter removal potential
10 µm	92 %
30 µm	74 %
40 µm	69 %

60 µm	62 %

5.4.1. 10 µM MICROSCREEN

The smallest tested mesh had a size of 10 µm. Since no filter in the farm was running on this fine filter mesh, the filter panels of one DF were changed to new 10 µm panels (compare figure 40). As presented in the result chapter, the filter screens removed a high percentage of the particles bigger than the mesh size (based on the PSD results). While the water entering the filter carried around 94 % of the total particle volume in the range above 10 µm, the filtrated water contained still 41 % of the particles over 10 µm (figure 36 and 37). This shows clearly that the 10 µm screen did not remove all particles above the mesh size, as would have been expected by the working principle of the filtration method. The actual removal of particles bigger 10 µm was 56 % according to the cumulative volume per cent (table 36). In comparison to that, the filter removed on a weight base 54 % of the TSS in the water. Hence, the removal efficiency based on the PSD measurement matches well with the weight based TSS results. The filtrated water carried particles up to the size range of 50 to 64 µm with dominating particles above 10 µm in the range from 40 – 50 µm. Hence particles six times the size of the mesh size have passed the filter unit. Since this phenomena occurred with all the tested filter mesh sizes, it will be discussed at the end of the chapter.

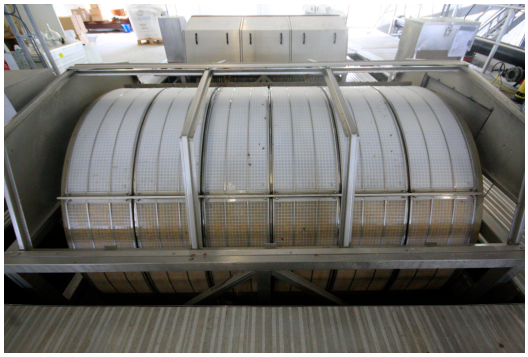

FIGURE 47: HDF 2006 WITH CHANGED FILTER PANEL – FROM 30 TO 10 µM

TABLE 10: COMPARISON OF THE THEORETICAL FILTER REMOVAL POTENTIAL (=ALL PARTICLES > FILTER PANEL MESH SIZE BASED ON PSD IN INFLUENT WATER) TO THE ACTUAL REMOVAL OF PARTICLES BIGGER THEN THE MESH SIZE (=REDUCTION OF PARTICLES > MESH SIZE FROM INFLUENT TO EFFLUENT WATER) OF A 10 µM FILTER

DF mesh size	Theoretical filter removal potential	Actual removal of particles >10 µm based PSD	Actual SS removal based on TSS
10 µm	94 %	56 %	54 %

5.4.2. 30 µM MICROSCREEN

The second filter screen size tested were the 30 µm filter panels moulded to a Hydrotech HDF 2006 filter. This test resulted in strong varying PSD results, which can be seen in figure 38. Some water samples taken of the effluent of the drum filter contained high amounts of particles bigger than 30 µm. As summarized in table 11, the theoretical filter removal potential based on the incoming PSD of the 30 µm was 87 % of the total particle volume. As observed previously with other mesh sizes, the results of the effluent water show lower efficiencies. After filtration the water carried still about 45 % of the particles in the range above 30 µm. This gives a reduction by 48 % of the particles bigger than the mesh screen.

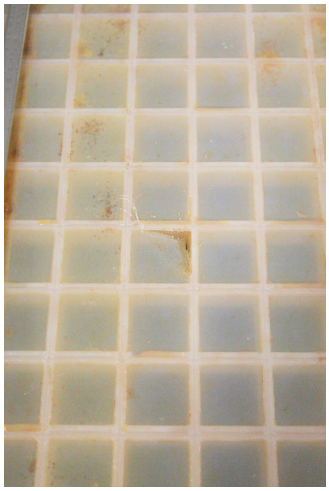

FIGURE 48: DAMAGED 30 µM FILTER PANEL

The filter efficiency calculated on the TSS removal in the drum filter illustrates a higher removal than the efficiency based on PSD. The TSS measurements from influent und effluent water result in a removal of about 69 %. This result differs to the around 20 % lower PSD-based filter efficiency. For this mismatch, no verifiable explanation could be found. Only a measurement error can be assumed. Especially the TSS analyses are susceptible to errors due to the low weight differences of the filter from before to after filtration.

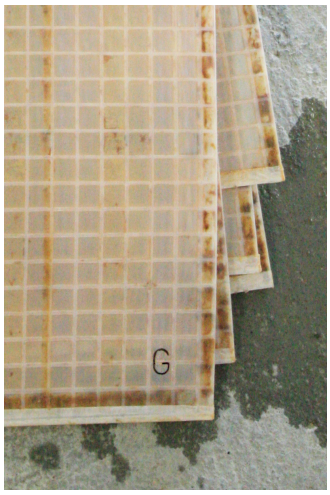

FIGURE 49: HYDROTECH LETTER CODE FOR FILTER PANEL MESH SIZE. G STANDS FOR 30 µM

For the strong variations in the upper size classes illustrated by the high standard deviation (figure 38), several explanations have been found. (1.) One filter panel was broken. The filter mesh had a hole of roughly 2 cm^2 where water could pass through the mesh without filtration (figure 42). This might explain some contamination of the water sample with unfiltrated water. (2.) Hydrotech marks all filter panels with letter-codes according to the screen size. The filter panels of the 30 µm filter on the farm are marked with “G” whereby one panel was also marked with ”J”. According to the information I got from Hydrotech, 30 µm screens have the code “G” and 60 µm screens the code “J”. It seems that the Hydrotech Filter has been equipped with one wrong filter panel when the facility was build. This contributes to the explanation for the unexpected high amount of particles bigger than 30 µm, the strong varying PSD results and the low filter efficiency.

TABLE 11: COMPARISON OF THE THEORETICAL FILTER REMOVAL POTENTIAL (=ALL PARTICLES > FILTER PANEL MESH SIZE BASED ON PSD IN INFLUENT WATER) TO THE ACTUAL REMOVAL OF PARTICLES BIGGER THAN THE MESH SIZE (=REDUCTION OF PARTICLES > MESH SIZE FROM INFLUENT TO EFFLUENT WATER) OF A 30 µM FILTER

DF mesh size	Theoretical filter removal potential	Actual removal of particles >30 µm based PSD	Actual SS removal based on TSS
30 µm	87 %	48 %	69 %

5.4.3. REVIEW – FILTER EFFICIENCY

In all experiments the results of the filter efficiency tests show a clear reduction of particles bigger than the filter mesh size. Yet, no filter performed as efficient as expected. Drum filters are screen filters, which retain particles larger than the screen opening (Chen, 1994). As seen in the results, the effluent of the Hydrotech contained indeed lower amounts of particles bigger than the screen, but no PSD result showed a clear reduction of all particles bigger than the mesh size, as it would have been expected by the work principle. Hydrotech gives a tolerance of their filter screen of +/-10 % (Hydrotech). In case of a 60 µm mesh, this tolerance gives a mesh size range from 54 to 66 µm. Hence, the given tolerance cannot explain the high amounts of particles bigger as the screen. Only the test of standard particle filtration units in the farm (compare 4.2.1), which treat 100% of the water flow (2 x 60 µm and 1 x 30 µm), the PSD based filter efficiency showed clear values. In the filtrated water only around 3 % of the SS were found to be bigger than 60 µm. In the other filter efficiency tests, the results showed lower PSD based efficiencies.

The comparison to other studies in literature show that these results are no exception. The results correspond well with previous literature about drum filter efficiency reported by (Patterson and Watts, 2003, Brinker, 2005, Langer et al., 1996, Sindilariu et al., 2009). Brinker et al. (2005) and Sindilariu et al. (2009) present PSD results measured with the same method as used for this experiment. Both found bigger particles then the filter screen in the samples taken from the effluent of the drum filters. Sindilariu et al. (2009) reported, that all particles smaller as the screen mesh size of 63 µm passed the screen more or less unaffected, whereby the screen blocked the particles in the range between 63 µm and about 200 µm, but larger particles were still found in the screen outflow. On a mass base, the TSS treatment efficiency was only 53 %. The author highlights that the low efficiency is caused by the emission of large particles from the screen. He cannot see any explanation for this result in the data and therefore assumes a constructional defect or installation problem of the screen. Brinker (2005) found in his PSD results of the filtrated water of a 40 µm screen, particles up to 128 µm, wherby the particle fraction bigger as the screen mesh represented only 8.1 % of the total particle volume. He explains this result with the assumption that the detected particles might originate from flocculation of small particles or are non-shperical particles that have passed the filter

gauze. The testing of the treatment efficiency based on PSD measuremtns done by several authors in literature has been summerized previoulsy by Orellana (2006). He concludes that large particles that were expected to be retained by a given mesh size, are passing through the filters. This seems to be a common feature in suspended solids derived from fish culture because of the flexibiltiy in changing shape by external forces. Additionally, the author assumes that faeces and particle fractions derived from system solids are being easily "squeezed" through the filter mesh and by that disintigrate further. The filter tests in this study reinforece the previous results in literature. Still, no reason for the appearance of bigger particle then the screen size can be proven to be correct.

The gaind drum filter efficiency results based on TSS measuremetns are difficult to compare to previous results from literature. The actual removal efficiency is highly depended on the PSD which enters the filtration unit. If a high fraction of the all SS in the water is smaller then the screen size, the filter efficieny will result low. In contrast if the same amount of particles (in weight), but mostly particles bigger then the filter screen enters the filter, the filter eficiency will result much higher. Since the PSD entering the particle filtration unit depends highly on the system design, fish species and feed composition, the comparison of filter efficincies out of different systems has to be taken with care. Hence the combination of PSD measuremtns combined with TSS analyses appear to be a more reliable and comperable method. Johnson and Chen (2006) have evlauated the method similar. The authors claimed PSD analyses to be the more accurated method to compare the effecitvness of solids collection devices. The experiment demonstrates, that only the combination of PSD and TSS analyses gives an idea about the removal efficiency of a filter unit based on particle size and weight.

Yet, most research in terms of filter efficiency has been done on a mass base by using TSS measurements. In Blancheton (2000) the author estimates that only 50 – 60 % of particulate matter (mainly faeces and feed dust) in the rearing tanks is removed from the water in a mechanical filter equipped with 60 to 80 µm microscreen panels.

Overall, the removal efficiency test of the particle control unit of the RAS exhibits unexpected low values. The drum filters installed for particle treatment on 100% of the water flow could not meet the estimates presented by Blancheton (2000). The two 60 µm filters together with the 30 µm filter (15% of total flow) had an average efficiency of around 34 % particle reduction based on TSS (table 12). This is far below the theoretical removal potential of 77 %, which is based on the PSD of the SS in the influent water of the filter units. In contrast to that only 3 % of the particles detected in the filter effluent exceeded the size of the 60 µm screen. This shows a mismatch between measured particle removal based on TSS and on the PSD analyses. Presumably the particle-breaking characteristics of drum filter had a strong impact on the effective particle removal based on TSS. Since the effective removal was less than half of the theoretical removal potential, it shows the strong impact of the

filter on the particles. Langer et al. (1996) reports a change of particle size distribution within the filter unit towards an increase of smaller particles with indication for particle breakdown of larger particles during the mechanical filtration. Brinker et al. (2005) tested the impact of binder-containing feed on the stability of trout feaces for higher removal efficiencies by drum filters in comparison to commercial extruded trout feed. He found significant higher removal efficiency for the effluent from the fish fed with feed enriched with the guard gum binder. In his experiment with regular, the expected removal potential based on the PSD measured in the raceway effluent was about 83 %. The actual removal after particle treatment with the installed 80 µm screen was 27 % (based on TSS). Hence Brinker's result is similar to the result of this study, where the removal potential of 77 % was not met by the effective removal based on TSS of 34 % (compare table 12). In comparison Brinker found the differences from expected removal potential to actual removal efficiency for the binder-containing feed to be smaller. Based on the PSD a particle removal of 88 % was estimated and an actual removal of 70 % was detected in the filtrated water based on TSS. Even though, in Brinker's study a centrifugal pump was used to pump the water to the drum filter and by that an impact of the pup itself on the PSD has to be assumed in addition to the particle breaking impact of the drum filter, it still shows, how fragile particles in aquaculture are. Exposing particles to high forces by pumping or in the filter itself, low treatment efficiencies have to be accepted.

TABLE 12: COMPARISON OF THEORETICAL FILTER REMOVAL POTENTIAL AND THE ACTUAL REMOVAL EFFICIENCY OF THE THREE IN PARALLEL RUNNING FILTER UNITS IN THE FARM BASED ON TSS MEASUREMENTS FROM INFLUENT AND EFFLUENT WATER. * THE TSS RESULTS ORIGIN IS A MIX FROM THE TOTAL WATER FLOW SAMPLED BEFORE AND AFTER THE SET OF DRUM FILTERS INSTALLED IN THE FARM. HENCE AROUND 15 % OF THE SAMPLE WAS TREATED ON 30 µM.

Screen size	Water flow	Theor. removal potential	Theor. TSS removal (15mg/l IN)	Effective TSS removal	TSS removal efficiency	Particles > screen size in effluent
µm	%	%	mg/L	mg/l	%	%
60	85	76	12.6	-	-	3
30	15	84	11.4	-	-	20
Total	**100**	**77**	**11.6**	**5.1***	**34***	-

An actual removal of 34 % of the TSS during the experiment is a fairly low result. Hydrotech presents different estimates for the efficiencies of micro screens according to mesh sizes, which are summarized below: In a case study for RAS, Hydrotech presents a removal efficiency on the suspended solids of 75 % for a 30 µm mesh, 36 % for a 60 µm mesh and 16 % for a 100 µm mesh (Hydrotech). The 36 % SS removal for a 60 µm mesh corresponds well with the detected 34 % of the

set of the drum filter installed in the farm. Yet, it needs to be taken in consideration that the 36 % removal presented by Hydrotech was measured on the particulate matter directly originated from feeding in an eel farm. Since in eel farms, feed paste has been used commonly, a comparison to the results to a smolt farm is difficult. Feed paste creates high amounts of fine particles, which is not the case with pellet feed, as used in smolt farms.

A general guideline given by Hydrotech for average removal efficiencies of SS from circular fish tanks with a 60 µm mesh is 80 – 90 % (Hydrotech). In an updated table Hydrotech distinguish between removal efficiency for race-way system and self-cleaning tanks. Here the company estimates the removal of SS to be 45-75 % and 55-85 % accordingly for a 60 µm mesh (compare table 13). The measured efficiency in the experiment does not fulfil the expectation of the estimates given by Hydrotech.

TABLE 13: REMOVAL EFFICIENCIES OF DIFFERENT FILTER SCREEN SIZES. (HYDROTECH)

Parameter	Race-way	Race-way	Race-way	Self cleaning tank	Self cleaning tank	Self cleaning tank
	40 µm	60 µm	90 µm	40 µm	60 µm	90 µm
	Efficiency (%)	Efficiency (%)	Efficiency (%)	Efficiency (%)	Efficiency (%)	Efficiency (%)
Tot-P	50-75 *	40-70 *	35-65 *	65-84 *	50-80 *	45-75 *
Tot-N	20-25 *	15-25 *	10-20 *	25-32 *	20-27 *	15-22 *
BOD_5	45-75 *	40-65 *	30-60 *	55-80 *	50-75 *	35-70 *
Suspended solids	50-80 *	45-75 *	35-70 *	60-91 *	55-85 *	50-80 *

** Efficiency values can only be indicated as intervals, as efficiency depend on inlet concentration to the filter, eg below 2.5 mg/l SS, efficiency is quite low, but at an inlet value of 50 mg/l SS, efficiency can be 91 %. At the same time optimal conditions(see above mentioned key issues)must be considered in order to achieve the best filtration result.*

The filter operation is presumably contributing to the low TSS removal. During the analyses the filter were turning and back flushing continuously. They have been operated in "HAND mode". Yet, to achieve optimal removal efficiencies in drum filter, a strict start and stop rhythm controlled by the water level in the drum needs to be followed ("AUTO mode"). Further the drum should not turn continuously since the constant movement is grinding down bigger particles to smaller ones. A filter cake on the screen, which supports higher particle removal, can only be established if no continues turning and backwashing is done.

6. CONCLUSION

The presented study of PSD analyses in a commercial smolt farm identified clear variations in PSD of the SS in the different water treatment compartments of the RAS unit.

The water collected from the fish tank outlets entering the drum filter carried the whole particle size spectrum with clear dominating particles in the upper size ranges. Up to 31 % of the particles were found to be bigger than 600 µm. The fine particle fraction below 20 µm was present in smaller amounts. 8 to 15 % were detected in this range. Overall the PSD of SS entering the filter units corresponded well with previous PSD analyses in literature (J.D. McMillan, 2002, Pfeiffer, 2008, Brinker et al., 2005, Brinker and Rosch, 2004, Sindilariu et al., 2009). No evidence for fine particle accumulation, as predicted as of being big threat of RAS technology by several authors (Martins et al., 2010, Orellana, 2006, Chen, 1993) could be found.

After drum filtration the PSD was limited to a maximum size of 128 µm whereby less than 4 % of the total particle volume was larger than the filter mesh size of 60 µm. Even though, the PSD of the influent water to the filter allowed the assumption of a highly effective particle removal of solids bigger than the filter screens (77 %), the effective removal indicated by the TSS results clearly show a low removal (34 %). The mismatch is most probably a result of the particle destroying impact of the drum filter. A high percentage of particles bigger 60 µm passed presumably the mesh as smaller fragments of broken solids.

The PSD of the filtrated water changed within the MBBR towards a higher percentage of bigger particles and lower percentage of smaller particles, presumably by the release of bacteria flocks. Particles in the range from 203 to 300 strongly dominated the water leaving the MBBR with 66 % of the total particle volume, indicating a particle increase of over 100 % in this range. The particle fraction smaller 60 µm decreased throughout the MBBR from around 70 % in the influent to around 23 % in the effluent. The indicated change in PSD in the MBBR towards bigger particles might be of interest, if further particle reduction in the system is needed. The PSD of the effluent carried about 70 % of the particles in range bigger than 100 µm. This indicates that a second particle filtration step, attacking the SS load on a relative coarse filter mesh (>100 µm), could lead to a high reduction in TSS. Especially, if further water polishing by UV, Ozon or AOT (Advanced Oxygenation Technology) is integrated as water treatment step in the RAS, a lower TSS entering these units will lead to a higher efficiency of the polishing units. In consideration of the fact that the industry demands static lower TSS levels in new RAS units to fulfill ideal water quality requirements for e.g. hatcheries, start-feeding departments or grow out units for sensitive fish species, highly efficient particle control will be of

growing interest. In parallel, the development towards lower water exchange rates in RAS units, to close systems further, requires efficient solution to handle particles (Martins et al., 2010).

Compared to the change of PSD throughout the drum filter and the MBBR, the impact of the degaser was measured to be more undistinguishable. The comparison of in- and effluent illustrated a particle decrease in the upper size ranges, caused by a particle breakdown. Presumably, the impact of waterfalls within the degaser exposed the solids to shear stress resulting in a decrease of particles bigger 203 µm from about 63 % to 37 % of the total particle volume percent.

Couturier (2009) concludes that solids which do not get captured during their first pass through the drum filter have little chances of getting captured during subsequent passes. This is because they get broken down into smaller particles in the interim. As a result, the TSS concentration along the loop segment between the exit of the drum filter and the inlet of the fish tank is indicative for the concentration of small particles, which must exit the recirculation loop with the effluent water. The present study does not support Couturier's conclusion. The analyses illustrate a more diverse PSD with a strong shift from dominant smaller particles to bigger particles within the MBBR. To assume, that the TSS level after particle filtration and all the way through the treatment compartments until fish tank inlet is indicative for the concentration of small particles, which cannot be caught on the next recirculation loop and must leave the RAS over the makeup water exchange, is not valid for the tested RAS. The water entering the fish tank carried particles up to 300 µm with clear dominance of particles in the upper size ranges (around 70 % > 100 µm). Since the particle filtration is running with 60 and 30 µm filter mesh, these particles are, at least partly, removed on the next loop.

The comparison of the PSD measured in the water before pumping (pump sump) and at the fish tank inlet showed no sign of particle breakage caused by pumping. Still, closer sampling right after pumping would have made the result more reliable. Since no access to the water was possible within the closed pipe system, more detailed analyses were not possible. The effect of pumping, water oxygenation in deepshaft cones as well as turbulences in piping could have been investigated in more detail. But overall no big change of PSD seemed to occur from the pump sump to fish tank inlet.

On some days the poor solid capture efficiency of the drum filters caused the TSS levels to be on the upper recommended value for salmonids of 10mg/l (Timmons, 2007) in the inlet water to the fish tanks. Because of that, it can be assumed, that the TSS level in some tanks exceeded the recommended value given by Timmons (2007). The PSD measurements at the filter inlets showed that the theoretical removal potential of the filter units is much higher than the effective removal based on TSS. Therefore it is of high importance to improve the overall solids removal efficiency in

the farm. One major point in this aspect is the prevention of solids breakdown within the filtration process. As discussed previously the Hydrotech filter operating in HAND-mode during the experiment resulted in continuous back-flushing and drum rotation. This caused a negative impact on the suspended solid capture. In comparison, the filter efficiency tested in AUTO-mode, in which drum rotation and backflushing is controlled by the waterlevel inside the drum, would be a logical test for further research. In general, the Hydrotech filters require more detailed efficiency tests. The detected efficiency of 34 % TSS reduction of the installed set of 3 drum filters (2 x 60 µm plus 1 x 30 µm) is a fairly poor result and cannot be explained by the selection of too coarse filter mesh sizes. The PSD measured in the inlet water clearly illustrates the high removal potential based on particle size. If the filters would have functioned accordingly to their functional principle as strainer (taking out all solids bigger than the filter mesh size) the TSS reduction should have been in the range of over 70 % (compare table 12). The test of a single DF equipped with 10 µm respectively 30 µm filter screen also shows that the predicted removal potential is not fulfilled. Different to the DF test on the full set of filters installed in the farm, the actual removal of particles bigger than the mesh size matches more accurately with the SS removal based on TSS values. Questionable stays the fact, why relative high volume percentages of solids bigger than the mesh size were found in the filtrate of the micro screens. Partly, this can be explained by construction failures, whereby flocculation and non-spherical particles passing the screen might have had an impact. Here, more detailed analyses are required, especially since this phenomenon was described previously in literature (Sindilariu et al., 2009, Brinker, 2005). In addition, the head loss through the filter units might have had an impact on the breakage of solids as well. The more head difference from the inside of the drum to the outside is applied, the more forces squeeze fragile particles through the mesh. Testing the impact of head loss on the filter efficiency could be the logical consequence. Future research needs to focus on improved particle removal, by operating Hydrotech drum filter with lower head. For dimensioning, this might result in necessary upsizing of the filter model and consequently in higher costs. Yet, since the effective removal measured on the full scale of 34 % gives room for improvement, even choosing coarser mesh size to keep the filter size and increase capacity to operate with lower head, could result in better particle removal. In this aspect, gentler particle handling might be the key for improvement.

This study included some challenges. One major task was the organization of the lazer equipment. Since SS of aquaculture origin are distributed extremely patchily in time and space and are of transient nature, no other option then on-side measurements has been found to measure PSD correctly until now (Brinker, 2005). Every type of transportation or storage affects the PSD and adulterates the results. Consequently in order to measure PSD on a full scale operating smolt farm, all required equipment needed to be transported and set up on side. The aim of this study was not,

to develop new methods for particle sizing or to experiment with different existing methods. The objective of this study was the result-orientated application of a well-tested analyze method for aquaculture on a full operating, industrial RAS was the objective. As known from literature, the particle sizing method invented by Alexander Brinker using the time-of-transition principle has been successfully used for particle sizing of SS from aquaculture origin (Brinker, 2005, Brinker and Rosch, 2004, Brinker et al., 2005, Sindilariu et al., 2009). Hence the use of this already well-tested laser technology for the particle investigation was the most promising. Since the GALAI CIS 1 laser sizer is not produced anymore, extensive research resulted in only two options: importing the equipment from a lab in Italy or from the "Fischerei Forschungstelle" (LAZBW – *"Fishery and Research Center"*) in Germany. With the kind support from Alexander Brinker and his colleagues Hans Peter Billmann and Mark Schumann from the LAZBW, the import of the equipment to Norway was arranged. In addition to that, a local training in the analyze techniques at LAZBW was agreed on. Therefore, time was a limiting factor for this study. The extensive and time-consuming organization of the equipment, including transportation and customs handling took several month.

Time also limited the amounts of repetition during the analyses. Each run of PSD test took between 25 up to 80 minutes. Each PSD comparison of influent and effluent of a water treatment unit was set up as 4 analyses per sample spot. Including time for analyses preparation such as laser calibration as well as sampling, the test of one water treatment unit took 6 to 12 hours. More detailed PSD test including a higher number of replicas would have been of benefit for this study, but not realizable. The main objective was to get a good conception of the diversity of PSD in the complete RAS, not to get highly accurate and statistical supported results on a smaller scale of sample points.

The instable nature of SS of aquaculture origin is the reason that all PSD results have to be taken under consideration. It has to be assumed that water sampling, sample handling and the analyze method itself had an impact on the PSD. Shear forces applied by several impact factors, as for example filling the water sample into the beaker on top of the flow meter, might have caused particle breakdown previous to the analyze. Further, flocculation might have changed the PSD as well. One technical limitation of the time of transition method is the assumption that all particles are of spherical nature. As proven previously by optical examination of particles in RAS, the particle shape varies from long spicule-like to round, sand-like particles (Patterson and Watts, 2003). Hence, the assumption of spherical particles might have caused overestimation of particle volume in this experiment.

The presented results clearly illustrate, within the limitation of the method, the diversity of the particle size distribution of suspended solids in an industrial scale RAS system. The obtained knowledge of dominant particle sizes within the different water treatment departments can be

applied for further RAS system development, especially in terms of particle control. The filter efficiency tests of the used particle control units in the RAS revealed a demand for further improvement. The presented study demonstrates that even though by today, RAS technology is applied successfully for several fish species, there are still challenges to be overcome.

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