EVALUATION OF FILTRATION EFFICIENCY OF CERAMIC FOAM FILTERS (CFF) USING A HYDRAULIC WATER SYSTEM

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Abstract The filtration efficiency of Ceramic Foam Filters (CFFs) of grades 50 and 65 has been quantitatively evaluated using a hydraulic water system. Distilled water seeded with Polystyrene Microsphere particles with a distribution of 20 and 50 µm. The polystyrene particles were illuminated during the filtration step by a continuous laser sheet placed before and after the filter. Images of the illuminated particles were acquired, and their number automatically distinguished and counted by the use of the image processing software. The filtration efficiency was further calculated based on the ratio of counted particles before and after the filter. Based on the obtained results the potential of the present method is discussed for evaluating the filtration efficiency of CFFs as the filtration media for molten aluminium.

1. Introduction

Ceramic Foam Filters (CFF) are irregular network structures of polyhedral like cells, connected through solid edges and open faces [1, 2]. Application of CFFs for the filtration of molten aluminium dates back to the 1970s [3]. In the recent years, however, the commercial applications of CFFs has been extended and in addition to molten aluminium filtration they are used for gas filtration, kiln furniture's, catalysts, flame stabilizer in porous burners, acoustic transfer in ceramic surface burners, etc. [3].

The three mechanisms that operate alone or in combinations in CFFs to remove the unwanted particles from a molten aluminium are sieving, cake formation, and deep-bed filtration [3]. The dominant mechanism, however, in the CFFs is the deep-bed filtration. This is due to the large surface energies in the system and smaller solid particle sizes compared to the average CFFs' cell size [3]. Mathematical models have been developed in designing depth filtration through CFFs as an aid to simulate and evaluate process of aluminium melt filtration [4-12]. Pilot scale experiments are necessary for a systematic evaluation of the molten aluminium filtration efficiency. Several grades of commercially available CFFs and different materials leads to many practical uncertainties surrounding the evaluation of aluminium melt filtration efficiency even in small scale experiments. However, performing pilot experiments evaluating filtration efficiency of CFFs are costly and time-consuming process. As a result, developing a robust procedure to evaluate the filtration efficiency of CFF under controllable conditions which is also economical, is interesting for aluminium industry as well as CFF manufacturers.

Water has been extensively used for simulation of flow characteristics of CFFs [5, 13-17] as well as other processes such as molten aluminium refining [18]. That is because the viscosity of water at the ambient temperature is equal to that of the molten aluminium at casting temperature. However, the surface tension between water, CFF, and Polystyrene particles is not equal to that of the molten aluminium, CFF, and particles. Unlike the aluminium, water wets CFF well that influences the particle removal according to Bao et. al. [19-21]. Therefore, evaluation of the filtration efficiency in a hydraulic system is not directly representative of CFF performance in a molten aluminium filtration process. Nevertheless, using water as fluid media in the tailor made set up instead of liquid aluminium might also provide valuable information on filtration characteristics of various CFFs materials (grade and quality) and they could be compared.

The objective of the study reported here is to introduce a water filtration method by using CFFs that has the potential to evaluate the filtration efficiency of different (grade and quality) CFFs in a reproducible way although not directly comparable to molten aluminium filtration.

2. Theoretical Background

The most common type of CFFs used for the filtration of aluminium wrought and foundry alloys are phosphate-bonded alumina in the grades from 30 to 65. The total filter collection efficiency, η, is defined as:

$$\eta = \frac{C_i - C_o}{C_i} \qquad (1)$$

where C_i and C_o are the concentration of the particles (g·cm^{-3}or %) in the inlet and outlet, respectively [8].

A large number of scientific papers have been published on the theory of filtration and the models that have been developed to investigate and compare the fundamental bed characteristics of deep bed filters and CFFs by quantifying the inclusion-removal kinetics [4, 5, 8-12]. Apelian et.al.[9] proposed a first order mass balance Equation 2 that relates the rate of change of entrapped inclusions in the filter bed as a function of inclusion concentration in the melt.

$$\frac{\partial \sigma}{\partial t} = KC \qquad (2)$$

where σ is the concentration of entrapped particles (g·cm^{-3}or %), t is time (s), K is the kinetic parameter (s^{-1}), and C the inclusion concentration in the melt (g·cm^{-3}or %). The kinetic parameter (K) may in general be a function of σ, the fluid physical properties, the flow rate and the shape and size of the particles and is expressed as:

$$K = K_{\circ}\left(1 - \frac{\sigma}{\sigma_m}\right) \qquad (3)$$

where $K_{\circ}$ is the kinetic parameter coefficient and σ_m the inclusion retention capacity of the filter bed. In the initial stage of filtration, the particle retention capacity is large compared to the number of entrapped particles. As a result, $\sigma / \sigma_m \rightarrow 0$, *i.e.* $K=K_{\circ}$, and by using the appropriate boundary conditions the solution to the first order partial deferential equation simplifies to:

$$\frac{C_o}{C_i} = \exp\left(-\frac{K_{\circ} L}{U_m}\right) \qquad (4)$$

where C_o is the outlet concentration, U_m the fluid superficial velocity (m·s^{-1}), and L the height of the filter (m). The assumption here is that $K_{\circ}$ is not a function of the fluid velocity (U_m).

By substituting for C_o in Equation 1 from Equation 4 we obtain:

$$\eta = 1 - \exp\left(-\lambda L\right) \qquad (5)$$

where λ is the filtration coefficient (m^{-1}) and could be determined experimentally by measuring the concentration of particles before (C_i) and after (C_o) the filter.

The derived coefficient, λ, if plotted as a function of fluid velocity offers a quantitative assessment of the filtration characteristics of various filters, that enables to investigate the influence of various parameters such as filter porosity, surface roughness, pore size, tortuosity, flow rate, particle´s shape, size and distribution, etc. on the filtration efficiency [9]. As a result, the determination of the kinetic parameter (*K*) could be probably the suitable approach towards the characterization of the performance of a filter.

3. Experimental

The idea of developing a system to evaluate the filtration efficiency of CFFs in a hydraulic system was inspired by particle image velocimetry (PIV) as an optical method of flow visualization. Nevertheless, the hydraulic system, used in the present work, is simple to operate, and allows continuous monitoring of the filtration performance. Fig. 1 shows a schematic of the experimental setup.

To prepare a suspension, microspheres polystyrene particles 20 and 50 µm, provided from Polysciences, Inc. and Dantec Dynamics respectively, were added to distilled water (≈ 20 °C). The distilled water in the reservoir tank was seeded up gradually and after the addition of the particles in each step one image was captured. The images were taken in a dark room, from the suspension in which the particles were illuminated using a laser generator unit. The laser unit with the power of 92.8 mW and a Powell lens of 30° that generate a laser sheet of green light with 532 nm wavelength and a divergent character (150 × 50 × 1 mm) in the position of the filtration chamber. A digital black and white camera Pike F-210B/C with resolution 1920 × 1080 pixels, equipped by a Samyang 35 mm F1.4 lens was used for capturing images before and after filtration. The images were analysed using image thresholding technique in ImageJ software to isolate the in-focus particles from the out of focus ones. As the particles could be detected after thresholding, that concentration was defined as the reference for all the trials with the same particle size. A black and white thresholding was used with the levels that have been defined in Table I.

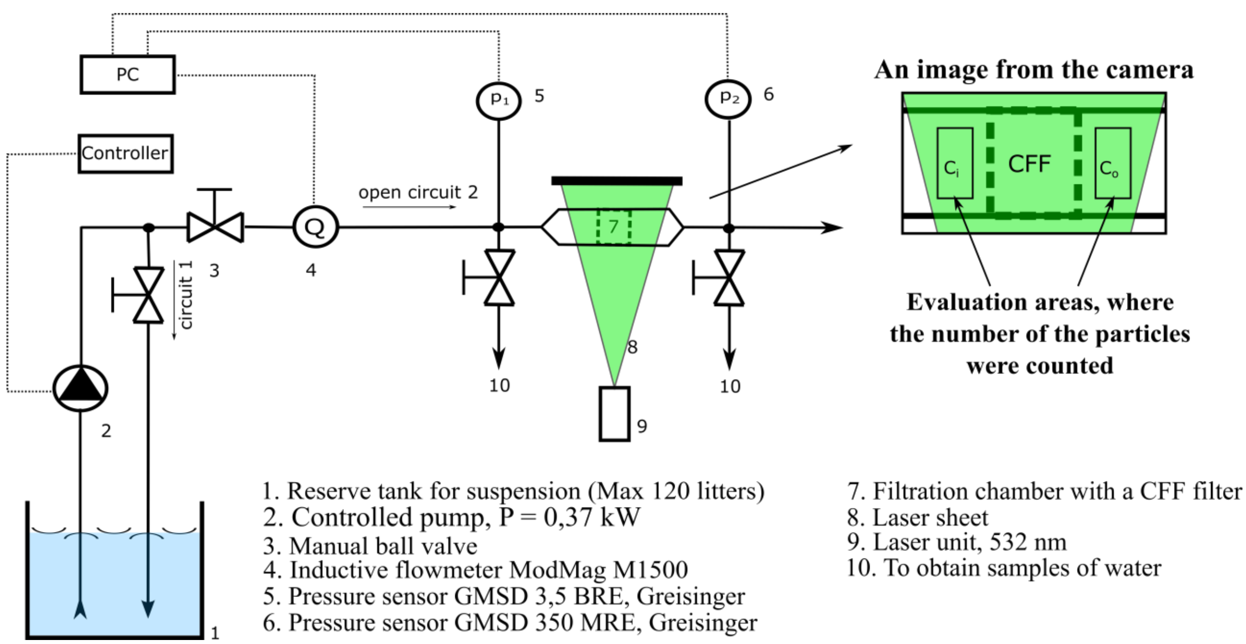

Fig. 1- Schematic drawing of the experimental test rig used to filtrate distilled water seeded by microspheres polystyrene particles to evaluate the filtration efficiency of CFF.

Table I. The experimental conditions.

CFF grade	Sample size	Particle size (µm)	Particle concentration (µg· L^{-1})	Experiment time (min)	Thresholding level	
					Up	Down
50	3	20	2000	30	14392	65535
65	3	20	2000	30	31868	65535
50	3	50	5000	30	19017	65535
65	3	50	5000	30	19017	65535

The CFF samples of the size ~50×50×50 mm³ were mounted inside the optical transparent filtration channel made of optic glasses. The suspension was drawn through the filtration channel with the velocity of 2-3.5 mm·s^{-1} and single images were captured in a dark room from the illuminated particles every three seconds for 30 minutes. An area with the size of 32.12×22.29 mm^2 was defined on the images just before and after the CFF sample and the number of the particles inside the area were counted after thresholding of the images using ImageJ. The same thresholding level that was used in defining the concentration of the particles was used here as well. The particles were counted automatically using the ImageJ software and the filtration efficiency was determined for each image using equation 1. However, C_i and C_o are the number of the particles in the inlet and outlet, respectively.

4. Results and Discussion

The filtration efficiencies of grade 50 and 65 CFFs were evaluated using a hydraulic water system. Fig. 2a shows the filtration efficiency of sample 65-1 (Table II) as a function of time and indicates that the filtration efficiency is not changing by time.

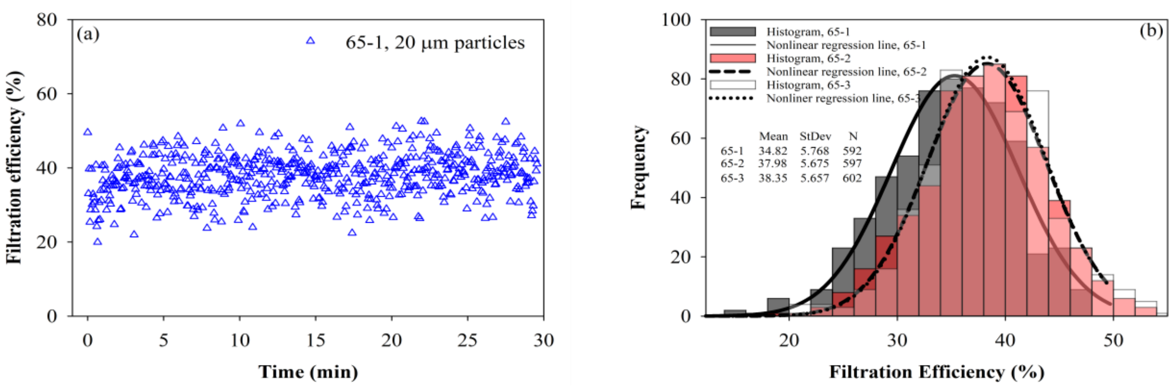

Fig. 2- (a) Filtration efficiency of the sample 65-1
(b) Histogram of the filtration efficiency of the samples 65-1, 65-2 and 65-3.

This is due to large surface area of the CFFs and low concentration (2000 µg·L^{-1}) of the monodispersed particles that led to have only depth filtration of the particles. A filter cake did not form since the particle size distribution, *i.e.* 20 µm, was significantly smaller than the CFF pore size, *i.e.* ≈ 880 µm, to be retained on the surface of the filter.

Fig. 2b shows the histogram of the filtration efficiency of the samples 65-1, 65-2 and 65-3, along with the mean value, standard deviation and number of counts for each sample. The number 65 that is used for naming the samples is the CFF grade number used in the subsequent test. The mean filtration efficiency and the standard deviation of three samples are close, *i.e.* 34.82, 37.98 and 38.35 respectively for 65-1, 65-2 and 65-3. This is probably due to having uniform light intensity from the laser unit before and after the CFF samples that caused a uniformly scattered light intensity from the particles, as well. In addition, the position of the camera and laser unit relative to the filtration chamber were constant all the way through the three experiments.

The filtration efficiencies of the all trials in Table I were more or less constant with time. As a result, the mean filtration efficiency was calculated to be able to compare the filtration efficiency of the filters of each grade as well as with CFFs of the other grade. Table II shows the mean filtration efficiency, standard deviation and margin of the errors with 95 % confidence interval for all the trials in Table I. The two first digits of the sample numbers define the grade of the CFF sample. From the results it is clear that the mean filtration efficiencies, except for the grade 65 used to filtrate the suspension with 20 µm particles, *i.e.* 65-1, 65-2 and 65-3, are varying.

To perform each group of the trials in the Table II, a specific amount of the suspension was prepared prior to the experiments by the addition of the particles directly to the distilled water. For doing the trials in group 1, almost 75 L of suspension were prepared. The mean filtration efficiency of the samples in group 1 that are plotted in Fig. 3a indicates that the sample 50-2 has higher filtration efficiency than the other two samples. The mean particle count before and after the samples are plotted in Fig. 3b. As can be seen in the graph, the concentration of the particles is decreasing in the inlet by time which implies that the particles in the suspension either adhere to the walls of the container or agglomerate to form larger particles.

Table II. The mean filtration efficiency, Standard deviation and margin of the errors.

Group	Sample No	Particle Size (µm)	Mean Filtration Efficiency (%)	Number of counts	Standard Deviation (%)	Margin of Error (%)
	50-1		22.98	637	11.17	±0.86
1	**50-2**	20	44.31	608	5.56	±0.44
	50-3		21.14	608	8.74	±0.69
	65-1		34.82	592	5.76	±0.46
2	**65-2**	20	37.94	592	5.68	±0.45
	65-3		38.47	592	5.59	±0.45
	50-4		47.89	611	10.58	±0.84
3	**50-5**	50	11.47	662	14.44	±1.10
	50-6		36.78	662	12.00	±0.91
	65-4		7.68	646	14.89	±1.15
4	**65-5**	50	70.91	644	7.46	±0.57
	65-6		28.46	661	14.03	±1.07

Contrary to the result of the filtration efficiency of the samples in group 1, the samples in group 2, *i.e.* the CFF grade 65 used to filtrate suspension with 20 µm particles, showed (Fig. 4a) rather close filtration efficiencies. Fig. 4b illustrates the number of the counted particles in the inlet and outlet and it can be seen that the number of the counted particles is decreasing by time. This result is in accordance with previous results showed in Fig. 3b.

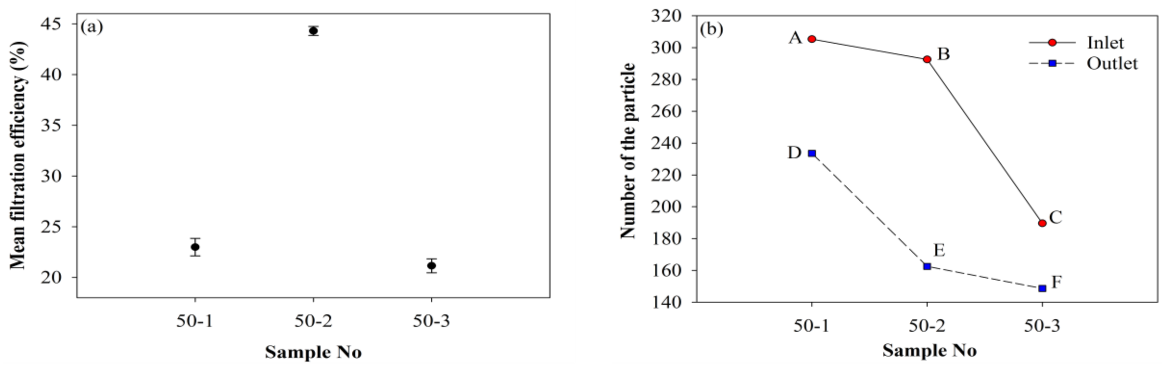

Fig. 3- (a) The mean filtration efficiency of the CFF samples of grade 50 filtrated suspension with 20 µm particles, (b) the number of the measured particles before and after the CFF.

However, the reduction of the particle number downstream of the filter in Fig. 4b shows a similar trend to that of the upstream and that is the reason for having comparative filtration efficiencies for samples 65-1, 65-2 and 65-3. In Fig. 3b, as the number of the particles in the inlet from point A to B reduces approximately by 2.2 %, the reduction in the outlet from D to E was 18.09 %, which explains the high filtration efficiency of the sample 50-2. This higher filtration efficiency can be attributed to either the sample 50-2 has different internal structure than 50-1 and 50-3 that leads to removal of more particles or some changes in the outlet light intensity due to changing the position of the laser unit that resulted in the illumination of less particles in the outlet and consequently particle counting was reduced in the outlet. The second assumption is more probable by comparing the filtration efficiency of the samples 65-1, 65-2 and 65-3 with 50-1 and 50-3. Since the CFF grade 65 has smaller pore size and higher surface area and tortuosity than the CFF grade 50, a higher filtration efficiency is expected for particles of the same size distribution. It can be seen in the Table II that the efficiency of 50-1 and 50-3 are almost equal and less than the efficiency of the samples in group 2, which is rational. On the other hand, the efficiency of the sample 50-2 is higher than that the filtration efficiency of all the samples in group 2, which probably is not correct. As a result, these findings are directly in line with the previous assumption that through the trail 50-2 probably lower light intensity in the outlet led to lower particle count.

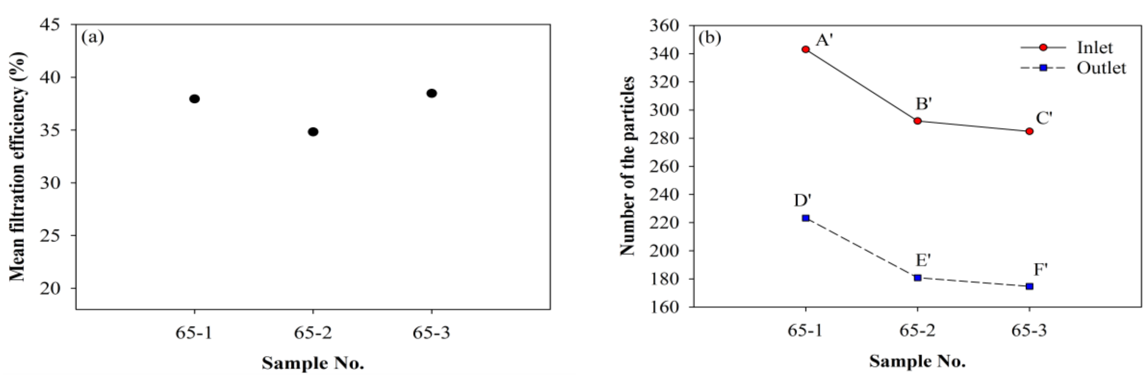

Fig. 4- (a) The mean filtration efficiency of the CFF samples of grade 65 filtrated suspension with 20 µm particles, (b) the number of the measured particles before and after the CFF.

Fig. 5a-b show the mean filtration efficiency and the number of the counted particles in the inlet and outlet of the trials in the groups 3 and 4. The margin of the errors was also calculated by 95 % confidence level, but it was very small and cannot be seen in the graphs. From Fig. 5a it is clear that the mean filtration efficiency is changing significantly for both CFF grades 50 and 65. By comparing the filtration efficiency of each trial in Fig. 5a with their corresponding particle counts in Fig. 5b

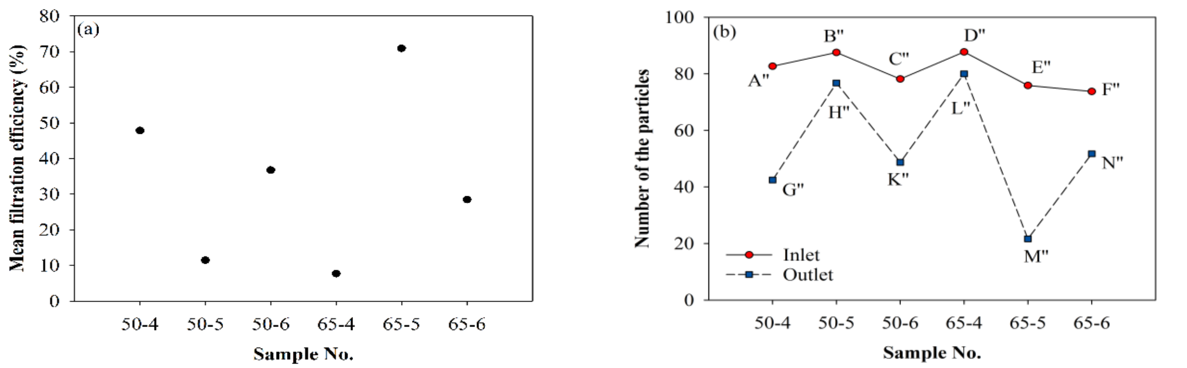

Fig. 5- (a) The mean filtration efficiency of the CFF samples of grades 50 and 65 filtrated suspension with 50 µm particles, (b) the number of the measured particles before and after the CFF.

The results demonstrate two things. First, when the number of the particles increases slightly in the inlet the number of the counts in the outlet increases significantly. For instance, when the number of the particles in the inlet from the point A´´ to B´´ and C´´ to D´´ increased 5.56 % and 5.76 %, respectively, the corresponding data for the outlet from the points G´´ to H´´ and K´´ to L´´ increased 28.8 % and 24.32 %, respectively. Second, as the number of the counts in the inlet decreases slightly, *i.e.* from B´´ to C´´ and D´´ to E´´ a reduction of 5.65 % and 7.24 %, respectively, the number of the counts in the outlet showed a notable reduction, *i.e.* from H´´ to K´´ and L´´ to M´´ a reduction of 22.3 % and 57.4 %, respectively. That might be deduced from the subsequent results that the filtration efficiency depends on the concentration of the particles in the fluid and decreases as more particles exist or are introduced to the fluid. However, as the number of the counts in the inlet is decreasing from E´´ to F´´, an increase occurs in the outlet. That is contrary to other observations shown in Fig 5b. The rise of the number of the particles in the inlet shown in Fig. 5b, *i.e.* points B´´ and D´´, occurred when the suspension in the container was stirred vigorously that resulted probably in the re-entrainment of the adhered particles to the walls of the container to the suspension.

The result of the filtration efficiency obtained for all the trials highlighted that in order to get a statistically reasonable evaluation of the filtration efficiency of the CFFs more experimental data is needed. This series of trials were the initial attempts towards the construction of a hydraulic system to evaluate the filtration efficiency of the CFFs and therefore the experimental conditions were not defined clearly in advance. As a result, we speculated that the experimental conditions, if not the only, but probably the main reasons of the fluctuation of the filtration efficiency of the CFFs and therefore are very much the key components in the future attempts.

5. Conclusion

The filtration efficiency of the commercially Ceramic Foam Filters (CFF) of grades 50 and 65 were quantitatively evaluated in a newly developed water filtration method. The main conclusions from this work is enumerated below.

1. The statistical evaluation of the mean filtration efficiency of the CFF using the introduced water (seeded with polymeric particles) hydraulic system was difficult to be obtained due to the lack of the experimental data points.
2. The main challenge in this set up is that experimental conditions should be held constant throughout the tests to get comparable results with respect to the filtration efficiency based on seeded water system.
3. The results of this work provided a sound basis for determination of the experimental conditions needed for the future trials.

6. Future work

Based on the experience gained from these tests a new and modified experimental set-up is under construction at the Department of Materials Science and Technology of Norwegian University of Science and Technology (NTNU) to evaluate the filtration coefficient, λ, as a function of fluid velocity, for CFFs of different quality grade 30-80, that offers a quantitative assessment of the filtration characteristics (for that particular set up and conditions). The characteristics of the new set-up that differentiate it from the one, which is used in this work, are having a vertical filtration chamber, applying an elevated water reservoir. This provides the fluid flow without using a pump, and with support of online particle counter make it possible to get a quantitative analysis of the particle concentrations more accurately.

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