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The Enhancement of Pre-Storage Filtration Efficiency for the Rainwater Harvesting System in Malaysia

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Abstract. A conventional design of rainwater harvesting system collects and directs the rainwater through water piping from roof of building to the water storage. The filtration system which locates before the water tank storage and first flush bypass system is the main focus of the research. A filtration system consists of a control volume of filter compartment, filter screen (stainless steel mesh) and water piping that direct the water flow. The filtration efficiency of an existing filter "3P Volume Filter VF1" by industrial company is enhanced. A full scale filter design prototype with filter screen of 1000 μm stainless steel metal mesh is tested to compare with the original filter system design. Three types of water inlet setups are tested. Among the proposed water inlet setups, the 90° inlet setup with extension provides the best filtration rate per unit time, following by the 45° inlet setup. The 45° and 90° inlet setup has similar filtration efficiency at low to medium flow rate while 45° inlet setup has better efficiency at high flow rate. The filtration efficiency with the 90° inlet setup with extension is observed to maintain at highest value at medium to high flow rate. The overall filtration performance achieved by the 90° inlet setup with extension at low to high flow rate is between 34.1 to 35.7%.

1. Introduction

Rainwater harvesting practice can be traced since thousands of years using different types of techniques to collect and store the rainwater from rooftops and land surfaces. A conventional design of rainwater harvesting system will collect and direct the rainwater through water piping to the water storage [1].

The dimensions of the rainwater harvesting system are highly dependent on the size of rainwater catchment area. For industrial scale usage, a simple rainwater filtration process is carried out before it is stored in storage.

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Particles like leaves, rocks, debris and dusts are removed at the filtration process to avoid the risk of clogging up in the water storage.

A conventional rainwater harvesting system consists of four major components which are shown as Fig. 1. The rainwater will first be collected by the catchment area at the rooftop. Filration system which locates before the water tank storage and first flush bypass system is the main focus of the research. A filtration system consists of a control volume of filter compartment, filter screen (stainless steel mesh) and water piping that direct the water flow.

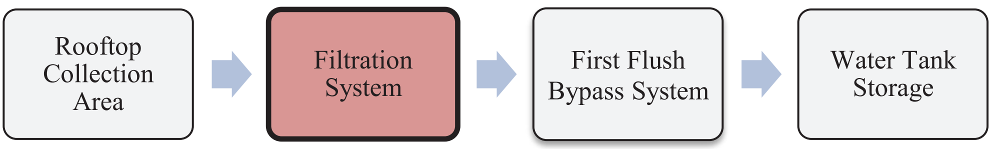


Fig 1. Components of rainwater harvesting system.

Large industrial scale filtration system which commonly used in the market is based on a parallel setup concept with a few of horizontal positioned filter compartments as shown in Fig. 2. More filter compartments can be added by increasing the number of the inlet.

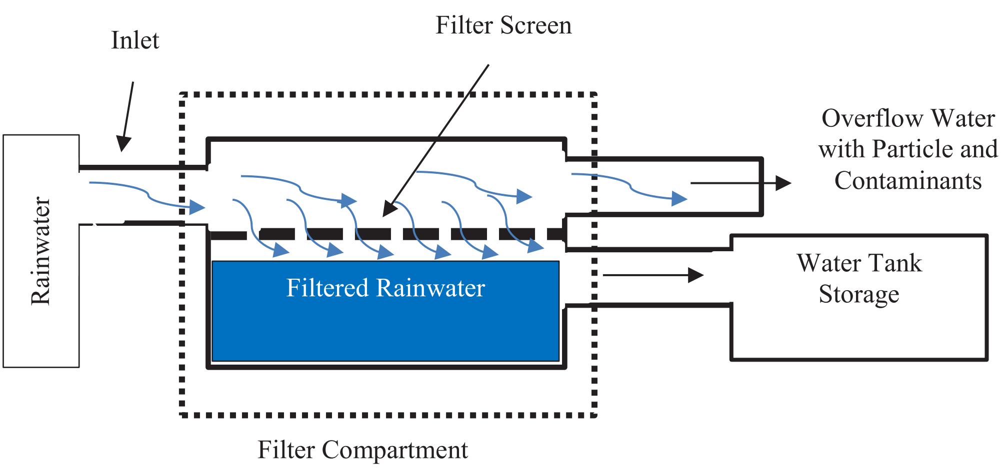
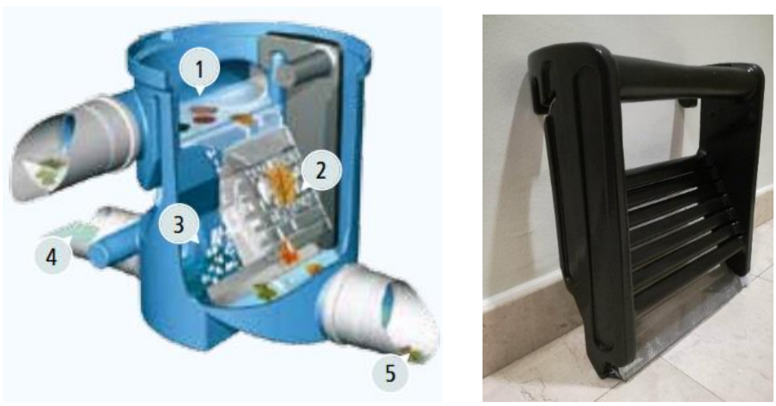


Fig.2. Schematic diagram of single filtration compartment in filtration system.

The inlet will direct the rainwater into the filter compartment which consists of a metal mesh filter screen for filtration process. The large particles and contaminants will be pushed out of the filter compartment by rainwater flow. Filtered rainwater that has passed through the horizontal positioned filter screen due to gravitational force will be stored into water tank storage. However, the performance of the design will decrease significantly during high rainwater flow rate operation. The small mesh size of the filter screen not only resist the particles from passing through, it also decreased the permeability of rainwater. The high rainwater flow rate which has filled up the whole water piping will only stay a short period in the filter compartment. There is just a small portion of water near the filter screen that can be directed to the water tank storage while large portion of water have overflowed and left the filter compartment [2].

1.1 Existing Filter "3P Volume Filter VF1"

This research was an industrial project in collaboration with the industrial partners, Bina Plastic Industries Sdn. Bhd. and Besstem Plastic Sdn. Bhd, which is a class leading plastic pipe and rainwater filtration system supplier in Malaysia respectively. Both companies have provided technical support to build the prototype and product testing. Fig. 3 shows the filter system 3P volume filter VF1 and its filter design, which is a product from Germany currently used by DD Techniche Sdn. Bhd. Company specialises in installation of rainwater harvesting system for both residential and commercial buildings in Malaysia. The rainfalls in Malaysia are commonly heavy but in a short period of time. The high filtration rate from the filtration system is desired to take advantage in harvesting more filtered rainwater in a limited duration. The projects that the company had done previously were to be capable of sustain a high rainwater flow rate range from 50 L/s to 200 L/s.



(a) (b)

Fig 3. (a) 3P volume filter VF1 by 3P Technik from Germany [3]; (b) Original filter design.

The design and functionality of the filter VF1 is similar to the parallel setup concept as discussed in Fig. 2. The filter VF1 is installed by the company whenever the installation location is limited, which will be discussed in this paper. The most significant difference is that the filter screen is placed at an incline instead of horizontal position. Refer to Fig 3(a), the rainwater flow into the filter compartment and accumulate at top section of the filter compartment at stage 1. At stage 2, the rainwater will be filtered while flowing along the slanted metal mesh filter screen (Fig. 3(b)). Next, the clean water that has passed through the filter screen is collected at the bottom section of the filter compartment at stage 3. While the clean water is directed to the water tank storage at stage 4, the suspended particle will be removed togetehr with the overflow water through a drain outlet at stage 5. The filter design does provide a self-cleaning process to increase the maintenance interval. However, the filter has the filter process characteristic same as the horizontal filtration method as large portion of rainwater flows towards the drain outlet directly during high flow rate.

Fig. 4 shows the official data by the company regarding on the graph of hydraulic efficiency against inflow of rainwater for filter VF1. Based on Fig. 4, the filter achieve 100% efficiency at flow rate of 0.01 L/s to 0.2 L/s but started to drop after that. It can be seen that the filter compartment has started to fail to capture all the inflow rainwater even before reaching flow rate of 1 L/s. Furthermore, the efficiency is just around 50% at flow rate of 3.5 L/s, which means only 1.75 L of rainwater is being filtered and collected into water tank storage every second. At this point, the filter has reached its peak filter performance as shown in the sudden drop of efficiency in the graph. Further increment of inflow of rainwater will only result in more overflow rainwater due to failure to capture. Hydraulic efficiency is the filtration rate efficiency, η is equal to the fraction of total filtered water, $Q_{out,filtered}$ devided by total inflow water, Q_{in} which is shown as Eq. (1).

$$\eta = \frac{Q_{out,filtered}}{Q_{in}} \quad (1)$$

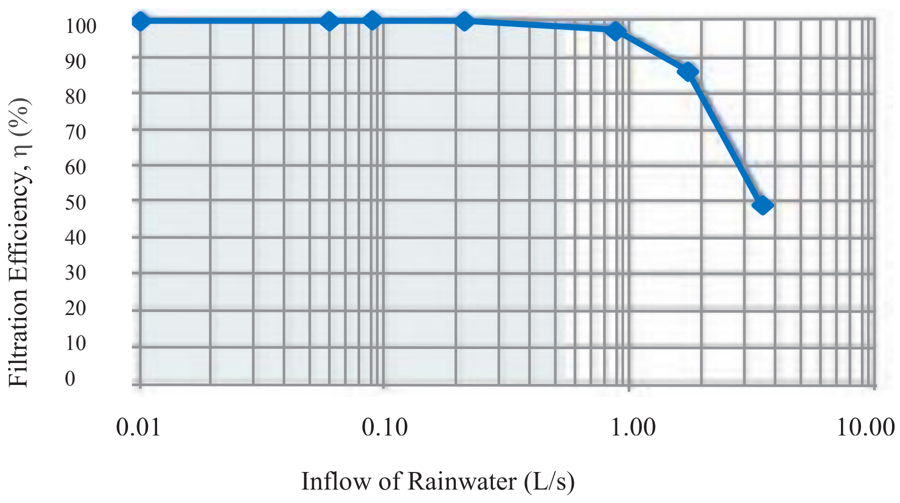


Fig 4. Graph of hydraulic efficiency vs inflow of rainwater for filter VF1 [3].

This paper aims to identify suitable filtration method to achieve higher filtration efficiency under high flow rate to coordinate with the heavy rainfall in Malaysia. The research focuses on developing a sustainable mechanical operated rainwater filtration system for home and small industrial scale usage. The desired solution is to attain higher hydraulic efficiency at higher inflow rate for this specific filter VF1 by applying suitable modifications without modifying the shape of filter compartment. The study of existing filtration system methods and designs available in the market globally were conducted and their specifications were compared. A prototype filter screen was built by integrating features from different types of filtration system. The filter screen must be able to fit inside the original compartment of filter VF1. The rainwater filtration efficiency, in term of filtration rate difference between the original and prototype filter screen design is to be obtained throughout the testing.

2. Specifications Comparisons of Different Types of Filter System

2.1 Cyclonic Rotation Filter

A cyclone filter is a design of rotational separator which leads the water flow to be circular in the filtration compartment. Fig. 5 shows a schematic diagram of rotational separator which direct the water from inlet to rotate around the compartment. The centrifugal forces produced by the rotating water will acts on large particles and contaminants pushing them outwards leaving the centre vertical axis-z. With the assist from gravitational forces, the suspended particles and contaminants will move towards the bottom of the compartment due to no drainage outlet while leaving the cleaned water to be directed into the storage.

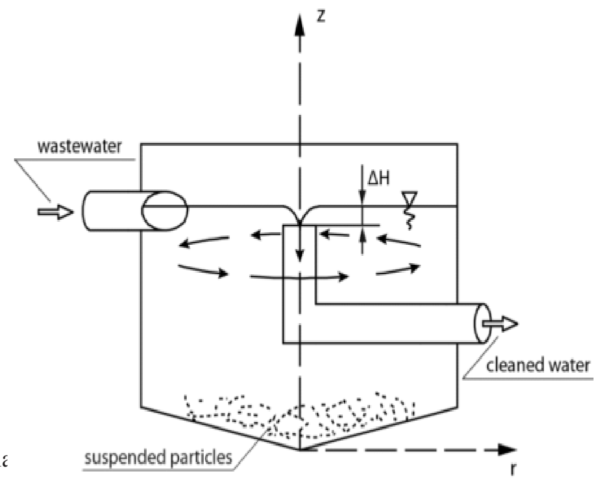


Fig. 5. Schematic dia

The cyclone filtration method performs well under high flow rates of water. However, the suspended particles are not removed from the cyclone filter compartment throughout the operation [4]. Fig. 6 shows an improved design of cyclone filtration method product by Rainharvesting Systems Company from UK. This design overcomes the challenges by having a self-cleaning process which will remove the suspended particle out of the filter compartment. The rainwater flow into the compartment from the inlet and perform cyclonic rotation. When the rainwater is approaching the cylindrical shape metal mesh filter, the centrifugal force will pull the water pass through the metal screen. The collected filtered water will be directed to the water tank storage, leaving the filtered particle falling through centre of the filter and are washed off by the overflow water [5]. However, it only work on high flow rate, else, the rainwater will not perform rotation and flow down the drain directly.

Fig 6. Wisy vortex filter by Rainharvesting Systems company from UK [5].

2.2 Gravity Downpipe Filter

The conventional method of installing the downpipe in any building is vertically from top to bottom. The rainwater catchment area is normally placed on the roof, which the collected rainwater will flow down in the pipe vertically at high speed. By utilising the gravitational force with the speed of rainwater flow, the rainwater can pass through the filter screen right below the inlet easily due to the extra downward force. Fig. 7 shows a filter product by Rainharvesting Company from Australia which utilises the gravitational force. The rainwater is directed from top of the filter and the cleaned water is directed to the water tank storage through the outlet at below. During this process, all the particles like leaves and debris are deflected by the filter screen and washed off out of the filter along the slanted filter screen. This design enhances the filtration efficiency as the particles are quickly removed without contaminate on the filter screen [6].

Fig 7. Leaf eater advanced filter by Rainharvesting company from Australia [6].

2.3 Justifications on Selecting the Suitable Filtration Features for the Prototype

Table 1 shows the specifications of different filter product in the market. By referring to Table 1, the general relationship between filter mesh sizes, filter rate and filtration method can be determined. First of all, product (1) using the largest mesh size among the other competitors. The filter has the horizontal filtration method design which only achieve a filter rate of 90 L/min. Secondly, a medium mesh size range from 0.8 – 0.955 mm is used for filter product (2) to (4) which utilise the gravitational force to speed up the rainwater along the downpipe. Even though a small mesh size is used, the filter manages to achieve a filter flow rate range from 113 – 120 L/min. The last group of products (5) to (7) have the feature of cyclonic rotation to filter the rainwater. It is found that they have the smallest mesh size among the competitors, however their filtration performances are better than both horizontal and gravity filtration method.

Table 1. Specifications of different filter product in the market.

Ref.	No.	Company (Country)	Metal Mesh Size	Roof Area	Rainwater Filter Rate	Filtration Method
[3]	(1)	3P Technik (Germany)	1.4 mm	350 m^2	90 L/min	Horizontal
[7]	(2)	SuperHead (Australia)	0.8mm	-	120 L/min	Gravity

[6]	(3)	RainHarvesting (Australia)	0.8 mm	-	113 L/min	Gravity
[8]	(4)	BRAE (US)	0.955	-	-	Gravity
[9]	(5)	Rainharvestmo (US)	0.28 mm	232 m^2	90% Recovery	Cyclonic Rotation
[5]	(6)	Rainharvesting (UK)	0.28 mm	200 m^2	66 L/min (not tested on maximum condition)	Cyclonic Rotation
[10]	(7)	Allegiance India (India)	0.25 mm	112 - 500 m^2	105-340 L/min (depends on the volume of collector)	Cyclonic Rotation

Based on real life application experiences, the space of the room that is prepared for the installation of rainwater system in the building and factory is very limited, especially the height of the room. During the installation, the height measured from ceiling to the ground is taken into consideration, conventionally 3.5 m per floor. The size of the water tank storage is normally installed with the largest size to store more filtered clean rainwater. Besides that, a stand is placed below the water tank storage for easier maintenance and cleaning purposes which result in a total of around 3 m in height. By taking into the consideration of the atmospheric pressure acting on water, the water tank storage inlet must be positioned as high as possible. Otherwise, the cleaned rainwater will not able to be pushed into water tank storage at higher level without the support from water pump if the inlet is positioned at lower level. Fig. 8 shows the schematic diagram of the installation of rainwater filtration system in a room for industrial scale usage.

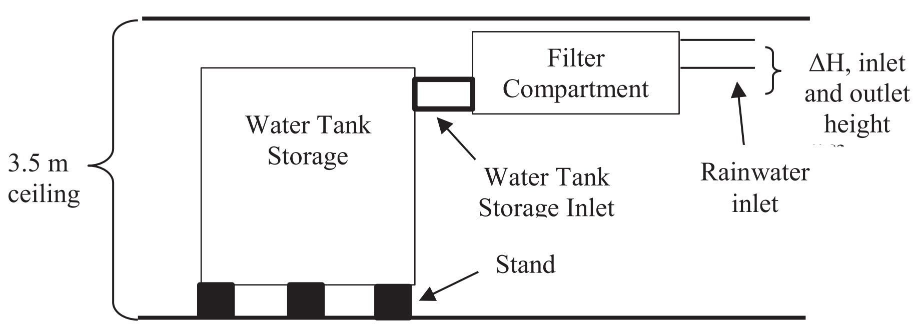


Fig. 8. Rainwater filtration system in a room for industrial scale usage.

Due to the space constraint of room, the overall height of the rainwater filter compartment must be maintained at smallest scale. Therefore, the height difference between rainwater inlet and water tank storage inlet, ΔH need to be taken into consideration at design stage. The compact sizing of the VF1 filter with dimension of 470 mm x 490 mm x 451 mm is very capable and has advantage during the installation in real life application.

The cyclonic rotation filtration method require a big and long in vertical dimension filter compartment to make it functional. Hence, it is more suitable for the installation area without space constraint. It is observed that the horizontal filtration method shows the least efficiency in filtering rainwater at high flow rate as discussed previously. However, by integrating the features from gravity downpipe filtration method may obtain significant improvement in filtration rate. Therefore, this feature is selected.

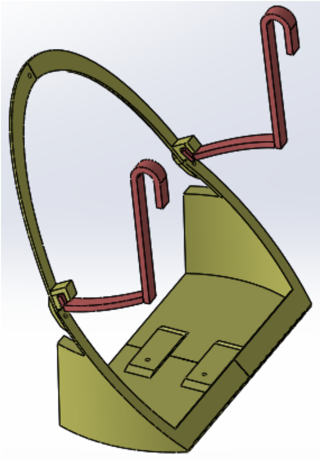
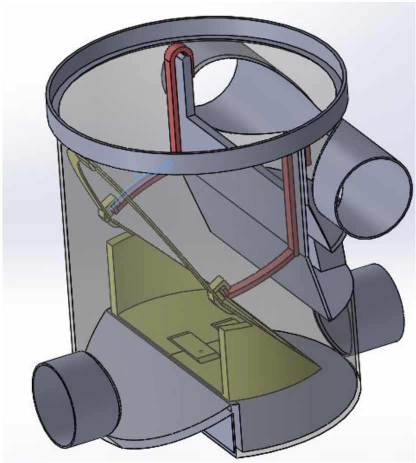
3. Development of New Filter Screen Design and Fabrication of Prototype

There were two preliminary designs for the filter screen before the final approved design was developed. To construct the new filter screen design to accurately fit into the filter compartment, the filter compartment VF1 was modelled into 3D geometry using SolidWorks (2015) as shown in Fig. 9. It had made the task easier to sketch and modify the new filter screen design within a round shape compartment with complicated structural design within it.

(a) (b)

Fig. 9. Existing filter compartment VF1: (a) Real life product; (b) 3D geometry model.

The new filter screen holder was designed to cover as much filtration area as it can within the limited space within the filter compartment. The model was then inserted into the original filter compartment VF1 to check any error in dimensions to achieve high fit and finish quality as shown in Fig. 10.

(a) (b)

Fig. 10. (a) 3D geometry model of new filter screen holder; (b) Filter screen holder inserted into original filter compartment VF1 model.

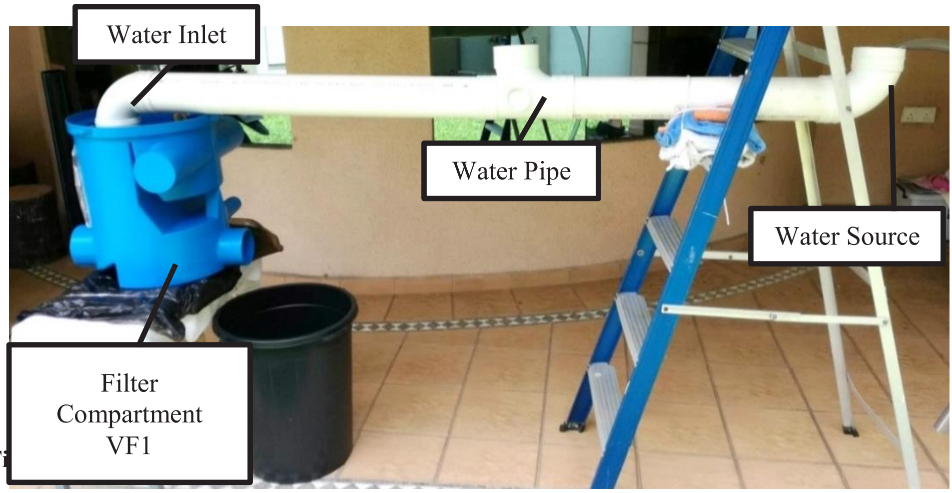
The approved 3D geometry model was then fabricated into full scale prototype using 3D printer with plastic PLA material. The filter screen holder was then attached a layer of 1000 μm stainless steel metal mesh, the same metal mesh size used for the original filter. The completed full scale prototype was fitted to the original filter compartment VF1 as shown in Fig. 11.


(a) (b)

Fig. 10. (a) Full scale new filter screen holder; (b) Filter screen holder inserted into original filter compartment VF1.

4. Experimental Testing of Filtration Rate for Original and New Design

The experimental equipment is set up as shown in Fig. 11. The setup is based on real life installation application where the water source is collected from the downpipe that linked to the roof. The horizontal water pipe will direct the water to the rainwater harvesting system room where the water flow into the filter compartment VF1 through the water inlet.



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Tap water is used for the testing of filtration rate because the lack of rainwater harvesting system in testing location. The water source is fed in through water tap and water pump to mimic the rainwater flow. Before starting the experiment, the water flow rate is measured. The filtration rate for the original filter system design is tested using the original method. Due to the horizontal positioned water piping that direct the rainwater flow, the positioning of water inlet is manipulated to test the differences in filtration rate as shown in Fig. 12. The step is taken to integrate the features of gravity downpipe filtration system onto the new filter system design. For the original filter system design, the 90˚ inlet will fill up the water at top section of the filter compartment and flow down to the filter screen. For the new filter system design, the 90˚ and 45˚ inlet allow the water to flow towards the filter screen directly.

(a) (b) (c)

Fig. 12. (a) Original filter system design with 90˚ inlet; (b) New filter system design with 90˚ inlet; (c) New filter system design with 45˚ inlet.

The filtration rate testing for both the original and new filter system design are carried out and the data are tabulated. Each round of testing is run for 15 seconds to collect the filtered clean water and 3 sets of data are recorded to obtain the average value. Low, medium and high flow rate for water inlet are used in testing. The low flow rate is obtained through normal water tap while medium and high flow rate are obtained by using a water pump with a reservoir.

Before starting the experiment, the water flow rate is measured. The low flow rate water is feed into the experimental equipment through the water source inlet and allow to run for 5 second to reach steady flow within the system. Next, an empty pail is used to collect the water from the water inlet for 15 seconds and then weighted on the scale. It is measured that the mass of empty pail is 1.5 kg, the total water mass flow rate at the inlet, $Q_{Total\ inlet}$ of the equipment can be obtain using the Eq. (2).

$$Q_{Total\ inlet} = \frac{m_T - m_{pail}}{t} \quad (2)$$

Where m_T is the total mass of the water with the pail and m_{pail} is the mass of the pail and t is the duration to collect the water, in this case t is 15 seconds. The density of water is 1000 kgm-3, therefore, 1 L/s mass flow rate of water at the inlet can be converted as 1 kg/s volume flow rate.

5. Results and Discussions

The original filter design was attached into the filter compartment VF1 for filtration testing. Table 2 shows the data of filtration rate testing for the original filter system design with the original filtration method which consists of low flow rate (0.203 L/s and 0.301 L/s), medium flow rate (1.134 L/s and 1.598 L/s) and high flow rate (2.167 L/s).

Table 2. Data of filtration rate testing for the original filter system design.

Inlet flow rate (L/s)	Total filtered water per second by original filter system design (L/s)				Filtration Efficiency
	1	2	3	Average	
0.203	0.137	0.122	0.130	0.130	0.639
0.301	0.187	0.198	0.191	0.192	0.638
1.134	0.705	0.689	0.711	0.702	0.619
1.598	0.949	0.956	0.962	0.956	0.598
2.167	1.208	1.197	1.205	1.203	0.555

Based on Table 2, it is observed that the filtration efficiency has significant difference with the official data by the company as shown in Fig. 4. At 0.2 L/s of inlet flow rate, the tested filtration efficiency is just 63.9% instead of nearly 100% from the official data. As the inlet flow rate increases, the filtration rate of the original filter system design continues to decrease and hence results in just 55.5% filtration efficiency at inlet flow rate of 2.167 L/s. Fig. 13 shows the graph of hydraulic efficiency against inlet flow rate for the original filter system design.

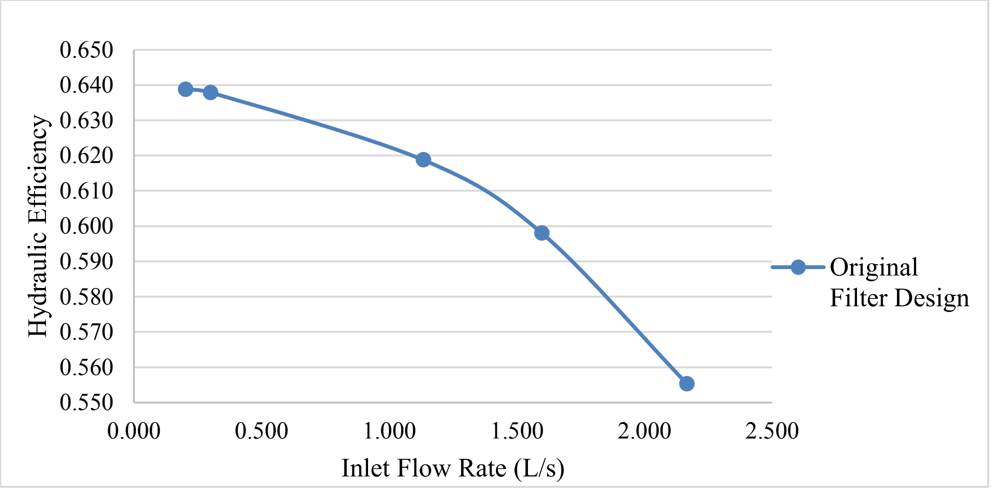

Fig. 13. Graph of hydraulic efficiency vs inlet flow rate.

By comparing Fig. 13 with Fig. 4, it is observed that the experimental data is nowhere near to the official data from the company. As a reference from both the graphs at inlet flow rate of 2 L/s, the tested hydraulic efficiency is just 56% while the official data shows an efficiency of 80%. Since the testing is done by the current equipment, the obtained experimental data is selected to be the reference for comparison with the new filter system design.

Throughout the filtration rate testing for the new filter system design, there is sign of water loss can be observed through overflow drain outlet of filter compartment. For the 45˚ inlet setup, the water is directly flowing towards the filter screen rather perpendicularly as shown in Fig. 14(a). This has caused some of the water being reflected away from the filter screen without being filtered and hence the loss of collectable water. As for the 90˚ inlet setup, due to the sudden change in direction of water flow, a portion of water do not flow downward vertically onto the filter screen as planned. Instead, the water is reflected by the wall of the 90˚ water pipe joint and flow towards the overflow drain outlet as shown in Fig. 14(b). The results of water loss from the 45˚ inlet setup is acceptable as it already meets the requirement of integrating the features from gravity downpipe filtration method. However, enhancement is needed to apply for the 90˚ inlet setup to determine the full potential of filtration rate. Therefore, a simple modification by adding a transparent plastic cover as extension around the 90˚ inlet joint to avoid the reflected water leaving the filter screen. Fig. 14 (c) shows the addition of transparent plastic cover extension around the 90˚ joint.

(a) (b) (c)

Fig. 14. (a) Water flow with 45˚ inlet; (b) Water flow with 90˚ inlet; (c) Addition of transparent plastic cover extension around the 90˚ joint

Table 3 shows the data of filtration rate testing for the new filter system design with integrated features of gravity downpipe filtration method. By referring to Table 3, there are no significant differences of filtration efficiency for 45˚ and 90˚ inlet setup between low and medium flow rate. The 45˚ inlet setup has slightly better filtration efficiency of 78.1% at high flow rate compare to 76% for the 90˚ inlet setup. Although there are water loss due to reflection at both inlet setup, there is still slightly advantage for the water to flow directly towards the filter screen with the 45˚ setup. The extra water flow speed act as external force to push more water pass through the filter screen while the 90˚ setup reduce the flow speed and reflect the water to opposite direction as the water hit the pipe wall. Hence, the 45˚ setup achieves better filtration rate by comparing to the 90˚ setup.

Table 3. Data of filtration rate testing for the new filter system design

Type of Inlet	**Inlet flow rate (L/s)**	**New Filter System Design**				**Filtration Efficiency**
		1	2	3	Average	
45˚	0.203	0.200	0.198	0.199	0.199	0.980
	0.301	0.296	0.297	0.299	0.297	0.988
	1.134	0.997	0.995	1.006	0.999	0.881
	1.598	1.359	1.367	1.364	1.363	0.853
	2.167	1.684	1.701	1.692	1.692	0.781
90˚	0.203	0.199	0.201	0.199	0.200	0.984
	0.301	0.297	0.299	0.296	0.297	0.988
	1.134	0.990	1.005	0.996	0.997	0.879
	1.598	1.368	1.357	1.362	1.362	0.853
	2.167	1.641	1.652	1.647	1.647	0.760
90˚ with Extension	0.203	0.198	0.199	0.200	0.199	0.980
	0.301	0.299	0.296	0.297	0.297	0.988
	1.134	1.071	1.076	1.079	1.075	0.948
	1.598	1.477	1.472	1.485	1.478	0.925

	2.167	1.984	1.975	1.970	1.976	0.912

For the 90˚ inlet setup with the transparent plastic cover extension, it is proven to be a good addition modification onto the filtration system based on Table 3. Water is now able to flow downwards vertically onto the filter screen with no wall reflection. The filtration efficiency is observed to maintain at higher value at medium to high flow rate. An overall increasing in filtration efficiency of 6.9% to 15.2% is achieved by comparing with the 90˚ inlet without the extension and 6.7% to 13.1% with the 45˚ inlet setup. Fig. 15 shows the graph of hydraulic efficiency against inlet flow rate for the new filter system design.

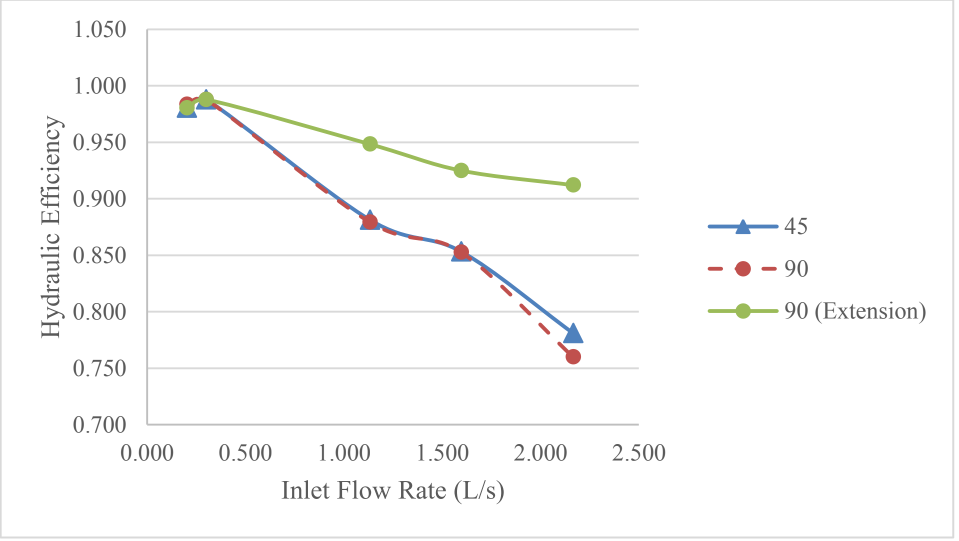

Fig. 15. Graph of hydraulic efficiency vs inlet flow rate with different inlet setup

Based on Fig. 15. It is observed that the 45˚ and 90˚ inlet setup has similar filtration efficiency at low to medium flow rate while 45˚ inlet setup has slightly better efficiency at high flow rate. The 90˚ inlet setup with extension has the highest efficiency among the three setups. By comparing the filtration efficiency with the original filter system design, all the new filter design manage to achieve higher filtration rate. The overall improved filtration performance achieved by the 90˚ inlet setup with extension from low to high flow rate is between 34.1to 35.7% compared to the original filter system design.

6. Conclusion

In conclusion, the objective to improve the pre-storage filtration efficiency of a rainwater harvesting system is achieved. Suitable filtration methods and modifications for the original filter system design to sustain high rainwater flow rate are proposed. The selections are justified with the researches done on the existing filter system in the market globally. The proposed prototype meets the requirements of fitting accurately inside the filter compartment VF1 and is operated mechanically.

Besides that, the rainwater filtration efficiency, in term of filtration rate difference between the original and prototype filter screen design is obtained throughout the testing. First, there is significant differences of filtration efficiency between the experimental and official data from the company for the original filter system design. As the testing is done by the current equipment, the obtained experimental data is selected to be the reference for comparison with the new filter system design.

Among the proposed water inlet setups for the new filter system design, the 90˚ inlet setup with extension provides the best filtration rate per unit time, following by the 45˚ inlet setup and the 90˚ inlet setup. The 45˚ and 90˚ inlet setup has similar filtration efficiency at low to medium flow rate while 45˚ inlet setup has slightly better efficiency at high flow rate. The filtration efficiency with the 90˚ inlet setup with extension is observed to maintain at highest value at medium to high flow rate. An increment in filtration efficiency of 6.9% to 15.2% is achieved by comparing with the 90˚ inlet without the extension and 6.7% to 13.1% with the 45˚ inlet setup. In comparison with the original filter system design, the overall improved filtration performance achieved by the 90˚ inlet setup with extension at low to high flow rate is between 34.1to 35.7%.

In this paper, the experimental results only cover one high flow rate of 2.167 L/s at the water inlet. The water pump that is used to represent the real life rainwater harvesting operation has reached it maximum output in the experiment equipment setup. Therefore, a water pump with higher water pumping rate can be used in future to further test the peak filtration rate of original and new filter system design. Moreover, more layers of filter screen with 1000 μm stainless steel metal mesh can be attached onto the new filter design to test on the filtration rate as future works. The smaller pore size of the filter screen will provide better filtration quality. The relationship between filtration efficiency against reduced pore size of filter screen can be determined.

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