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The Analysis of Fluid Flow on Different Kapok Filter Orientations using Computer Fluid Dynamics

Ab Aziz bin Mohd Yusof[1], Norhafini Hambali[2], Mohammad bin Abdullah[2], Nur Darina bte Ismail[3], Azizul Hakim bin Samsudin[1*]
[1]School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, Johor Branch, Pasir Gudang Campus, Malaysia
[2]School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA, Johor Branch, Pasir Gudang Campus, Malaysia
[3]Nexsol (Malaysia) Sdn Bhd PLO61, Jalan Tengar, Kawasan Perindustrian Tanjung Langsat, Pasir Gudang, Johor
[*]corresponding author: azizulhakim@uitm.edu.my

ABSTRACT

Kapok fibres, known for their hydrophobic (water-repellent) and oleophilic (oil-attracting) properties, could be used as a filtration medium. In the context of oily water filtration, kapok fibres might naturally attract and capture oil droplets from the water while allowing water to pass through. However, the effectiveness of the filtering process depends on the filter orientation, which affects the fluid flow, either turbulent or laminar. Thus, the study investigated the effect of filter orientation housing during installation on the fluid flow around the kapok filter. The study used Computational fluid dynamic analysis, CFD, for two different kapok filter orientations, parallel and perpendicular to the water flow. It found that the kapok filter oriented perpendicular generates turbulence on the surrounding flow and hydraulic jump as compared to parallel orientation. A higher risk of clogging could happen due to debris accumulation and reduced filtering process.

Keywords: Kapok; filter; pressure drop; flow condition; water surface and wave.

Nomenclature (Greek symbols towards the end)

A_s	surface area of the TEG (m^2)
D_h	nozzle hub diameter (mm)
R_L	external circuit resistance (Ω)
R_{TEG}	internal thermal resistance of the TEG (Ω)
α	Seebeck coefficient (0.0438 V/K)
Θ_m	vane angle (°)
ΔT_{TEG}	temperature difference of the TEG surfaces (°C)

Abbreviations

CHP	combined heat and power
MPP	maximum power point (W)

1.0 INTRODUCTION

The major environmental problem that threatens the marine ecosystem is caused by oil spillages and the discharge of various oily wastewater (water pollution). This is due to the expansion of oil exploration and the high usage of oil in various sectors, including petrochemical, heavy metal, food processing, paint, and automotive [1]. Oily wastewater is characterised by the presence of fats, oils, greases, and dissolved organic and inorganic components in suspension [2]. This effluent, tainted with oil, harms human health because it can cause mutations and cancer, and stunt plant growth. Suppose that such an oily water stream is disposed of into water bodies without any suitable treatment. In that case, it raises the BOD and COD levels and creates a barrier to sunlight at the top of the stream, which restricts the entrance of sunlight and leads to the disturbance of aquatic ecosystems [1].

This water pollution might harm human health if the toxic compounds in oil enter the food chain. Furthermore, any oil spillage or inefficient extraction implies environmental issues and economic loss [3]. It is imperative to perform better oily wastewater treatment before discharging wastewater into water streams to improve the overall quality of the wastewater and ensure that it satisfies the requirements of wastewater discharge [4]. Several conventional and proven methods, including biological, physicochemical, and chemical approaches, are utilised to clean up oily wastewater. Among these are gravity-based separation methods like flotation and filtration, filtration-based separation methods and biological process remediation [5]. Using the difference in density between oil and water, the gravity separation method is the most fundamental way of treating oily wastewater. This process is carried out by using the difference in density between oil and water. The effect of separating the oil and water is improved when the two substances have a more significant density difference. Gravity separation equipment may have a straightforward design. However, it has several drawbacks, including a large surface area,

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a low capacity for separation, complicated operation and maintenance, and an ineffective treatment effect for emulsified oil [6].

On the other hand, oily wastewater can also be treated by using a filtration process where oil can travel through a layer of porous media, simultaneously eliminating the water and collecting oil droplets and other particles found in the sewage. The research and development of filtration separation materials have been the primary focus of recent reports on the filtration separation of oily wastewater. These materials include polymer mesh, porous hydrogel, aerogel, cotton fabrics, membranes, and so on [7-11]. However, in comparison to natural sorbents, synthetic filtration materials have certain drawbacks, such as the fact that they are not biodegradable. As a result, when these materials are removed after use, they cause environmental problems [12]. Natural sorbents are rich, they are suitable for the environment, and they are inexpensive. In light of this, the researchers have started to develop oil-sorbent materials made from natural fibres.

Therefore, an environmentally friendly natural material using kapok fibres to extract oil from water was introduced [13, 14]. Kapok filtering involves using kapok fibres as the main medium, which could be considered environmentally friendly as kapok is a natural and biodegradable material. The fibre is hydrophobic, which tends to repel water and oleophilic, that are attached to the oil content in the water. The oleophilic property of kapok fibres makes them valuable when it is necessary to separate or remove oil from water, especially in situations like oil spills or industrial processes involving oily water [15]. Kapok is often available in loose form. Kapok fibres are naturally found within the seed pods of the kapok tree (Ceiba pentandra). These fibres are soft, fluffy, and buoyant due to their hollow structure.

The performance and filtering mechanism of the kapok to separate oil was explored by Huang, X., and Lim, T. T. (2006) [16]. The study found that kapok fibre's hydrophobic-oleophilic nature allows effective filtration of oil/water mixtures, achieving 100% removal of diesel and over 99.4% of hydraulic oil. The optimal packing density for removal is 0.07 g/cm3, influenced by oil type and concentration. In addition, T. Dong et al. mentioned kapok fibres' capability to absorb different types of oils (diesel, used motor oil, motor oil, and vegetable oil), where vegetable oil has the highest absorbance percentage [13]. The study also found that kapok fibres have better adhesive energy to retain the absorbed oil than polyester fibres. Using kapok as oil sorbents is enhanced by combining the kapok with polypropylene fibres to produce nonwovens. Compared to loose fibre assemblies, the regulated pore size and distribution of these nonwovens enable them to achieve a higher level of oil sorption. The cotton fibre-based nonwoven was found to absorb 26 g of oil/g of fibre while also having a very low water sorption capacity of approximately 1.67 g/g. Furthermore, the nonwoven did not demonstrate any signs of chemical degradation or microbiological attack even after being exposed to the oily wastewater for ten days [17].

The loose kapok fibres create a comfortable and supportive filling that can conform to the user's shape. Due to its form, the kapok must be placed inside the filter housing to ensure it can function correctly. The filter housing plays a critical role in maintaining the effectiveness and integrity of a filtration system [18]. However, the effectiveness of the design and orientation of the filter in the water is still questionable. There is still a lack of knowledge and study on the design and orientation of the filter [19, 20]. C.-G. Liang et al. [21] did mention that the flow distribution does affect the filtering efficiency since it might influence the trajectories of particle motions and collisions. Therefore, this study aims to analyse the effect of fluid flow on two (2) different orientations (perpendicular and parallel) of the kapok filter housing using computational fluid dynamics, CFD. Based on the result, the fluid flow around the filter based on the housing orientation could be identified and used to further the development of the kapok filter. Every relevant factor, such as laminar or turbulent flow, pressure drop, the influence of a free surface, and the possibility of a clog or disruption in the filter material, is considered.

2.0 METHODOLOGY

2.1 Computational fluid dynamic

The flow analysis used Solidworks software (Dassault Systèmes, USA). Setting up a Computational Fluid Dynamics simulation using SolidWorks Flow Simulation involves several steps after modelling the filter. The steps involved are shown in Figure 1. The first step is assigning appropriate material properties to the fluid domain, such as fluid type, density, and viscosity (Table 1). The condition of the two (2) orientations of perpendicular and parallel is assigned at the processor section (Figure 3).

The kapok filter geometry is shown in Figure 2. The filter size is based on the fabricated filter mentioned in section 2.2 (5 feet long and 50mm in diameter). The middle section is designed with simplified mesh netting to represent the filtering part, and both ends are designed as solid cylinders. This study focused on the flow of water that passes through the kapok filter based on the two (2) different orientations. The CFD analysis focused on the mesh netting part (Figure2: Detail A), where the kapok is placed in the filter.

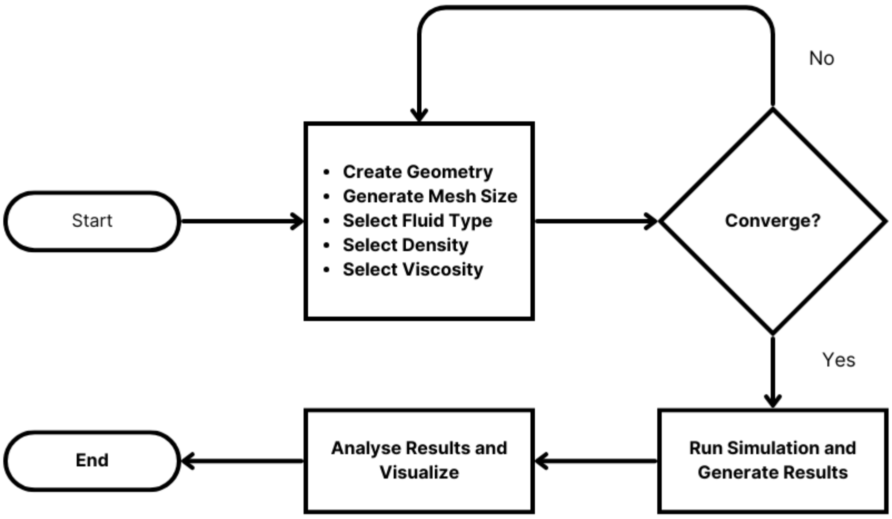

Figure 1. CFD simulation flowchart

This study focused on the fluid flow around the kapok filer, where the housing is the primary component that affects the flow before the water interacts with the kapok to catch the oil. Some simplifications were applied to the CFD model (Figure 2) to ensure the model represents the real Kapok filter and agrees with the study's interest. The first simplification was that the middle part of the kapok insertion was simplified as the solid cylinder. The second simplification was on the net design, and the side cylinder was combined as one part. Besides that, the CFD study focused on one filter to compare both parallel and perpendicular filter orientation.

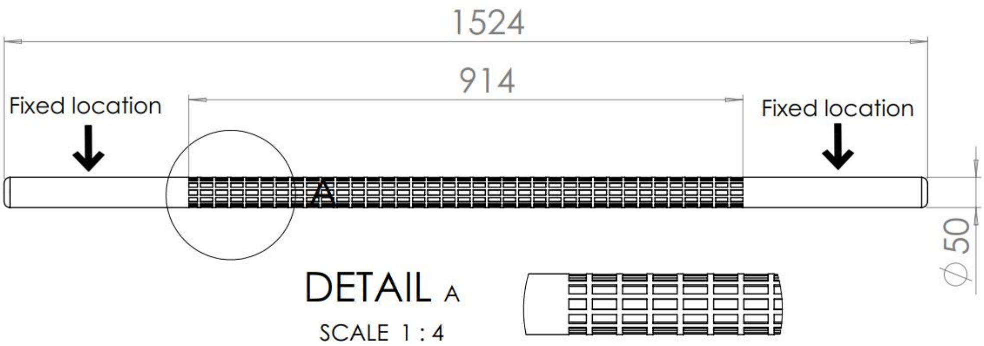

Figure 2. Model of the Kapok filter used in the CFD simulation (All units in mm)

Both types of turbulence and laminar were included in the study to determine the style of the flow that dominates the filter. The flow conditions around a filter play a significant role in determining the capability of filter's process, pressure drop, and overall performance. As fluid enters the filter, its velocity and direction are critical. How fluid approaches the filter impacts the distribution of oil and water across the filter surface. Inlet and outlet side of the filter, smooth, uniform inlet flow helps ensure that particles are evenly distributed over the filter medium. The flow conditions as fluid exits the filter also impact the overall system. Smooth exit flow helps prevent disturbances that could lead to downstream turbulence or re-entrainment of captured particles. To represent the on-site flow condition, 5m/s flow was set to flow from the inlet to the outlet, where it was set at 0 Pascal of static pressure.

Filter orientation was set in two conditions, as in Figure 3. The first condition is where the water flows parallel to the filter toward the outlet. The second condition is where the water flows perpendicular to the filter toward the outlet. The studies were run spreadly to compare the dominant flow type around the filter. The water surface was set just above the filter. Specifically, as the water depth was close to the filter diameter, the water surface was considered in the analysis. Air and water were assigned to the study using a multiphase fraction of air and water. The distribution of air and water was set up using the fluid F(y) depth. The size of the fluid domain was 1800mm in length, 1800mm in width and 400mm in height. The size was selected based on the on-site drain size where the kapok filter was installed (Figure 5) and simultaneously to ensure both filter orientations fit. Since multiphase was included in the study, 200mm water height was set initially from the bottom of the fluid domain, where the other half of the domain was set for the air.

Physical time in Table 1 refers to the actual time corresponding to the behaviour of the simulated fluid or fluid-related phenomena. 1 s was selected as the flow reached a constant, unchanging state where the flow behaviour has stabilised. It was reconfirmed with convergence error, where the iterative solvers used to solve linear systems of equations reach a sufficiently accurate solution within the set time.

Figure 4 shows the mesh sensitivity study of the kapok filter based on the pressure generated. The CFD model was varied for five mesh numbers up to 2 million. Based on Figure 4, as the number of mesh increased from 72000 to 176386, the pressure increased about 2%. Further increase in the mesh number causes a reduction in pressure generated by about 0.67%, representing "mesh independence" or "convergence" of consistent results. Considering the design complexity of the filter mesh and computational power to solve the calculation, the model mesh was meshed with 1117210 of the parallel orientation and 1247382 of the perpendicular orientation.

Table 1 shows the CFD setting for both filter orientation analyses. Generally, the important setup is maintained to produce consistency in the final result except for inlet and outlet locations.

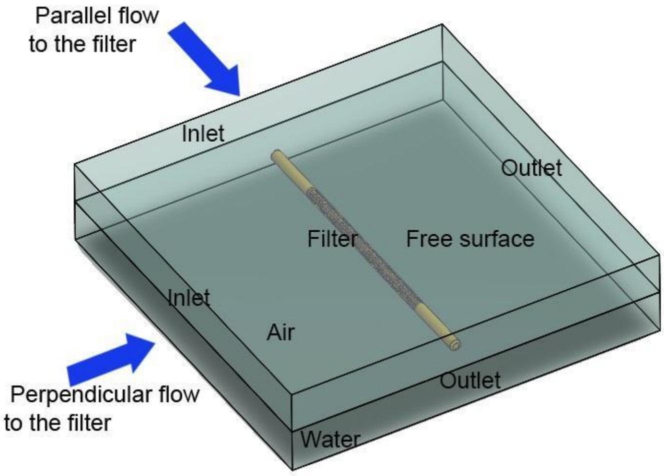

Figure 3. CFD model and setup

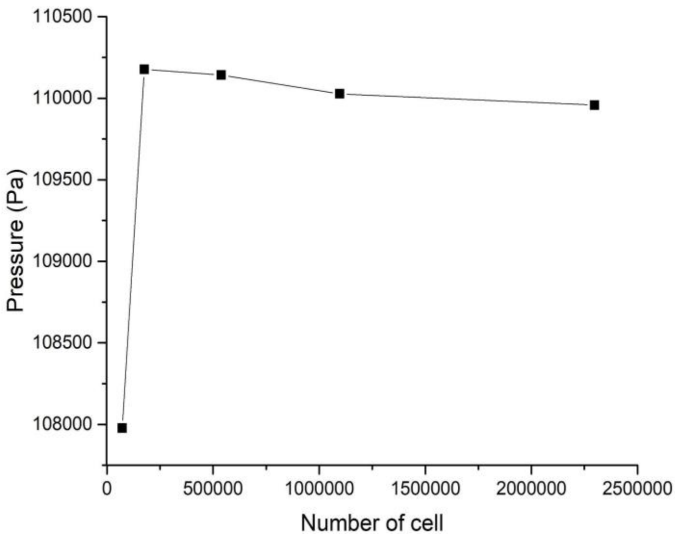

Figure 4. A numerical investigation of mesh sensitivity for the generated pressure on the filter housing

Table 1. Computational fluid dynamic setup

CFD Setup	Parallel orientation	Perpendicular orientation
The velocity of water inlet (m/s)	5 m/s	5 m/s
Out	0 Pascal	0 Pascal
The water surface on the y coordinate	0 m	0 m
Flow type	Turbulence	Turbulence
Fluid 1	Air	Air
Fluid 2	Water	Water
Total cell	1,117,210	1,247,382
Fluid cell contacting solids	56,134	53,712
Transient solver	Time-dependent	Time-dependent
Time step size	$1x10^{-3}$ s	$1x10^{-3}$ s
Convergence criteria for residual	$1x10^{-4}$	$1x10^{-4}$
Physical time	1s	1s
Running core	16 cores	16 cores
Inlet axis direction	X-axis	Z-axis
Outlet axis direction	X-axis	Z-axis

The simulation study was set as turbulent flow to capture the chaotic and irregular motion of the fluid flow around the filter. In this study, flow simulation for transport equations of the turbulent kinetic energy and its dissipation rate were applied using the k-epsilon (k-ε) model, and the study was handled similarly to flow around the obstacles.

The flow condition was determined initially before the analysis based on the following turbulence formula. The Reynolds number provides a preliminary overview of the study.

$$Reynold\ number = \frac{\rho VD}{\mu} \quad (1)$$

where:

V is the flow velocity (5m/s on a rainy day or higher volume discharge)
D is the characteristic length (0.05m diameter of the kapok filter as in Figure 2)
ρ fluid density (1000 kg/m^3)
µ dynamic viscosity (0.001 Pa·s)

The Reynolds number presents the flow condition over the kapok filter. The boundary layer grows in the flow direction across the filter based on its orientation since the drain where the kapok filter was placed is managed as a channel with a free surface, characteristic length, D. For a cylindrical kapok filter, the diameter of the cylinder can be used as the characteristic length (D).

The Reynolds number value based on the formula and the given value are as follows:

= (1000 kg/m³ * 5 m/s * 0.05 m) / 0.001 Pa·s
= 250000 (For turbulent flow: Re > 4,000-5,000)

So, the Reynolds number for water flowing with a velocity of 5 m/s over a characteristic length of 0.05 m is approximately 250000. This value indicates that the flow is likely to be turbulent, as Reynolds numbers in this range typically correspond to turbulent flow conditions.

From on-site data collection, the flow of the water was 5m/s, but since in the drain, there was a filter that acted as an obstacle that could disrupt the smoothness of the water and magnify the transition from laminar to turbulent flow. However, it might exhibit different characteristics than pure turbulence at higher Reynolds numbers. The disturbances or irregularities in the flow worsen, as they can create more vortices and eddies around the filter.

2.2 On-field filter orientation for installation

The filters were installed on the industrial water drain to filter the excess oily water. Figure 5 shows the installation orientation used on-field. Both filter orientations were used on the interested site; however, the effect on the surrounding fluid flow and related hydrodynamic effect are not yet fully explored. Figure 5 (a) shows the filter orientation suitable for fast-flowing water. Filters were arranged parallel to the flow direction and expected to trap oil based on the longer interaction between water and filter. Figure 5 (b) is then used for steady water flow. The filter acted as a barrier to force the water to pass through and filter the water. Both orientations required the filter installed in the drain close to the floor. This ensures that oil mixes with the water attached to the kapok properly. The depth of the water level in the drain is 100mm, double the filter height. Thus, the kapok filter is expected to be submerged in the drain. The red colour shape in Figure 5 shows the actual location of the fixed location of the filter on actual site.

The filter size was 1524 mm (5 feet) long, following the drain size. The filter diameter was 50mm, and the main part of the filtration was 914 mm (3 feet). The measure was selected to ensure the fabricated filler was strong enough to stand extreme water flow. The speed of water in a drain on an average day can vary widely based on factors such as the size of the drain, the amount of water flowing through it, and the specific drainage system design. As a rough estimate, for a small to medium-sized drain in the industrial area during calm weather conditions, the water speed might range from 0.1 to 0.5 m/s and, on a rainy day, could go up to 8m/s.

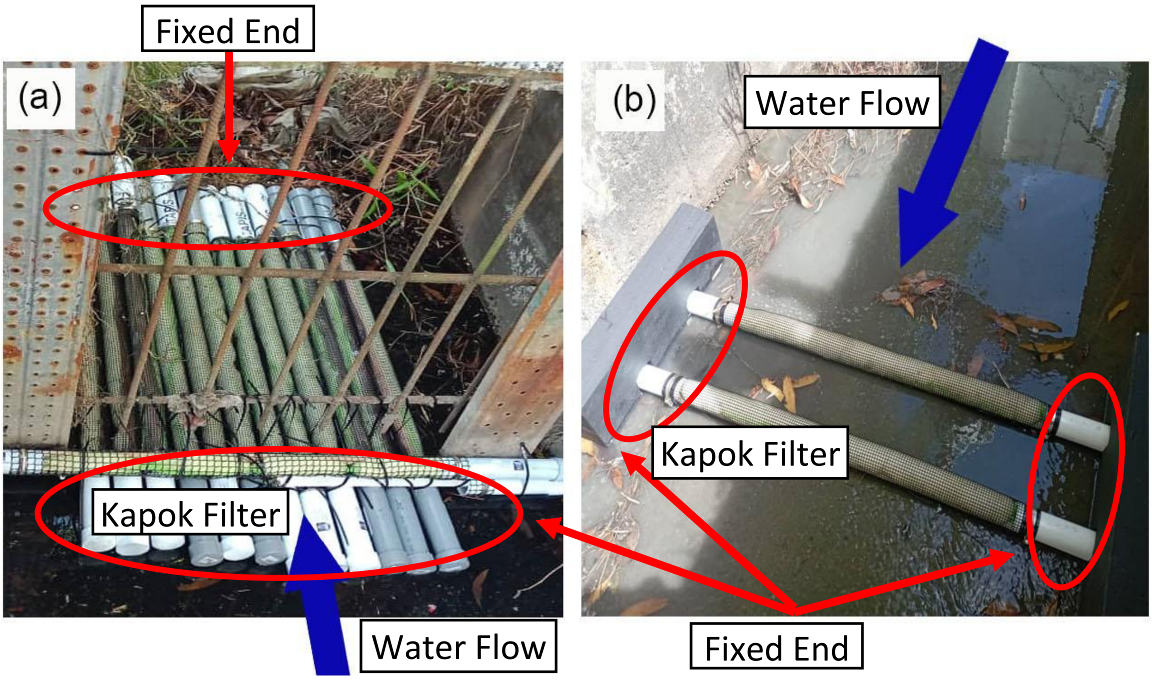

Figure 5. (a) Kapok filter arranged in the parallel orientation (b) Kapok filter arranged in the perpendicular orientation

3.0 RESULTS AND DISCUSSION

3.1 Flow condition

Figures 6 and 7 show the flow condition of both parallel and perpendicular orientations, respectively. For the parallel filter orientation (Figure 6), laminar flow was shown as fluid flow from the front to the end of the filter. It is a smooth and orderly movement of water in which layers of the fluid slide past each other without significant mixing or turbulence. Meanwhile, perpendicular filter orientation is observed to cause the flow of the water to become turbulent, which refers to the chaotic and irregular movement of fluid particles passing the kapok filter (Figure 7). This happens as the filter acts as an obstacle to capturing the oil. When it comes to filtration processes, turbulence can negatively impact the filtering capability by stirring up particles that have settled in the fluid. The resuspended particles can clog or disrupt the filter media, decreasing its effectiveness and potentially leading to a shorter lifespan for the filter. Besides, turbulence also causes uneven distribution of particles within the fluid. This might lead to concentrated areas of particles hitting the filter media, causing local clogging and reducing overall filtration capability.

When flow separates as water passes the filter, it can become unstable and exhibit turbulent behaviour, especially if the separation region becomes oscillatory or undergoes secondary flow instabilities. This phenomenon is captured in Figure 6. The turbulence at low Reynolds numbers might not resemble the chaotic, high-energy turbulence observed at higher Reynolds numbers. However, it can still significantly impact the flow behaviour and the distribution which could affect the filter process.

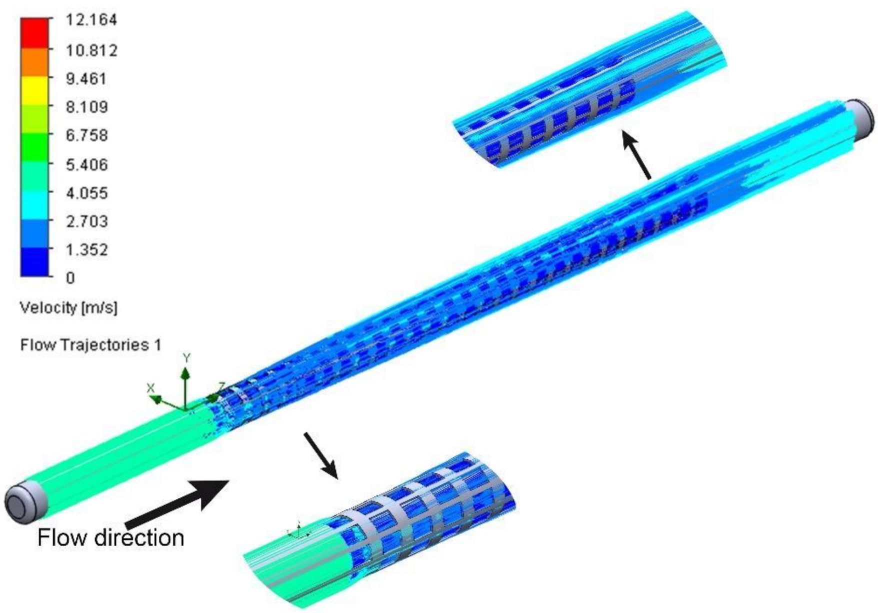

Figure 6. Flow trajectory of the parallel orientation filter

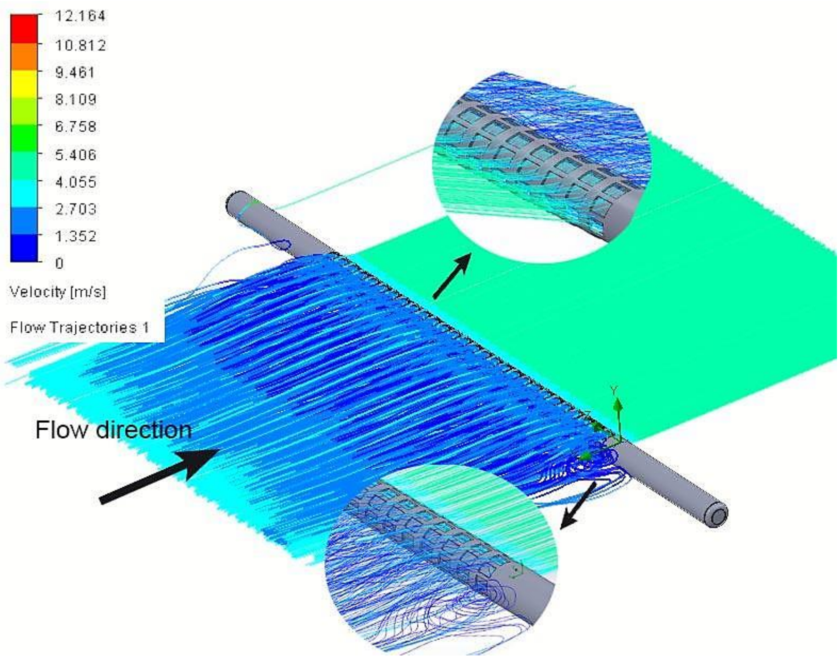

Figure 7. Flow trajectory of the perpendicular orientation filter

3.2 Pressure drop

Figure 8 and Figure 9 show the results of the pressure distribution of the parallel and perpendicular orientations of the filter on water, respectively. Meanwhile, Figure 10 compares the two (2) different orientations (parallel and perpendicular) of the filter on water. The pressure drops for both filters occurred at the total pressure difference between two points in a fluid-carrying network. When liquid material inflows one end of the piping system and leaves the other, a pressure drop or loss of pressure occurs.

For a perpendicular filter shown in Figure 9, the pressure drop is relatively low due to the liquid passing through it at a close distance. Compared to a parallel orientation shown in Figure 8, the pressure drop is expected to be relatively high since the liquid passing through the filter is longer. A pressure drop arises once frictional forces produced by resistance to flow act on the fluid as it flows through the filter channel. In this study, the frictional force produced by the resistance to flow is low for perpendicular orientation compared to the parallel orientation filter on water.

The difference in pressure drop between the parallel and perpendicular orientations is important in this study. Figure 10 shows that the pressure drop for perpendicular orientation results in a higher pressure drop than the parallel orientation. The parallel flow of water towards the filter observed a minimal trend of water disruption, hence decreasing the pressure drop experienced on the filter. It is interesting to note that the parallel orientation of the filter is inferred to be lower in pressure drop. However, parallel orientation also resulted in lower filter capability than perpendicular orientation. Although the perpendicular orientation indicates a higher pressure drop than the parallel orientation, it does provide a significantly higher filter effectiveness at the cost of the highest pressure drop.

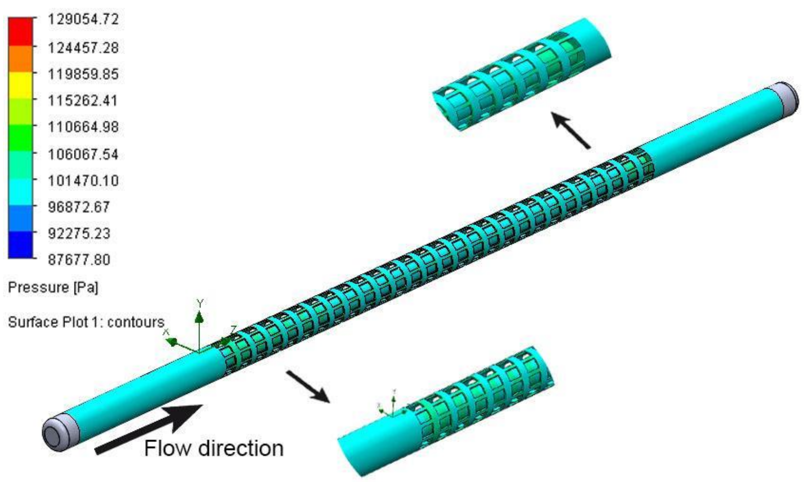

Figure 8. Pressure distribution of the parallel orientation of the filter on the water

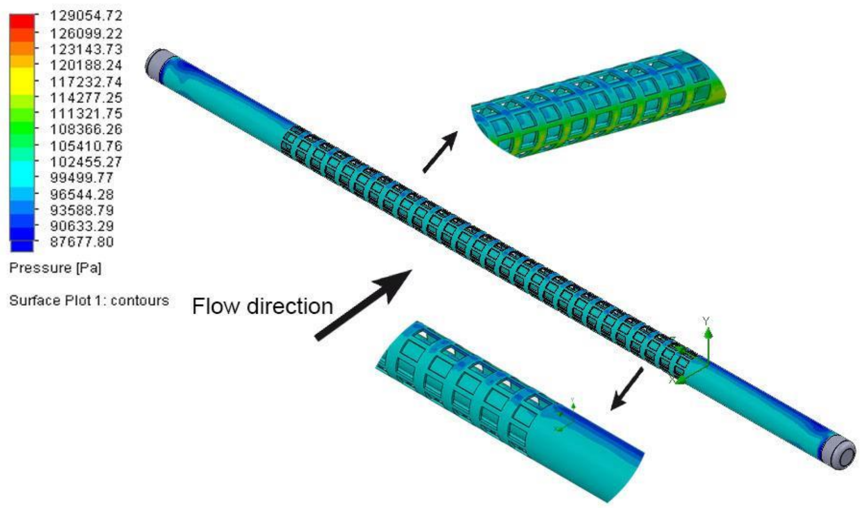

Figure 9. Pressure distribution of the perpendicular orientation of the filter on the water

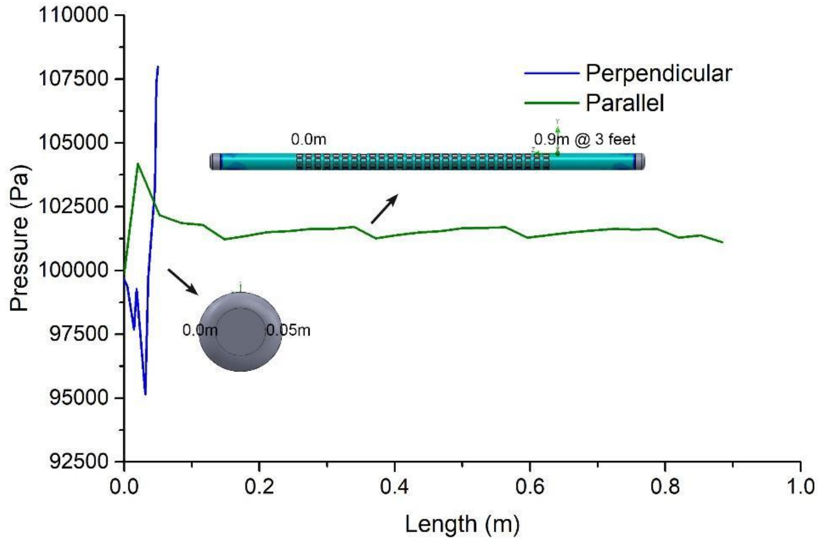

Figure 10. Pressure distribution across the filter for both parallel and perpendicular orientation

Nonetheless, the turbulence can negatively impact the filter's process by stirring up particles that have settled in the fluid. Therefore, achieving the highest filter effectiveness at the lowest possible pressure drop might be possible by optimising the distribution of the water that flows towards the filter. From the above discussion, it can be concluded that the perpendicular orientation of the filter depicted a higher pressure drop due to its orientation as altering the fluid flow, and parallel orientation is observed to have a lower pressure drop due to the lower filter as fluid passed by its length and interacted differently compared to perpendicular orientation.

3.3 Water surface and wave

Computational fluid dynamic analysis for the kapok filter involves two fluid properties as it is placed close to the surface. Due to this aspect, free surfaces need to be included in the study. Figure 11 shows the free surface condition as it passed the filter. Figure 11 (a) shows calm water surface conditions as water flows parallel to the filter from end to end, reflecting its laminar flow type as discussed in the previous section. Meanwhile, Figure 11 (b) shows the presence of the wave before the filter and hydraulic jump phenomena as water passed the filter, demonstrating the complex interaction between fluid dynamics and turbulence in open-channel flows. In the perpendicular, incoming water was blocked by the filter and caused the water level to increase at a certain height before passing the filter. Even though the water was entering the filter, most of the flow to the upper and lower side as the filter introduced a specific resistance for water to flow.

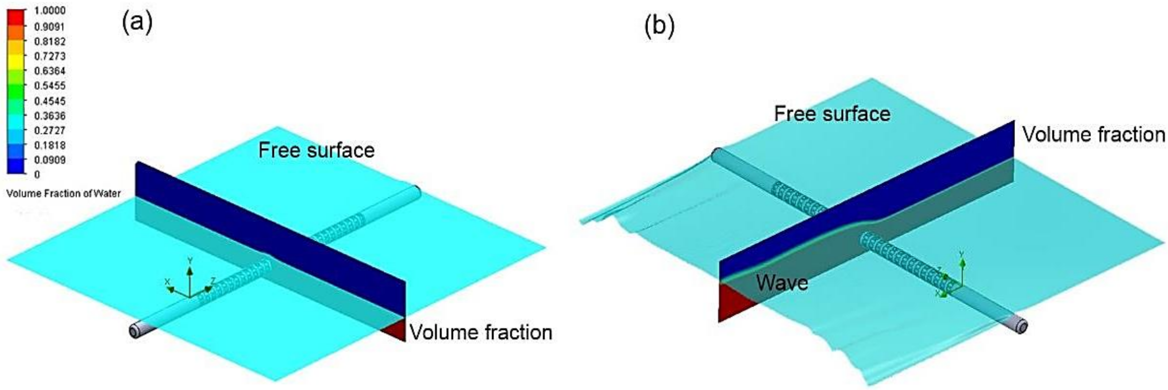

Figure 11. Free surface and wave formation around the filter (a) Free surface condition of the parallel filter orientation (b) Free surface condition of the perpendicular filter orientation.

A hydraulic jump occurs when a high-velocity flow of water abruptly slows down since the filer is oriented perpendicular. This leads to a sudden increase in water depth, turbulence, and energy dissipation. This phenomenon is commonly observed in open-channel flows, such as drains where water flows in a channel with a free surface. It affects the back side of the filter as the abrupt reduction in velocity leads to waves and turbulence within the flow. These waves are typically visible as a distinct white water region, and the surface becomes uneven and changing. Placing a filter perpendicular to the flow as an obstacle can affect a hydraulic fluid flow. There is the risk of clogging due to debris accumulation. Clogging can further alter the flow dynamics and reduce the effectiveness of the filter system. Regular maintenance is required to prevent this issue.

4.0 CONCLUSION

In conclusion, the position of parallel and perpendicular orientations does affect the fluid flow around the kapok filter on water. The turbulence water caused by the orientations might reduce the capability of the kapok filter to filter the water. The filter's orientation during installation and its impact on the filtering process is a relevant study area that can be explored. Understanding the filter's positioning concerning the fluid flow of water around the filter will affect its performance, which could contribute to optimising the filtration process for various applications.

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