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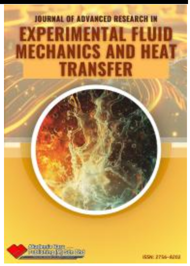

Vortex Control at Pump Intake Using Double- and Triple-Plate Floor Splitters

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ABSTRACT

Vortices are one of the main contributors to efficiency loss and damage issues in centrifugal pump components, particularly those aligned with the axis that facilitates water transfer from the reservoir. This problematic scenario arises due to a non-optimal pump reservoir design and irregular water flow entering the reservoir. The unsteady flow disrupts the pump's functionality, leading to inefficiency and potential damage over time. However, this issue can be mitigated by installing anti-vortex devices (AVD) around the pump reservoir. The ANSI/HI 9.8 2018 standard outlines various AVD designs, specifying that the swirl angle in the flow should not exceed 5° to ensure efficient operation. Here, we use customised double- and triple-plate floor splitters (DPFS and TPFS). A floor-type flow separator plate is an effective measure to reduce swirls and vortices in the pump intake flow. Vortex intensity was measured using a swirl meter, and it was found that installing a plate in a single-pump system could reduce swirl angle by approximately 60%. The approach used involved visualizing flow structures with a particle image velocimetry (PIV) device to obtain data on vortex intensity before and after the plate installation. In an effort to improve AVD design, six plate samples with different dimensions were tested. This study also examined the effects of adding plates to the AVD design to optimise flow separator design in various pump reservoir geometries. We found that the DPFS 260 mm (25 mm) setup effectively minimised vortex formation with a high reduction in vorticity. The results of this experiment can provide guidance for reducing vortex problems in pump reservoirs, which in turn can save time and cost in pump system planning and management.

1. Introduction

Pumping system contributes to nearly 22% of the energy supplied by electric motors in the world [1] and therefore optimisation of its energy efficiency may result in significant improvements in the energy sector. The world's energy utilization is reflected in one of the climate change objectives in

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which the global annual energy intensity is set to decline by 2.6% annually between 2016 and 2030 [2]. Access to clean water is vital for human survival, recognised by the UN as a human right and a key Sustainable Development Goal (SDG). Despite available freshwater, 1.1 billion people lack sufficient clean water, and this may rise to 3 billion by 2025. SDG 6 focuses on improving water management and sanitation through increased infrastructure investment to ensure clean water (6.1) and sanitation (6.2) access [3]. The formation of swirls and vortices near the pump inlet in a pump intake sump is a phenomenon that have to be avoided as it is known to be the cause of reduction in pump efficiency and damage to pump components. The best way to prevent such problems is by constructing an optimal intake sump design which is outlined in standards such as ANSI/HI 9.8 [4] and BSI 13930 [5].

In the face of rapid globalisation, many people move to industrial and urban areas for better jobs and quality of life. However, rapid urban growth can cause land loss and flash floods, stressing drainage systems vital for protecting communities from health risks and flooding [6]. According to Norizan *et al.,* [7] uneven approach flow in suction inlets leads to hydraulic issues such as cavitation, impeller imbalance, excessive vibrations, and reduced pump efficiency. Achieving optimal pump reservoir design can be challenging due to space constraints and continuous modifications at pump stations, especially in rural areas where relocating infrastructure is costly [8]. Batcha *et al.,* [9] noted that monsoon seasons often cause severe flooding in low-lying areas. To mitigate this, pump stations divert excess water to designated flood retention areas. Hydraulic issues like cavitation, vibrations, and loss of suction momentum may arise during flood management, affecting pump efficiency. Furthermore, it is not always possible to apply the design in real situations as there are on-site restrictions which hinder the process such as limited space for construction [10,11] low channel depth [12] and retrofitting requirements. Study on the formation of vortices in pump intake flow and methods to eliminate vortices and reduce swirls has been continuously studied due to its influence on pump efficiency. Guo and Young-Do [13] performed a numerical simulation to study the influence of water level and flow rate of the pump towards the formation of vortices.

Guo *et al.,* [14] performed a three-dimensional simulation of air entrainment in a pump sump which caused by a free surface vortex. The process of air entrainment was successfully simulated and the installation of a circular plate at a designated position was proposed to eliminate the entrained air. The effects of pump submergence and flow rate on the formation of free surface vortices was studied by Shin [15] using a numerical simulation model in which it was concluded that lower submergences or larger flow rates contribute to stronger free surface vortices. In the case where modification on the sump structure is not possible, localised flow correction devices can be installed. Among the proposed flow correction devices to eliminate vortices in pump intakes efficiently were cross-shaped anti vortex device [11], serrated vortex elimination cone [16] and floor splitter with trapezoidal shaped cross section [17,18]. However, the optimal design of anti-vortex device is still to be discovered as proposed by Tsou *et al.,* [19] and Kang *et al.,* [17] because an efficient pump intake design must not only be free from air-entraining vortices but also allow only swirls at acceptable values as proposed in the design guidelines for pump intake design [4].

This study aims to analyse vortex patterns along the water flow path in the pump reservoir using particle image velocimetry (PIV) under two conditions: without an anti-vortex device (AVD) and with an AVD installed, to gain insight into vortex formation. Additionally, it seeks to evaluate the impact of flow direction changes on swirl angle in the pump intake, both with and without the implementation of AVDs, to assess their effectiveness in reducing swirl angles. Furthermore, the study aims to assess the effect of design modifications and the addition of anti-vortex plates on reducing swirl angles within the pump reservoir.

2. Methodology
2.1 Experimental Setting

The experiment was conducted at the Coastal and Water Resources Engineering Laboratory, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, to evaluate the effectiveness of the AVDs in reducing vortices at the pump intake area. The submergence depth of the intake pipe is a key factor influencing the type of vortex that may develop in the sump. In this study, the submergence was set to prevent surface vortex formation, limiting the occurrence to potential sub-surface vortices only. The pump flow rate was determined using the principle of similitude, scaled from the prototype pump to the model used in this experiment, and was set at 0.0094 m^3/s, with the flow velocity in the sump measured at 1 m/s. There is a requirement of inlet submergence S_{min}, which is to prevent the formation of free surface vortices. S_{min} has been calculated by the following equation:

$$S_{min} = D(1.0 + 2.3F_{rin}) \tag{1}$$

where, D is the inlet diameter (which is 150 mm), and Fr_{in} is the Froude number at the inlet. $Fr_{in}=v_{in}(gD)^{1/2}$ [8]. In this case $S_{min} = 436\ \mathrm{mm}$ and the Froude number is $Fr_{in} = 0.83$.

A swirl meter, an instrument designed to measure the swirl, details of which will be discussed in the next section, reads the swirl strength. The intensity of the swirl is determined by the swirl angle in the flow, which can be calculated using the following equation:

$$\text{swirl angle}, \theta = \tan^{-1}(\frac{\pi d n}{u}) \tag{2}$$

where u indicates the average axial velocity at the swirl meter, and d refers to the pipe diameter at the swirl meter place, which in this study is 94 mm. Additionally, n is the number of revolutions per second of the swirl meter. According to the ANSI/HI 9.8 (2018) standard, the swirl angle should be less than 5° to avoid loss in pump efficiency and imbalance loading on the pump impeller.

The selection of an anti-vortex device (AVD) design using a floor separator has been proven effective in reducing vortices. Nazmy *et al.,* [20] stated that twin AVDs are more effective than a single-floor separator. The trapezoidal shape showed better vortex reduction results compared to the rectangular shape based on Figure 1. The experiment includes six distinct conditions, involving the installation of a double-plate floor splitter (DPFS) and a triple-plate floor splitter (TPFS) positioned in six different configurations. The inset on the right side of Figure 1 shows the common axis. These six configurations are shown in Table 1.

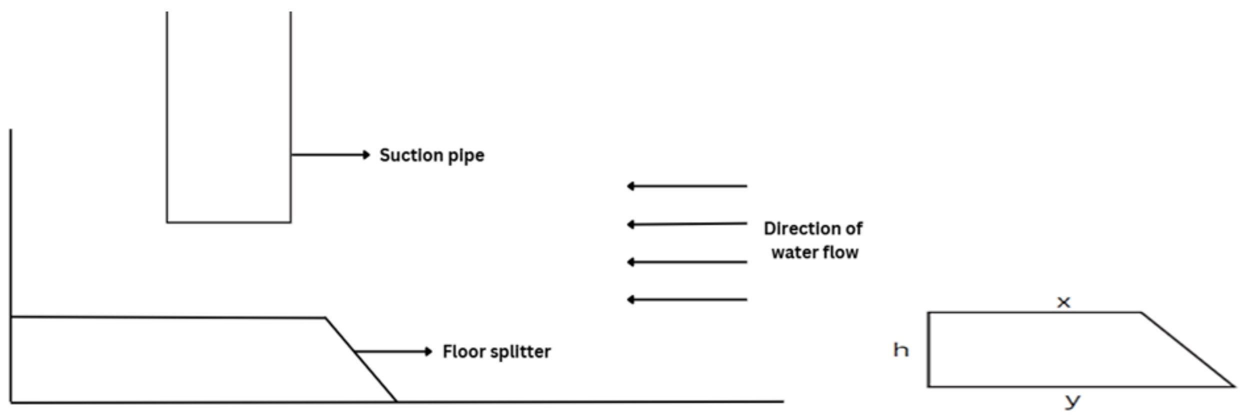


Fig. 1. Floor splitters general dimensions

Table 1
Dimension of AVD

Type of AVD	h (mm)	x (mm)	y (mm)
DPFS 25 mm	20	180	210
DPFS 50 mm	20	180	210
TPFS 25 mm	20	180	210
DPFS 25 mm	20	260	285
DPFS 50 mm	20	260	285
TPFS 25 mm	20	260	285

Next, Figure 2 shows a schematic of the experiment for measuring water flow patterns and vortex formation. The details of particle image velocimetry (PIV) are shown in Batcha *et al.,* [9]. The experimental rig is as shown in Norizan *et al.,* [7] and Batcha *et al.,* [9].

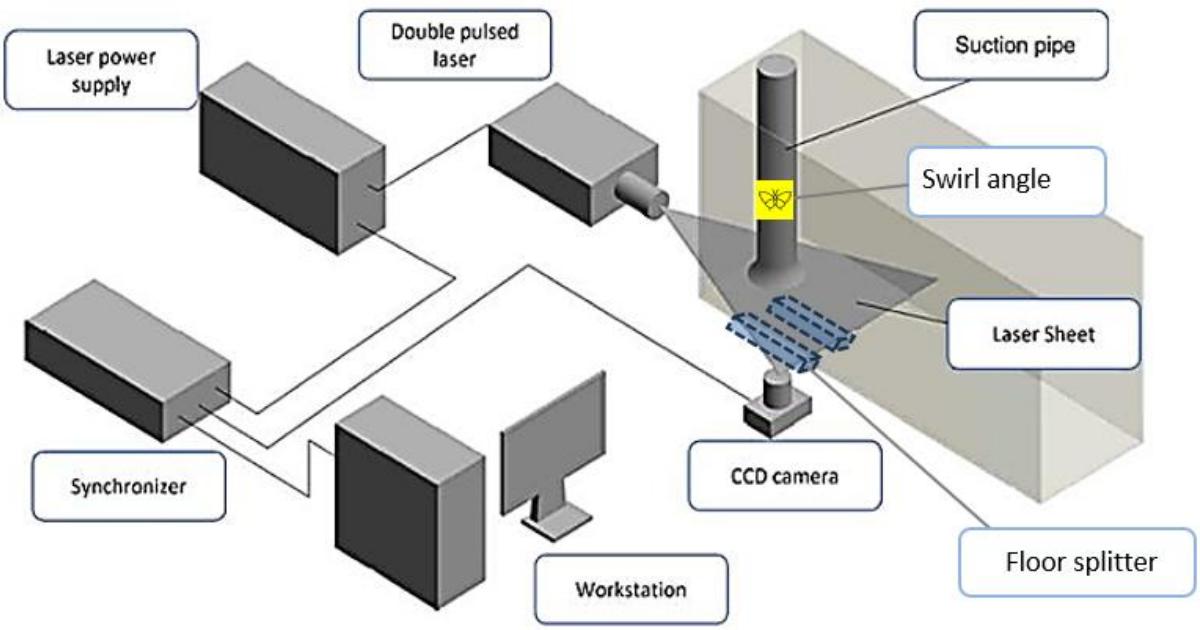


Fig. 2. Schematic diagram of PIV measurement system

2.2 Setup for Measurement Swirl Angle

A swirl meter is installed in the intake pipe to measure the swirl angle of the flow. In this case, a swirl meter is built in-house, consisting of a four-piece wing attached to a ceramic bearing, in the intake pipe, installed according to the ANSI-HI 9.8 standard [4]. The ceramic bearing is used because of its negligible force and its corrosion-free nature. The location shown in Figure 2 is in the upper section of the vertical section of the inlet pipe. A laser beam sent by a vortimeter is subsequently deflected by a reflective sheet attached to one of the four wings of the swirl meter. One complete rotation can be counted by a successful detection of the reflected laser beam, this is shown in Figure 3.

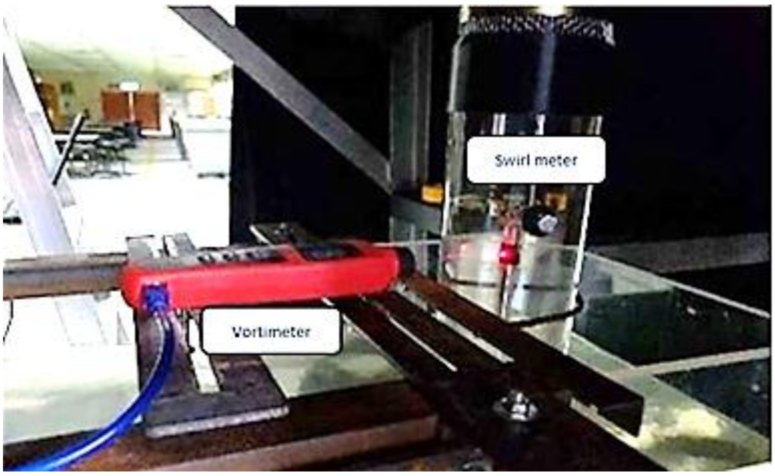
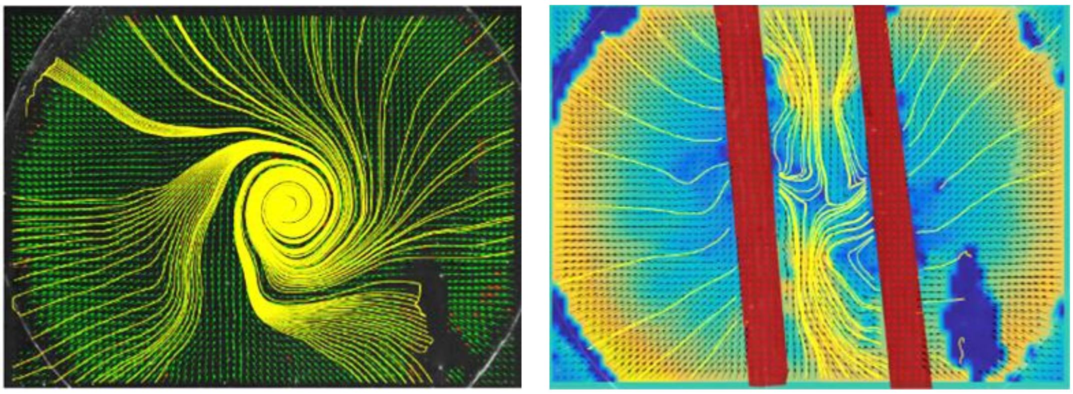


Fig. 3. Position of the vortex meter inside the suction pipe

3. Results

This section explains the results acquired from images captured by the PIV system. The collected image was analysed in PIVlab to visualise streamlines, as seen in Figure 3. Table 2 provides a summary of the vorticity strength values derived from the contour plots. The red dashed line indicates the boundary corresponding to the diameter of the suction pipe. The results reveal seven notable differences in vortex formation across the conditions. Without a floor splitter, a single vortex core with a large diameter forms the centre wall of the sump, rotating clockwise. This occurs due to uneven velocity profile in the approach flow. Vorticity strength quantifies the intensity of local fluid rotation. Higher values indicate stronger rotational motion, such as in vortices or turbulent eddies. Particle image velocimetry (PIV) tracks the displacement of seeded particles in the fluid to calculate velocity vectors. The vorticity strength in this case is 350 1/s.

Further observation with the 25 mm DPFS revealed no vortex formation. The floor splitter effectively suppressed the collision between the inlet flow and the back wall. The circular motion, driven primarily by the pump's suction through the bell mouth inlet, exhibited a vorticity of 190 1/s. The 25 mm DPFS achieved a reduction in vorticity, decreasing by 45.7%. When the distance between the DPFS was increased to 50 mm, two vortices of varying diameters, both rotating clockwise, were observed. This resulted in an increase in vorticity strength to 210 1/s. For the TPFS 180 mm which uses 25 mm spacing, the vorticity is measured at 190 1/s. This configuration shows the streamlines circle around the vortex core more tightly.



(a) (b)

Fig. 3. Streamline plot showing vortex formation for different conditions (a) No floor splitter (b) DPFS 180 mm (25 mm)

Table 2
Vorticity strength with and without floor splitter

Experiment	Vorticity (1/s)	Reduction
No. FS	350	-
DPFS 180 mm (25 mm)	190	45.7%
DPFS 180 mm (50 mm)	210	40.0%
TPFS 180 mm (25 mm)	190	45.7%
DPFS 260 mm (25 mm)	160	54.3%
DPFS 260 mm (50 mm)	200	42.9%
TPFS 260 mm (25 mm)	180	48.6%

The DPFS 260 mm (25 mm) setup exhibits a lower vorticity of 160 1/s and shows a reduction to 54.3% which is the highest reduction achieved in these experiments. The flow direction indicates that the floor splitter causes the fluid to move in a more controlled pattern and reduces flow disturbances. Conversely, increasing the spacing between splitter plates in the DPFS 260 mm (50 mm) configuration leads to a higher vorticity of 200 1/s, with more pronounced swirling, indicating that wider splitter spacing diminishes the effectiveness of flow control. Lastly, the TPFS 260 mm (25 mm) configuration, with a vorticity of 180 1/s, shows a moderately controlled flow, where the additional splitter plate helps dampen swirling motions but still allows some vortices occur, albeit less than the TPFS setup at 180 mm. Overall, the DPFS 260 mm (25 mm) configuration is the most effective in reducing vorticity, while the DPFS 180 mm (50 mm) configuration is the least effective.

Figure 4 shows the distribution curve of the swirl angle for all cases. Each swirl angle was determined using Eq. (1), which indicates the average swirl angle for every 10 s interval for a measurement period of 5 minutes. Over a measurement period of 5 minutes, the use of a floor splitter has generally proven effective in reducing the swirl angle under all tested conditions. According to the ANSI/HI 9.8-2012 standard, the swirl angle must not exceed 5°, serving as the benchmark for the effectiveness of the floor splitter. In the absence of a floor splitter, the swirl angle was measured at 8.83°, which significantly exceeds the allowable standard. The introduction of a DPFS (25 mm) reduced the swirl angle to 7.4° for length 180 mm and 6.85° length 260 mm. This represents a noticeable improvement, though it still falls short of the required standard. When the distance of the DPFS was increased to 50 mm, the swirl angle slightly increased to 8.31° for a length 180 mm and 7.92° for length 260 mm, indicating that a greater splitter distance does not necessarily result in better performance. The use of a TPFS at 25 mm yielded better results, with a swirl angle of 7.56° for length 180 mm and 7.17° for length 260 mm.

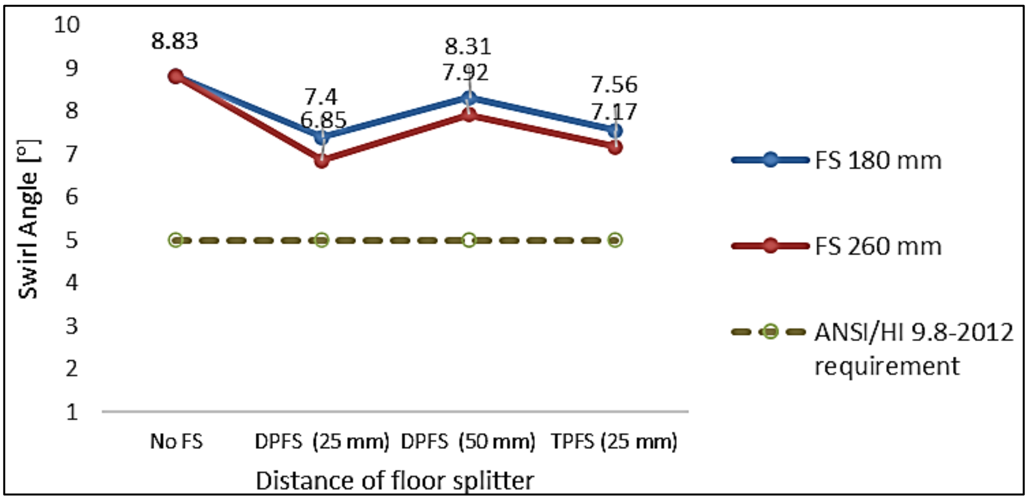


Fig. 4. Swirl angle values with and without floor splitter

4. Conclusions

The experimental study aligns well with the prior observations and results related to the behavior of vortex formation and the effects of different configurations of floor splitters. The submergence depth used is $S_{min} = 436 \text{ mm}$ and the Froude number is $Fr_{in} = 0.83$. In both cases, it is demonstrated that the installation of floor splitters significantly reduces vortex size and vorticity strength. Particularly, the DPFS 260 mm (25 mm) setup effectively minimised vortex formation with a high reduction in vorticity with a reduction of 54.3%. This setup still demonstrated the best performance, achieving the lowest swirl angle and reduced vortex formation, but it was not sufficient to meet the ANSI/HI 9.8-20212 standard that required below 5°.

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