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VELOCITY AND FLOW PATTERN AROUND BOTTOM OUTLET AS REVEALED BY PARTICLE IMAGE VELOCIMETRY

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Abstract: This experimental study is to determine the velocity vector and flow contours in a reservoir with a bottom outlet. Velocity vector flow and contour characteristics are studied by making laboratory studies using acrylic models. The model combines the first pond as a constant head tank and the second pond as a reservoir with a hole at the bottom or bottom outlet. Particle Image Velocimetry (PIV) is an optical visualization qualitative and quantitative technique for measuring the velocity of a fluid by measuring the slight movement of a particle or object in a particular fluid area by observing the location of the tracer particle used in education and research detail. The PIV method relies on recording particle images and measuring object markers (tracer particles) distribution at several locations to measure instantaneous velocity and different phases, velocity fluctuations, and accelerations well in fluid flow. Brown shellac was chosen and used for tracer particles after several experiments using other seeding materials such as white shellack, glitter, and glycerine. The brown shellack is crushed manually, filtered to pass sieve 30 (0.5 mm), and retained on sieve 50 (0.3 mm). The recorded image file is then read and processed to obtain the magnitude and direction of velocity at the tracer particle locations captured in the image recording. The experiment was carried out by running the water flow from the constant head to the reservoir model by giving tracer particles of brown shellac. Experiments produce the most significant velocity around the bottom outlet is 265 cm/s or 2.65 m/s.

Keywords: Particle Image Velocimetry, Reservoir, Bottom Outlet, Velocity

1. INTRODUCTION

Particle Image Velocimetry (PIV) is a measurement technique that captures fraction fields. The basic idea of PIV is the direct determination of the two main parameters of the velocity: length, and time, compared to hot wire or pressure probe techniques. While it measures the velocity of the tracer particles rather than the fluid's, the measurement method is indirect. The interaction of the particles with the surrounding fluid must be investigated to minimize major disparities between fluid and particle motion. The method is imaging-based. As a result, identifying the right tracers depends in a significant way on the optical characteristics of the seeding particles. [1].

The method relies on recording particle images and measuring object markers (tracer particles) at several locations to measure instantaneous velocity well in fluid flow. The recorded image file is collected and processed to obtain the magnitude and direction of velocity at the tracer particle locations captured in the image recording. The PIV system, which may produce two or three-dimensional vector fields, was developed to monitor wall-bounded turbulent flows with only a single point of velocity. The benefit of PIV is that the entire field can be measured with little apparatus interruption. When PIV is in operation, it is feasible to identify individual particles by particle concentration [2].

PIV can visualize qualitative and quantitative results in the flow field, including the distribution of instantaneous velocity and different phases, velocity fluctuations, acceleration, tracer particle distribution, and water flow [3]. PIV consists of irradiation, image recording, and data processing. PIV will produce sheets or sheets in a double pulsed flow field area recorded by a recording medium (photo or video camera) at a specific time and duration. Jahanmiri claims that PIV, the newest player in the field of fluid flow measurement, offers instantaneous velocity fields over worldwide domains.

The position of tiny tracer particles put into the flow over time is recorded by PIV, which is a quantitative extension of the qualitative flow visualization techniques used to determine the local fluid velocity. Some of the earliest quantitative measurements in fluid flows were obtained using ponds and pitot-static tubes. A class of flow measurement techniques known as Particle Image Displacement Velocimetry (PIDV), sometimes known as Particle Image Velocimetry (PIV), captures the displacement of tiny particles that are submerged in a fluid area.

The basic idea behind a PIV system is straightforward: The flow of light from a light source is used to record the positions of the particles, which are then imaged onto a recording media like photographic film or a matrix detector by the light that is scattered from the tracer particles [4]. Phironmmark et al., analyzed the particle flow and a simulation using Computational Fluid Dynamics (CFD) that can call a similar method to PIV [5]. Bigillon and Garcia, implemented PIV using moving particles to connect suitable structures and detectable sediment particles based on the quadrant method [6]. The method provides a quantitative description with the same frame as the PIV that tracks individual particles in the stream. The investigated exploration of particle flow interactions in small water tunnels was recorded following the PIV technique. Flow turbulence and particles carried by the current are obtained from the analysis frame using particle tracking [5]. Kuok and Chiu used PIV to measure surface runoff velocity by analyzing images captured using the MatPIV code. Various palace particles, including food coloring, beads, and ping pong balls, were used for experiments [7].

The research applies a common correction factor with an error of less than 5%, which is considered entirely accurate [6]. Chang et al. developed a portable image velocimetry measurement system to measure flow surface velocity [8]. Adrian and Yao observe that a typical data analysis technique for particle image photographic recordings is the beam reading technique. One of the most critical parts of the PIV process is the method for analyzing the recorded image field, which works in conjunction with the image-acquisition process to assess the measurements' precision, dependability, and spatial resolution. This method also takes the most extended [9].

2. RESEARCH SIGNIFICANCE

The general picture that emerges from the explanation of the fundamental aspects of digital particle image velocity is that the technique's limitation appears directly due to the choice of implementation [9]. This research wants to study the movement, particle velocity, and velocity contours that occur in reservoirs with bottom outlets that are modeled on physical laboratory models. The results of this study are expected to be a reference for further research. The physical characteristics of the scattering particle that is the source of PIV impact the signal's quality. When choosing seed particles, it is essential to consider their size, composition, density, form, and concentration. Velocity measurement uses indirect velocity measurement, and the PIV technique indirectly measures the velocity of fluid elements by measuring the velocity of particles in the flow [1].

3. METHODOLOGY

PIV relies on recording particle images with tracer particles at several well-measured locations. Several software programs have been developed to identify "particle images," differentiate particle images between different phases, determine the containment of each phase, calculate bubble sizes, find the center of mass, and calculate displacements between image pairs. The recorded image file is then read and processed to obtain the magnitude and direction of the velocity at the tracer particle location captured in the recorded image. The performance of the light-reflecting tracer particle also dramatically affects the quality of the recorded images that can be processed. The tracer particle must float at the same velocity as the water particles. Seeders are small, flat-like pieces with a high drag coefficient, especially when positioned perpendicular to the flow direction. Tracer particles must be able to float in random dynamic positions to move with flow velocity and reflect light toward the recording media. The material for the tracer particles must be chosen carefully for each experiment because the tracer particles must be able to follow correctly and precisely the movement of the water flow to be observed. The tracer particles can reflect light to a size small enough to follow a stream but large enough to exhibit the required exposure. Some of the used tracer particles will first be tested by mixing these particles into a tube filled with water.

According to Adrian, the fundamental definition of velocity and estimate of the local velocity u from the Eq. (1) [10]. This equation is also used by Willert, Gharib, Lourenco, and Krothapalli (2000) to find a the average effect of PIV (Fig. 1) [11].

$$u_{(x,t)} = \frac{\Delta L_{(x,t)}}{\Delta t} \tag{1}$$

U is the local velocity of fluid flow, ΔL is the displacement tracer particles between known time intervals Δt, with the assumption the particle tracers move with the same velocity as local flow velocity. Measurement of particle velocity is particle velocity equal with flow velocity.

Due to averaging over the interrogation window (IW), Willert and Gharib have discussed PIV's low pass filtering effect without looking directly at the spectrum. The research results show that the curvature of the particle trajectory between two successive exposures is lost by PIV [12]. The recording of particle movement is carried out with a high-speed camera that can take consecutive pictures. After getting the image recording, then the image is obtained at a speed of 30 frames per second.

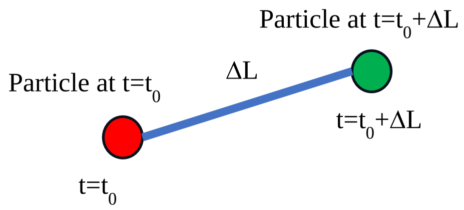


Fig. 1 Displacement tracer particles

Analysis of processing the distance and direction of particle movement from the first image to the second image uses image processing. Particle velocity is the instantaneous velocity of the same particle displacement in the first and second images during the PIV by dividing the distance and sampling time [1]. PIV digital data processing by processing tracer particle data captured on the camera in image-forming dots. Processing is assisted by using software that can mark and know the location of the particle coordinates in a frame. Each data contains point location information. PIV data analysis processing that measures particle velocity or particle motion by subtracting the point value in frame one with the same point value in successive frames can be seen in Eq. (2).

$$C_{(i,j)} = A_{(i,j)} - B_{(i,j)} \quad (2)$$

where (i, j) is the position index for *i*-row dan *j*-column, $C_{(i,j)}$ is the pixel value of frame *C* at position (i, j), $A_{(i,j)}$ is the pixel value of frame *A* at position (i, j), $B_{(i,j)}$ is the pixel value of frame *B* at position (i, j).

The reduction of coordinate points is carried out at the same point in two or more consecutive frames. Subtraction at a point location that does not change on two consecutive frames will result in a value of zero (0). Clipping, cutting, or limiting a frame is done so that the calculation results do not exceed or fall short of a specific value due to a calculation error that can be seen in the Eq. (3).

$$C_{(i,j)} = \begin{cases} A_{(i,j)} - B_{(i,j)}, & A_{(i,j)} > B_{(i,j)} \\ 0, & A_{(i,j)} \leq B_{(i,j)} \end{cases} \quad (3)$$

Particles in the frame are separated from the background using morphological analysis, namely digital image segmentation, by following the object's boundaries. The analysis was carried out by thresholding with the calculation results on binary images with pixel values of only 0 and 1, which are similar to clipping, which can be seen in equation (4)

$$f_{B(i,j)} = \begin{cases} 1, & f_{g(i,j)} \leq T \\ 0, & others \end{cases} \quad (4)$$

$f_{g(i,j)}$ is the original image, $f_{B(i,j)}$ is resulting biner image dan *T* is the specific threshold value. This method is performed on the frame to separate the object from the background.

4. EXPERIMENTAL SETUP

4.1 Tracer Particles for PIV

To estimate the kinematics of the local fluid, seeding trace particles are put into the flow and their motion is employed. Tracer particles should be neutrally buoyant, totally followable, and large enough to effectively disperse illumination light [13]. The ratio of the refractive index of the particles to that of the fluid has a significant impact on the scattering effectiveness of trace particles. The dynamic velocity range (DVR), which is equal to about 50 according to Eq. (5), is calculated as the ratio between the greatest and least recorded tracers' velocity. The range of scales that can be resolved at small flow scales reduces when the interrogation window's size is increased. The interrogation window's size determines the range of scales that can be resolved. Eq. (6) provides the dynamic spatial range (DSR), often known as the scale range. [1].

$$DVR = \frac{\Delta x_{max}}{\sigma \Delta_x} = \frac{U_{max}}{\sigma U} \quad (5)$$

$$DSR = \frac{x_{max}}{D_I} \quad (6)$$

With x_{max} being the sensor size in pixel and *Di* the size of the interrogation window. If the sensor measures 2560 pixel in length and the interrogation window 16 pixel the DSR is 160 and 250 for a sensor with 4000 pixels. The corresponds to a 250 mm long tape measure with a millimetre scale.

The x and y axes are integrated within the particle image's identified boundaries. Identify the particle frame regarding the particle size distribution. The PIV can obtain by calculating the centroid from one frame to the next to obtain the vector velocity. In this experiment, some tracer particle materials are considered prepared, such as glitter, glycerine, white powder shellac, and brown shellac. Glitter is a tiny particle that can reflect light made of aluminium, titanium dioxide, or iron oxide. Glitter was tried to be used as a material in PIV because of its light and shiny characteristics, and it is widely available on the market. Yee et al., succeeded in conducting velocity profile research in medical and biological engineering and computing using glitter in PIV [14].

Bress and Dowling applied the PIV technique with glitter to the flow of molten plastic during injection moulding [15]. Koos et al. applied glitter as a PIV to determine media flow velocity [16]. Ostdiek examined the liquid seed glycerine in the inlet flow field as a laser velocimetry seed with several temperature requirements used glycerine to find the velocity vector in parallel model planes. [17]. Corino and Beodkey used glycerine in experiments that required more accurate glycerine studies [18]. Shellac is a naturally occurring thermoplastic. When heated, the material is soft and flows under pressure but becomes rigid at room temperature. There are two types of shellac in the general market, namely white and brown, which are still in the form of plates. Both types of shellac have favourable characteristics. Rahardjo et al. measured flow velocity in water structures using the PIV method, with the type of particle being brown shellac powder [19].

4.2 Setting Experiment

This research was conducted in the physical laboratory using a model made of acrylic. The experimental investigations mainly focused on the characteristics of two-dimensional bottom outlet. They were conducted in the Department of Civil and Environment Engineering at University of Gadjah Mada Yogyakarta, Indonesia. The model has two parts: the first part (Pond 1) is a constant head, and the second part (Pond 2) is a reservoir model with a hole at the bottom, which is assumed to be a reservoir with the bottom outlet (bo). The research section is part of Pond 2, a reservoir with a bottom outlet, and the research objectives are the velocity vector and flow velocity contours in the upstream bottom outlet. The research section gives a clear area which is assumed to be a video capture area with a width of 23 cm and a height of 25 cm, shooting using a highly evolved camera. At the top is a perforate board with a top width of 1 cm and conical with a width of 0.5 cm (Fig. 2). The research model is covered with a black cloth for clear video capture. The experiments examine the fluid region's behavior within the freeboard. Tap water is used as the liquid in the experiment. A storage tank uses pump-to-pump tap water to the constant head tank or Pond 1.

The selection of glitter particles was not used because after the experiment was carried out by immersing it in water and trying to flow it in a glass container, it turned out that the glitter particles had floating properties. The experiment mixed glycerine as a material in PIV because the specific gravity of glycerine was 1.26 gr/cm^3, which is close to the specific gravity of water, which is 1 gr/cm^3. A mixture of glycerine and water was poured into the water stream and is visible in the camera capture. This study did not use glycerine due to the substantial volume of glycerine used. Shellac White Powder was not used because after being soaked in water in the water bowl and stirred, it changes the characteristics of the water to become cloudy. Brown shellac powder chose to be particle seeded because it was light and shiny when exposed to light and does not interfere with water flow characteristics. The selected tracer particles are brown shellac in the public market as small sheets. Then the shellack was crushed manually, filtered to pass sieve 30 (0.5 mm), and retained on sieve 50 (0.3 mm).

After preparing the equipment and selecting tracer particles, the PIV experiment was carried out according to the data consistency test procedure. The experiment was done in the afternoon until evening with minimal lighting. The test results in the form of video will be converted into image frames, which will be analyzed to obtain flow patterns and vector velocity that occurs around bo. One of these results aims to determine the uniformity of the sediment placed in the second pond. Sticker measurements are affixed to the wall along the flow field.

4.3 Data Processing

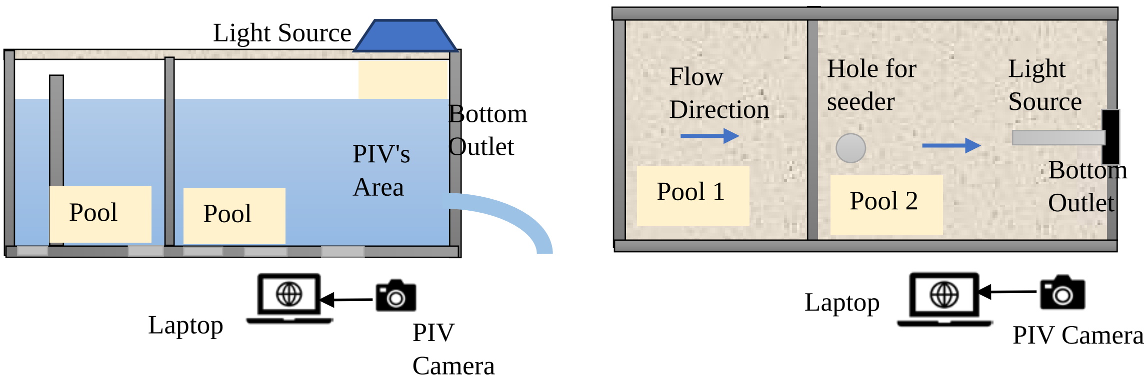
Nguyen et al., investigated how image overlapping improved measurement accuracy in micro-PIV for flows without particle clumping. The best accuracy is achieved without the use of image pre-processing by combining image overlapping with band-pass filtering. There was still no sign of pixel locking [20]. After the pump turns on, the tap water from the storage tank will go to pond one and then to pond two. The depth was adjusted according to the scenario and waited to stabilize. After the depth and water in pond two are stable, a tracer particle gives through the hole, and the video shooting begins. Video capture was carried out within a specific time duration, approximately 3-5 minutes. The video was divided into several parts of about 1 minute to make it easier for particle analysis. The divided video converts into an image frame with 1/8 second. Particle movement can be known by analysing continuous frames. The video was taken for 3 minutes with a frame of 3840 x 2160, an average total bitrate of 2300 and a frame rate of 30 fps.

The video was divided into three parts of the video, each with a duration of 1 minute. Choose one part of a divided video that showed the clearest and the most excellent video particles.

Videos with a duration of one minute convert to approximately 500 frames at 1/8 fps and 96 dpi. The frame has size and pixels 1920, 1080 pixels high, with a horizontal and vertical resolution of 96 dpi (Fig. 4). To digitize particles or identify particles in the frame, use a double frame/single exposure technique with the help of a simple Trace.id software. For vector and contour depictions of velocity, use the Surfer software. Trace.id has a weakness: digitizing only a few particles that can be processed.

While for particle data, the more appropriate makes, the better. The way to cover the shortfall is then in the process trace.id works are to prepare ten consecutive frames, which will be identified with a double frame exposure, namely taking each of the two consecutive frames as the first data, for example, Frame No. 1 and Frame No. 2, then Frame No. 2 and Frame No. 3, and so on or frame i and frame i+1. Open the trace.id software application, call the first frame to identify and activate the "particle" available in the software, then identify the particle by pressing the mouse at the particle. Fig. 5 shows an image frame with the particle identified by its trace.id and is referred to as Frame No. 1. Frame No. 2 is accessed by starting a new frame and selecting the next image from the previous one. Identifying the particle by pressing the mouse on the particle at the editor setting on the screen will show a red dot. The red dot represents the particle identified from the previous frame in Frame No. 1. If the particle was identified, click the red particle, then click the white particle that would become green. The red dot was the particle location in the first frame, and then the green particle was the same as the red particle in Frame No. 2, shown in Fig 6. Particles that must identify will have coordinates of x and y values stored in the software record. The identification on the first frame was complete. Activates by calling the next sequential frame, i.e., the second frame.

After opening the second frame and activating the particle settings in the software, a red dot will appear, which is the particle point in the next frame. Trace the next particle, then activate the particle by pressing the mouse on the next particle, which will turn green. After the particle identification is complete, click the file button, then a save note in note form will appear. The note contains the x and coordinates of the first frame particle and subsequent frames with the same particle. Do this until the tenth frame. The data obtained from Trace.id was in the form of a note, copied to Excel considering the scale of the image, to get the directional velocity which is the resultant of the velocity.



(a) Side view (b) Top view

Fig. 2 Experimental apparatus.

Fig. 3 Experimental apparatus (a) area of PIV; (b) area of PIV inside the pond

Fig. 4 Image frames with particle from trace.id

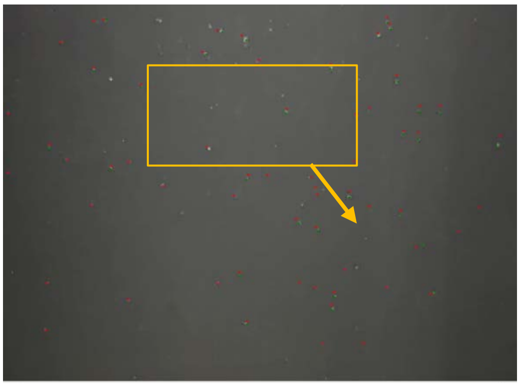


Fig. 5 Image frames with particle analysis $t=t_0+\Delta t$.

5. RESULT AND DISCUSSION

The experiment was conducted in water with a bottom outlet or hole. The material for the seeder, brown shellack, has undergone particular gravity testing. The specific gravity of the brown shellac powder employed for this study, as determined by soil mechanics laboratory data, was 1.11. The brown shellack, chosen to be a seeder, had a specific gravity like water.

The experiment lasted for three minutes. As seen in Fig. 4, that is a frame where the video is changed into a framed image with white dots that are particles. The next frame's particle identification is green. In contrast, the first particle's identification is red (Fig. 5). There are several locations throughout the flow plane where particles may not detect the information flow of a stream under study. The correct interpolation process can help obtain further flow information for the flow field with limited data experiments, and position data can be seen in Fig 6. Each phase's random velocity field displays a vector originating from the particle image location of the first selected sub-plane.

Figure 8 illustrates a typical velocity vector obtained through several measurements (all runs from the current study) using the Particle Image Velocimetry (PIV) technique. Measurements are made along the longitudinal direction of flow, which is the direction of fluid flow. This direction ranges from upstream (x/L=0) to downstream (x/L=1), with the bottom outlet at the downstream end. The graph plots non-dimensional values, where the distance along the flow direction (x) is normalized to the total length of the stream (L), and the distance to the depth of flow per point (y) is normalized to the total depth of flow (H). The x-axis coordinate is a dimensionless horizontal distance, the ratio of x and L, where L is the length of the x-axis. The y-axis coordinate is a dimensionless vertical distance which is the ratio of y and h which is the length of the y-axis. X is the distance in the x direction, y is the displacement distance in the y direction, while ΔL is the x and y displacement tracking particles.

The velocity vector (Fig 8) and the velocity contour (Fig 9) reveal an essential insight that as the fluid or stream moves closer to the channel bottom and pool walls, its velocity decreases. This decrease in speed is caused by friction with the bottom of the channel and the walls. As a result, the direction of the vector shifts, pointing upwards on the flow surface and to the center point towards the bottom outlet. This behavior shows the effect of frictional forces and the boundary layer close to the base wall.

Velocity vector and velocity contour in the longitudinal direction from the upstream (x/L = 0) to the bottom outlet (x/L = 1), the velocity is increasing. However, no distinct characteristic pattern appears when observed over the entire flow depth (y/H) from the bottom of the channel to the flow surface, especially in the range x/L = 0 to x/L =0.7. In Figure 9, the velocity contour plots describe the specific velocity values at various locations along the upstream and downstream areas (from x/L = 0 to x/L = 0.7). Here, the flow velocity varies from 5 cm/s to 50 cm/s. Particularly at x/L < 0.7, the presence of a bottom outlet does not significantly affect flow velocity. Conversely, for the velocity value at position x/L> 0.7, it is evident that in this region, the speed starts to increase; this shows a significant effect on the bottom outlet. In detail, a very significant change in the flow velocity occurs in the area close to the bottom outlet at positions x/L=1 and y/H = 0.5. Namely, the flow velocity increases until it reaches a maximum speed of 265 cm/s. A fundamental change in velocity near the bottom outlet underscores the significant impact of this feature on flow dynamics. It will affect sediment scour near the bottom outlet, which needs further study.

In summary, Figure 8 depicts the evolution of the velocity vector along the flow direction, emphasizing the changes due to friction with the bottom wall and the presence of a bottom outlet.

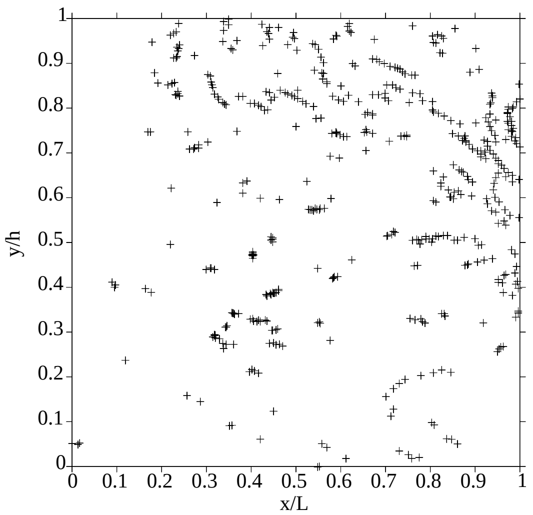


Fig. 6 Point position data around the bottom outlet

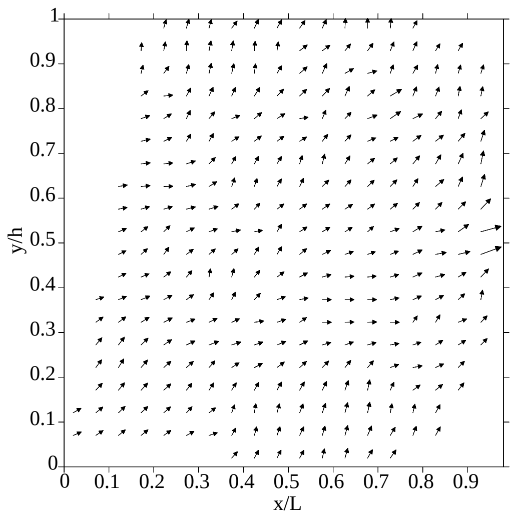


Fig. 7 Flow pattern around the bottom outlet

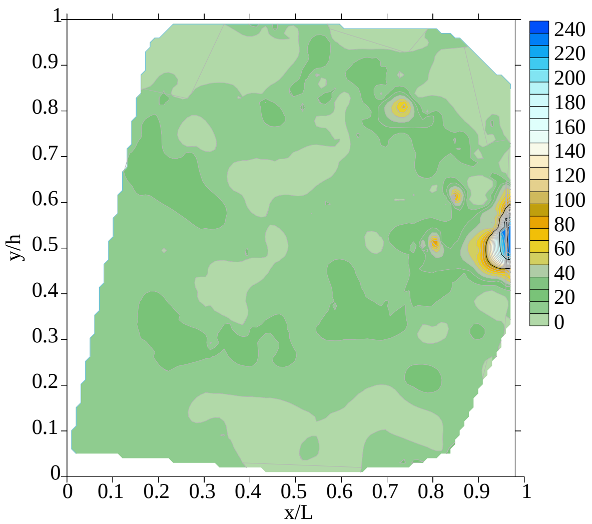


Fig 8. Contour velocity around the bottom outlet

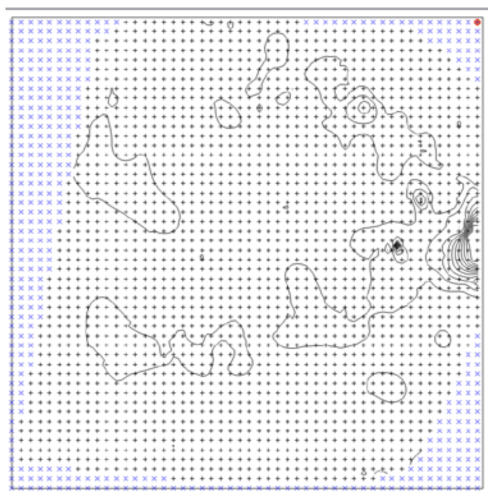


Fig 9. Grid interpolation contour velocity around the bottom outlet.

Figure 9 complements this illustration by providing detailed velocity contours, revealing the varying impact of the bottom outlet on the reservoir. In particular, the marked velocity spike near the outlet proves its significant influence on flow dynamics which is helpful for flushing sediments in the reservoir.

The PIV approach supports real-time experimental parameters such as seeder density, seeder adjustment, video capture, switching from video recorder to picture, video recorder quality, software aid use, and more. It is advised that more studies be done using sensor technology that can be employed in pond models, higher spatial resolution, and higher resolution photos. For the design of the pond, sensors must also be considered. Future tests may be tried with higher spatial resolution, allowing more precise vorticity measurements in the bottom outflow core region. Other properties of the flow, including average and fluctuating velocity and displacement, slip velocity between different phases, acceleration, and vortices, can also be calculated.

6. CONCLUSION

Experimental Investigations were conducted on a physical model made in a hydraulics laboratory, carried out on a reservoir model with a bottom outlet. The simulation was on a reservoir model that gets water from a constant head tank with an open bottom outlet by recording the particles that seed into the water flow. The particles used are brown shellack filtered to pass sieve 30 (0.5 mm) and retained on sieve 50 (0.3 mm), which specific gravity 1.11. Particle observations were carried out to determine the water flow movement around the bottom outlet using the PIV method. The PIV interrogation technique utilizes fields to sequentially identify the same particle lock from one frame to the following software using a Tracer.id to identify differences in particle images on different frames in each phase. The time interval between two successive frames is constant. The video obtained is then converted into a frame in an image with a time size of 1/8 second. The captured image has the same size and pixels as 1920, 1080 pixels high, with a horizontal and vertical resolution of 96 dpi. The frame rate of the PIV measurement 20 m/s The Result of vector velocity that occurs before the resulting bottom outlet is 265 cm/s or 2.65 m/s.

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