

Design, Fabrication and Experimental Validation of Bernoulli Apparatus for Fluid-Flow Measurements

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Abstract- Interpreting the interdependence of pressure, velocity, and elevation heads in fluid flow is critical for understanding fluid behaviour and for designing efficient engineering systems. Bernoulli's theorem, which describes the conservation of mechanical energy along a streamline and quantitatively relates pressure, velocity, and elevation heads, serves as the fundamental theoretical framework for the present study. This experimental research aims to design and fabricate Bernoulli's apparatus for demonstrating the principle and measuring the discharge and flow rate of fluids. The apparatus consists of a smooth, narrow flow channel with gradual contraction and expansion sections, pressure taps, and flow rate and discharge measurement devices. The fabrication involves selecting suitable materials, fabricating the flow channel, installing pressure taps, and integrating flow rate and discharge measurement devices. The experimental setup includes connecting a fluid supply, controlling the flow rate, measuring pressure and discharge, and analyzing the data to verify Bernoulli's principle and calculate flow rate and discharge. Experimental results exhibited well-defined pressure head variations along the test section, aligning closely with theoretical expectations, and enabled accurate calculation of both theoretical and actual discharge. The apparatus provides a practical tool for students and researchers to visualize and quantify fluid flow behavior, enhancing understanding of fluid dynamics and hydraulic engineering principles.

Keywords: Bernoulli's apparatus, Discharge, Fluid flow, Pressure head, Velocity head, Venturimeter.

I. INTRODUCTION

In fluid mechanics, precise measurement of flow rate is essential for numerous industrial and engineering applications. Among the most widely used instruments for this purpose are the venturimeter and the orifice meter, both of which are based on the principles of fluid dynamics and pressure variation. These devices evaluate the flow rate of a fluid through a pipe by measuring the pressure difference created as the fluid passes through a constricted section [1–3]. Due to their reliability, simplicity, and adaptability, venturimeter and orifice meters are extensively employed in sectors such as oil and gas, chemical processing, water distribution, and HVAC systems [2,4]. The theoretical foundation for these flow-measuring devices can be traced back to the work of Daniel Bernoulli (1700–1782), who established the relationship between fluid pressure, velocity, and elevation through the conservation of energy principle.

According to Bernoulli's principle, an increase in the velocity of a fluid results in a decrease in its static pressure. This principle is commonly demonstrated using Bernoulli's apparatus, which allows observation of pressure changes along a flow passage and assists in determining fluid discharge with precision [5]. Assume incompressible flow and no frictional losses, from Bernoulli's Equation;

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 \quad (1)$$

From continuity equation

$$Q = AV = A_1V_1 = A_2V_2 \quad (2)$$

$$\frac{p_1 - p_2}{\gamma} + (z_1 - z_2) = \frac{v_2^2}{2g} \left[1 - \left(\frac{A_2}{A_1} \right)^2 \right] \quad (3)$$

Now V_2 becomes

$$V_2 = \frac{1}{\sqrt{\left[1 - \left(\frac{A_2}{A_1} \right)^2 \right]}} \sqrt{2g \left\{ \left[\frac{p_1 - p_2}{\gamma} \right] + (z_1 - z_2) \right\}} \quad (4)$$

And theoretical value of discharge Q_{th} is given by

$$Q_{th} = A_2V_2 = \frac{A_2}{\sqrt{\left[1 - \left(\frac{A_2}{A_1} \right)^2 \right]}} \sqrt{2g \left\{ \left[\frac{p_1 - p_2}{\gamma} \right] + (z_1 - z_2) \right\}} \quad (5)$$

These two laws and the definition of work and pressure are the basis for Bernoulli's theorem and can be expressed as follows for any two points located on the same streamline in the flow: where:

- P: pressure,
- g: acceleration due to gravity,
- v: fluid velocity, and
- z: vertical elevation of the fluid.

In this experiment, since the duct is horizontal, the difference in height can be disregarded, i.e., $z_1 = z_2$

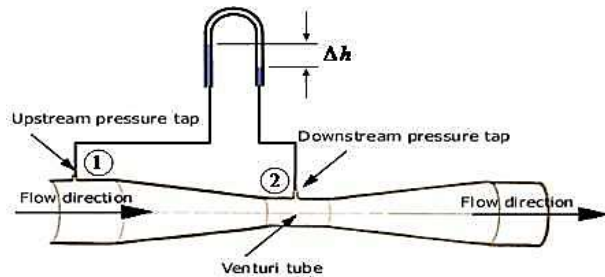


Figure 1. Venturimeter [18]

In orifice meter, often referred to simply as an orifice, is a widely used device for determining the flow rate of liquids in a pipeline. It operates on the same fundamental principle as a Venturi meter, relying on the pressure drop produced when the fluid passes through a restricted section of the pipe. The orifice meter consists of a flat, circular plate provided with a sharp-edged, concentric opening known as the orifice.

As the fluid flows through this opening, a pressure differential is developed across the plate, which is typically measured using a manometer or differential pressure gauge, as illustrated in the corresponding diagram [6-7]. As the fluid accelerates through the orifice plate, the stream contracts to its minimum cross-section slightly downstream of the restriction which is represented by equation 6 and 7.

$$C_c = a_2/a_0, \quad (6)$$

where C_c is Coefficient of contraction. Now area at vena contracta will be given by

$$a_2 = a_0 C_c, \quad (7)$$

As the fluid accelerates through the orifice plate, the stream contracts to its minimum cross-section

slightly downstream of the restriction. This narrow region, known as the vena contracta, plays a crucial role in defining the discharge characteristics and is essential in accurate flow-rate calculations [8]

II. LITERATURE REVIEW

There have been progressive research of design and fabrication of Bernoulli's apparatus in the past decades for both educational and research applications. For instance, [9] designed and fabricated a Bernoulli's apparatus using acrylic material and demonstrated its effectiveness in reinforcing fluid dynamics concepts among engineering students. Similarly, [10] developed a low-cost Bernoulli's apparatus constructed from PVC pipes and fittings, which proved suitable for undergraduate laboratory experiments. In another study, [11] introduced a Bernoulli's apparatus with a modified flow channel geometry and demonstrated its capability to measure flow rate and discharge with improved accuracy.

The design and fabrication of Bernoulli's apparatus require consideration of several parameters, including the geometry of the flow channel, placement of pressure taps, and the selection of appropriate flow-rate and discharge measuring devices. Study of [12] evaluated the influence of flow channel geometry on measurement accuracy and concluded that a smooth, narrow passage with gradual contraction and expansion offered the most reliable results. Additionally, [13] developed a numerical model to simulate flow patterns within Bernoulli's apparatus and found that the positioning of pressure taps significantly affected the precision of recorded pressure differences as shown in figure.

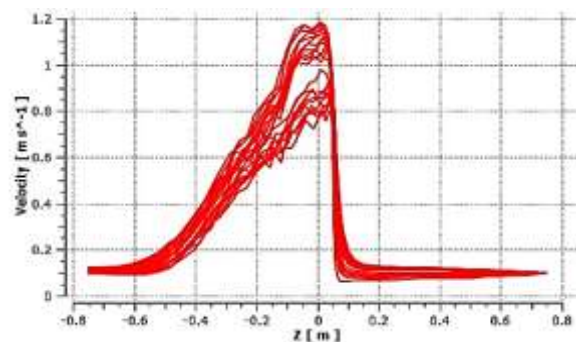


Figure 2 Velocity profile of flow in pipe [13]

Low-cost venturi-based setups have been used to explore energy conservation and pressure loss, revealing that minor loss coefficients can range from approximately 0.28 to 0.86 depending on the configuration, with deviations in measured velocity and discharge observed due to energy losses in the throat section [13-14]. Experiments have also been conducted to determine permanent pressure loss in simple venturi setups, reporting discharge coefficients around 0.88 and minor loss coefficients near 0.29, highlighting the importance of accounting for real-world energy losses in flow measurements[15].Recent designs have implemented compact, transparent flow channels with integrated manometer tubes and total-head probes, enabling the classification of flow regimes across a wide Reynolds-number range while remaining cost-effective and suitable for instructional purposes [16].

Additional modifications of traditional Bernoulli apparatuses have focused on reducing measurement errors and examining the effects of operational conditions, demonstrating that careful calibration and attention to non-idealities are essential for accurate experimental results [17]. From these studies it can be concluded that Bernoulli's principle can be verified in laboratory setups. However there occurs minor energy losses and measurement deviations which keeps up motivating to make improvements in apparatus design and calibration procedures.

III. DESIGN OF BERNOULLI APPARATUS

The whole apparatus is to be designed on the basis of space available, permissible height for taking readings and watching the meniscus of capillary tubes to be installed on the actual prototype of project.

Design considerations:

Prior to fabrication of actual working model, following factors were taken into consideration in design:

Flow Channel (Pipe) arrangement:

The piping arrangement is the core component of the Bernoulli apparatus, and its design directly affects the accuracy of pressure and velocity measurements. It ensures a smooth and uniform passage to guide the fluid with minimal disturbances. To ensure laminar or streamlined flow gradual contraction section and a gradual expansion section is provided in the venturimeter. It allows the fluid to move smoothly, minimizing the formation of eddies or turbulence. The smoothness of the internal surface is crucial because rough surfaces induce friction losses and flow separation, which can distort pressure readings. The material of the flow channel is selected as Ultra Plastic Polyvinyl Chloride (UPVC) keeping in view the cost of project.

Pressure Taps:

Pressure taps are small openings or ports along the flow channel that allow measurement of static pressure at specific locations. The placement of these taps is critical: they are usually positioned at the entry, narrowest (throat), and exit sections of the channel to capture the variation in pressure due to changes in velocity. These taps are connected to manometers or pressure sensors, which indicate the fluid pressure at each point. Correct alignment and sealing of the taps are essential to avoid leakage or measurement errors.

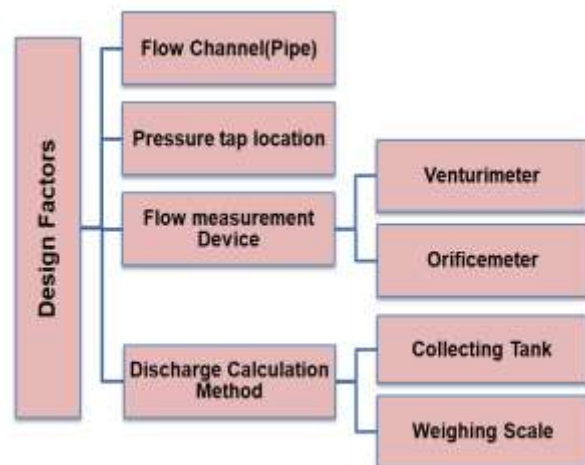


Figure 2. Design consideration for Bernoulli Apparatus

Flow Rate Measurement:

In order to estimate pressure and velocity in the channel, the volumetric flow rate of the fluid must be known. This can be achieved using devices such as rotameters, orifice plates, venturimeter or by using velocity-time methods which provide a quantitative measure of flow. Accurate flow rate measurement is essential because Bernoulli's equation requires knowledge of velocity, which is derived from the flow rate and cross-sectional area of the channel.

Discharge Measurement:

Finally, measuring the total discharge from the apparatus is often necessary for experimental validation. This is usually done by collecting the fluid in a calibrated tank for a known period and determining the volume, or by using a weighing scale to measure mass over time. The discharge measurement serves as a check on the flow rate calculations and allows for experimental verification of continuity and energy conservation in the system. Proper calibration and timing are critical to minimize errors in discharge measurement.

IV. METHODOLOGY

Design and fabrication of Bernoulli's apparatus begins with idea generation and concept finalization, where various design possibilities are brainstormed and the most feasible concept is selected. This is followed by market survey and work estimation, which involves assessing the availability and cost of materials, components, and resources needed for the project. Keeping in mind the cost of total project to be born (no external funding was available), the material of the frame was selected as ms sheet (18 gauge) and UPVC for pipes and plumbing fittings. Further venturimeter was also made from UPVC material.

The next step is the design of working model components, including the tank, frame, and venturimeter using Solid works(Student version) software. All parts of the project were designed individually and then combined as a whole model. During the entire designing process, it was made ensure that each component meets the functional requirements and integrates smoothly with the

overall system. Water Pump is the main component of the project model which supplies water at required head and discharge. Technical parameters of the project model are given in table 1.

Table 1. Specification of Pump

S.No	Parameter	Specification
1	Model	Sagar AL
2	Type	Monoblock Centrifugal Pump
3	Head	14-21m
4	Power (Rated)	0.5 HP
5	Discharge	6000 liter/h
6	Speed	2750 rpm
7	Size	25 x 25 mm
8	Suction lift	7.5 m
9	Priming	Self-Priming
10	Thermal protection	load Auto -cut load protection

Once the design is finalized, the fabrication of the working model is carried out, where the physical components such as the tank, frame, and venturimeter are constructed based on the approved design. Experienced professional persons were employed for carrying out fabrication and plumbing work. Proper leakage test of every fabricated part (tank and pipe fittings) during fabrication in order to prevent chances of fluid leakage at joints.

As soon as fabrication was done, plumbing work and electrical work is performed according to the drawings, ensuring proper connections and functional integration of mechanical and electrical systems. Subsequently, installation of pressure taps and flow control valves is undertaken to enable accurate measurement and control of fluid flow within the system. This is complemented by painting and finishing of the tank and frame, enhancing durability, safety, and aesthetic appeal.

After assembly and finishing, the final assembly model was undergone trial run on half and full load in order to verify that all components operate correctly and the system meets design specifications. The final stage involves experimental testing and data validation, where the working model is subjected to various operational scenarios to collect performance data, validate theoretical predictions, and ensure that the system functions reliably under expected conditions. This comprehensive

methodology ensures a systematic approach from conceptualization to practical testing of the working model.

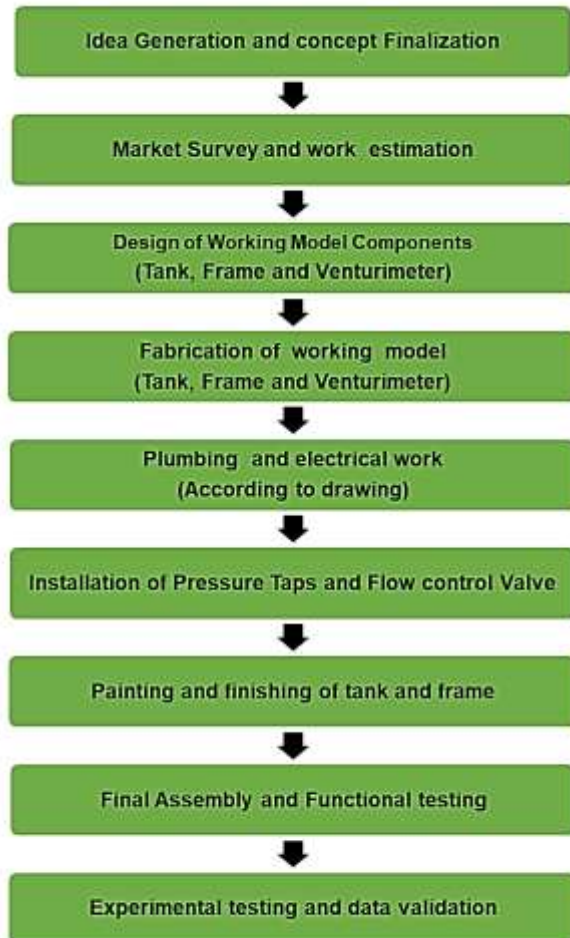


Figure 3 Methodology followed in fabrication of Project

V. CONSTRUCTION AND WORKING

In this project all parts were designed on Solid Works (student version) and are assembled together. The experimental apparatus consists of several interconnected components, each designed to ensure efficient water circulation and precise measurement of fluid flow parameters. The whole set is driven by a centrifugal pump capable of delivering approximately 373 watts of mechanical energy. This pump converts electrical energy into hydraulic energy, enabling it to lift and transport water with

the required head and discharge essential for conducting flow experiments. The water used in the system is initially stored in a sump tank fabricated from durable 18-gauge mild steel sheets, with dimensions of 900 × 410 × 410 mm. This tank acts as the primary reservoir, holding sufficient fluid to maintain continuous operation.

The entire apparatus is mounted on a robust supporting frame made from mild steel square pipes, measuring 1250 mm in length, 1065 mm in height, and 550 mm in width. This frame provides the necessary strength and stability, ensuring that all components remain securely fixed during operation and preventing unwanted vibrations or displacement. Once pumped through the system, the water eventually enters a measuring tank, also constructed from 18-gauge mild steel sheets, sized 410 × 310 × 310 mm. This tank serves as the key unit for determining flow rates, as it collects the discharged water and enables accurate measurement based on the volume–time relationship.

The fluid travels through galvanized iron (GI) pipes, which are corrosion-resistant and durable, making them suitable for continuous water flow applications. These round-shaped GI pipes, totaling 3.5 meters in length, connect the pump inlet and outlet, ensuring smooth and consistent water transport between the sump tank and the measuring tank. To facilitate accurate readings during flow experiments such as those involving venturimeter or orifice meters, two measuring scales with a least count of 1 mm are provided. These allow fine measurement of water levels, ensuring precision in calculating flow parameters. Additionally, a 2-inch release valve is installed at the bottom of the measuring tank to enable quick drainage of collected water back into the sump tank.

This feature is essential for conducting repeated trials, as it allows the system to be reset rapidly without significant downtime. Together, these components form a reliable and efficient setup for studying fluid flow characteristics under controlled laboratory conditions. The whole assembly of project drawn in solid works is shown in Figure 4.

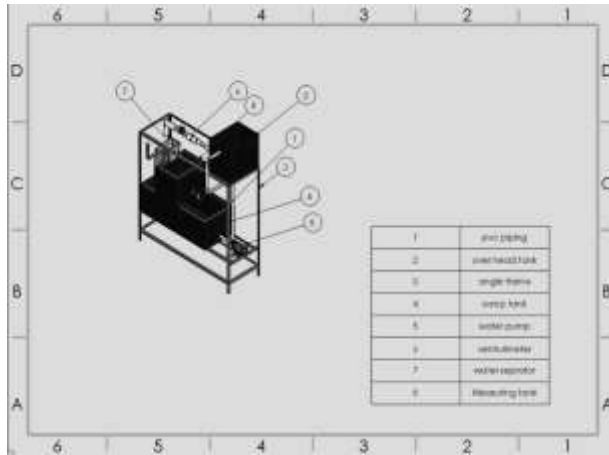


Figure 4 Solid work drawing of working project

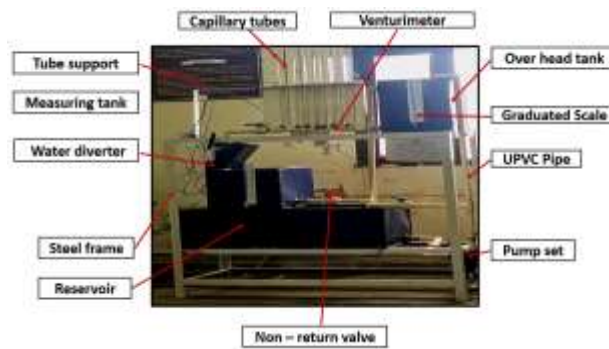


Figure 5 Actual assembled working project

Working of Bernoulli's Apparatus

The experimental setup begins with a closed-loop water circulation system in which a centrifugal pump lifts water from a sump tank and transfers it to an overhead reservoir. This elevated tank acts as a constant head source, ensuring a steady and uninterrupted supply of water to the test section through gravity. From the overhead tank, water flows into a specially constructed converging-diverging tube made of PVC pipes of gradually changing diameters, designed to replicate the behavior of a Venturimeter.

This section consists of a smoothly tapering converging part that accelerates the flow, a narrow throat where the velocity peaks and the pressure reaches its minimum, and a diverging part that allows partial recovery of pressure as the velocity decreases. To capture the pressure distribution along these regions, seven pressure tapping points are incorporated at strategic locations and connected to transparent manometric tubes. These

tubes provide an immediate visual display of the pressure head at each point, clearly showing higher fluid columns in wider sections and lower columns near the throat, thereby demonstrating the inverse relationship between pressure and velocity. After exiting the test section, the water is directed into a calibrated measuring tank, and the discharge rate is determined using the calculating the volume of water collected in tank in one minute. In addition to it, vertical glass capillary tube is also used at selected points along the test section to measure the total head, enabling verification of the near-constant energy line predicted by Bernoulli's equation.

Flow regulation within the apparatus is achieved using two valves: the flow control valve at the outlet, which influences the flow velocity and downstream pressure, and the bench supply valve, which adjusts the rate of water entering the system from the overhead tank. By examining the manometer readings in conjunction with the calculated velocities, the experiment allows a clear visualization of how fluid pressure drops as velocity increases. From the experiment, it was observed that the total head (sum of pressure head, velocity head, and elevation head) remained nearly constant along the flow direction, confirming the validity of Bernoulli's Theorem for steady, incompressible, and frictionless flow.

VI. DESIGN AND CALCULATION

Calculation of Sump Tank Volume

To calculate the volume of a rectangular water tank with dimensions of 900 (length) × 410 (height) × 410 (width) mm Use the formula $V = l \times w \times h$, where V represents the volume, l is the length, w is the width, and h is the height.

$$\text{Volume of sump tank} = 0.900 \text{ m} \times 0.410 \text{ m} \times 0.410 \text{ m} = 0.15129 \text{ m}^3$$

Calculation of measuring tank volume

To calculate the volume of a rectangular water tank with dimensions of 410 (length) × 310 (height) × 310 (width), (mm)

$$\text{Volume of measuring tank} = 0.410 \text{ m} \times 0.310 \text{ m} \times 0.310 \text{ m} = 0.0039401 \text{ m}^3$$

Pump selection

Max discharge required = 6×10^{-4} m³/sec. = 0.0006 LPS (Liter Per Second).

By considering by-pass flow = $0.0006/0.6 = 0.001$ LPS.

The discharge of that pump = 800LPH = 0.222 LPS (Liter Per Second)

Concerned with availability of pump in market, we have selected pump of 0.5 HP. So, in order to control the discharge by reducing it, we have provided one more by-pass pipeline and the outlet of by- pass line is released in Sump tank.

Pipe selection

The selected 0.5 HP pump is connected through pipe having standard inlet and outlet of 1". Hence, all the pipes are of same 1" diameter.

Valve selection

All the standard valves are used which are suitable for 1" dia. Pipe. Pipe is having standard diameter of 1" so, All the standard valves are used which are suitable for 1" dia. pipe. As there is need to release the water from measuring tank to the sump tank so the valve which can be used at to release this water that should be bigger in size to release the water quickly and user can take another measurement quickly. So, we have selected valve of 2" to release the water from measuring tank.

Discharge

Discharge is of two types, actual discharge which is calculated by volume -time method and theoretical discharge which is calculated after loss of energy.

$$\text{Actual Discharge } Q_{th} = \frac{\text{Volume}}{\text{Time}} = \frac{v}{t} \quad (8)$$

When the loss of energy is considered, the theoretical discharge is given by

$$Q_{act} = \frac{a_1 a_2 \sqrt{2gh}}{\sqrt{a_1^2 - a_2^2}} \quad (9)$$

where,

a_1 = area of venturimeter at inlet in m²

a_2 = area of venturimeter at throat in m²

But, in actual practice there is always some loss of energy as liquid flow through manometer on account of which the actual discharge in fraction Cd

Coefficient of Discharge (Cd)

It is defined as the ratio of the actual discharge to the theoretical discharge. It is denoted by Cd

$$Cd = \frac{Q_{act}}{Q_{th}} \quad (10)$$

VII. PROCEDURE OF OPERATION

To begin the experiment, ensure that all the on/off switches on the control panel and throughout the setup are in the OFF position to avoid accidental operation. Next, verify that all valves (V1 to V5) are completely closed. This prevents unwanted flow through the system during the initial preparation. Once the system is secure, fill the sump tank with a sufficient amount of clean water, as this tank serves as the primary reservoir for the entire experiment. After filling, open the bypass valve V2 to create an initial path for water circulation without directing it into the test section.

Switch on the main power supply to the apparatus and then turn on the pump to initiate water movement. With the pump running, gradually and partially close the bypass valve V2. This allows the water to begin filling the overhead tank. Continue adjusting until the overhead tank starts overflowing, indicating that it has reached its maximum capacity and is now ready to deliver a constant head for the experiment. Once the overhead tank settles into steady overflow, control the flow passing through the test section using valve V1, located at the end of the test section.

This valve regulates the amount of water moving through the Venturimeter or test tube. Before taking any readings, ensure that all necessary valves in the system are open and functioning correctly. Switch on the pump if it was temporarily turned off. Next, remove any entrapped air from the manometer tubes by opening the air-release valves provided on the manometric board. Air bubbles can cause significant errors, so wait until the manometer columns stabilize and then close the air-release valves carefully to seal the system.

Once the flow is steady and free from air pockets, gradually adjust the control valve to set the desired flow rate. Observe and record the height of water columns in all manometer tubes; these readings reflect the pressure distribution along the test section. Simultaneously, measure the discharge using the measuring tank by collecting water and noting the time required to accumulate a known volume. This volume–time data is crucial for calculating the actual flow rate. Repeat the entire process for four to five different flow settings by adjusting valve positions to vary discharge. For each flow condition, record the manometer readings and the corresponding discharge measurement. These data sets will allow for detailed analysis and verification of fluid flow principles such as Bernoulli's equation and continuity.

VIII. RESULTS AND OBSERVATIONS

It has been observed that fluid flowing through the constricted section of the venture tube experience an increase in velocity due to reduced cross- section area.

Rise of water level in tank = 3.5 cm
 Time taken= 59 seconds.
 Length of capillary tube = 100 cm
 Number of glass capillary tubes used= 7
 Diameter of glass capillary tube= 5 mm
 Diameter of pipe used in project = 2.5 cm
 Area at vena contracta = 0.196 cm²
 Area at entry and exit section = 7.91 cm²
 Hence volume collected in 59 seconds = 30 × 30 × 3.5 = 3150 cm³
 Therefore, volume per second = Discharge Q_{th} = 53.39 cm³ / s
 The variation of head is shown in table 2

S. No	Piezometer Head (h)	Diameter	Cross-section area = $(\frac{\pi}{4} \times d^2)$	Velocity (m/s)	Total head $H= h + \frac{v^2}{2g}$
1	h ₁ = 27cm	1.25"	7.91	11.56	27.068
2	h ₂ = 24cm	¾"	2.84	18.06	24.166
3	h ₃ = 21.5cm	½"	0.196	32.112	22.025

4	h ₄ = 22cm	½"	0.196	72.25	24.66
5	h ₅ = 23.5cm	¾"	2.84	72.25	26.16
6	h ₆ = 25cm	1"	5.06	32.51	25.52
7	h ₇ = 26.5cm	1.25"	7.91	11.56	26.118

From the table it's clear that the head remain constant at all point with in the venturimeter tube. Therefore, Bernoulli's theorem is verified.

Mean Head = h = 25.38 cm
 Error percentage = $\frac{27.068 - 25.38}{27.068} = 6.42\%$

Experimental discharge Q_{act} = 43.75 cm³ / s

IX. CONCLUSION

This experiment successfully demonstrated the fundamental relationship between pressure and velocity within a flowing fluid using Bernoulli's apparatus. By observing the pressure distribution along the converging–diverging channel, it was evident that static pressure decreases as the flow velocity increases, validating Bernoulli's principle. The measurements also supported the continuity equation, confirming that volumetric flow remains constant across different sections. Although minor deviations occurred due to frictional losses, instrumentation errors, and slight fluctuations in flow conditions, the overall results closely aligned with theoretical predictions.

Moreover, the flow-rate and discharge measurements validated the continuity equation, as the volumetric flow remained constant across different sections of the apparatus. Any minor deviations observed were attributed to experimental factors such as energy losses, frictional effects along the channel walls, and slight fluctuations in the water level in the supply tank. The experiment also highlighted the importance of accurate instrumentation and controlled flow conditions. Proper calibration of the manometer, maintaining a steady and bubble-free flow, and ensuring clean pressure-tap connections were shown to be crucial for obtaining reliable data.

In conclusion, the experiment successfully validated Bernoulli's principle, demonstrated the practical application of the continuity equation, and enhanced understanding of pressure–velocity relationships in internal flows. The insights gained from this study are valuable not only for academic learning but also for real-world engineering applications involving pipelines, nozzles, diffusers, and various hydraulic systems.

X. FUTURE SCOPE

Future enhancements to the experimental setup may include integrating advanced digital or wireless pressure-gradient sensors to achieve higher accuracy and real-time data monitoring, similar to the MEMS-based systems [19]. The use of high-speed pressure-measuring devices, such as dynamically responsive Pitot-tube sensors, can also improve transient-flow measurement accuracy [20]. To broaden the analytical depth of the study, CFD simulations can be conducted and compared with experimental results making use of numerical approaches applied in divergent pipe [21]. Additionally, modifying the setup to allow higher flow rates would help evaluate deviations from Bernoulli's principle under turbulent conditions, complementing the findings on pressure-loss mechanisms [22].

Further exploration may include quantifying major and minor head losses (friction, expansions, contractions, and fittings) under more complex geometrical conditions, inspired by the detailed flow-loss investigations in rock-blasted tunnels [23]. The setup may also be adapted to use fluids with different viscosities or densities, enabling investigation of fluid-property effects on pressure and velocity profiles.

Finally, incorporating these developments would allow the system to simulate practical engineering components such as venturimeter, diffusers, and nozzles for realistic validation of energy-loss behavior and the applicability of Bernoulli's principle in real fluid-transport networks.

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