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Development and Test Performance of a Benchtop Venturi Tube

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Abstract

A Bench Top Venturi tube was developed in this study. The specific objectives of the study were to; develop a benchtop Venturi tube using locally sourced materials, determine the relationship between the volumetric flow rate or discharge of the Ventri tube and the pressure head and validate the experimental result. The components include a 0.5hp water pump, a control switch, water tank, 5 manometers, a Venturi tube, inlet and outlet control valves, inlet hose, discharge hose, hydraulic bench board. However, successful test runs of this bench top Venturi tube at its design operational parameters shows that the bench top Venturi tube is a good apparatus for learning. The construction of the Venturimeter was based on the knowledge gained from the workshop technology practice, fluid mechanics, engineering drawing and technical drawing and researched work. The results were analysed and compared with a standard Khurmi (2006) analysis of flow discharge through Venturimeter and was in good agreement; hence confirming the usefulness of the Bernoulli's principles and continuity equation in the analysis of flow discharge through Venturimeter. The proposed concept is a highly effective solution for the precise control and measurement of fluid flow in various industrial settings, such as oil fields, irrigation systems, automotive industry, wastewater treatment plants, and collection systems. The portable benchtop Venturi tube is designed with an easy-to-assemble and disassemble feature, making it incredibly convenient for use. This flow system is an invaluable tool for practical demonstrations in fluid mechanics studies within Mechanical Engineering Laboratory, facilitating precise fluid control and measurement. Moreover, the affordability of this system makes it an excellent investment for businesses looking for cost-effective fluid measurement and control solutions.

1. Introduction

In many of today's industrial processes, it is essential to measure accurately the rate of fluid flow within a system as a whole or in part. The accuracy and repeat-ability of the flow rate measurements are necessary for process development and control [1]. The most widely used flow metering principle involves placing a fixed area flow restriction in the pipe carrying the fluid. This flow restriction causes a pressure drop that varies with flow rate. Each of the flow measurement devices inherently has its own advantages and disadvantages. Some of those instruments are: orifice, Venturi nozzle, classical Venturi (Herschel type) or V-Cone. Venturi meter is much more predictable and

repeatable for wide ranging flow conditions. Furthermore, the smooth flow pattern in Venturi meter reduces frictional losses which increase the reliability of the Venturi [2].
A Venturi meter or Venturi flow meter is a device used to measure the velocity, or flow rate, of fluid flowing through a pipeline. The Venturi meter constricts the flow using a Herschel Venturi tube. As the liquid flows through the pipeline, the device measures the pressure of liquid before it enters the Venturi tube and as it exits the constricted area [3]. These measurements are then compared to figure the volumetric flow rate of the fluid. The flow meter is commonly used in plumbing applications to determine the flow of fluids such as water, liquid propane, and oil. For this procedure the Venturi tube is typically a long pipe with conically shaped entry and exist points. The entry point is usually a thirty-degree cone which constricts to five-degree cone at the exit. The Venturi meter result is less degradation of the head pressure due to the tube's design [4].
The Venturi mater can accurately measure flow rate using Bernoulli's principle. Bernoulli stated that the velocity of liquid increases in direct proportion to a decrease in pressure. When the liquid is forced through a constricted pipeline, it begins to make at a higher rate of speed because the majority of the pressure is held behind the constriction [5].
A common example of Bernoulli's principle in action can be found in the nozzle of a garden hose. As the nozzle is turned fully open, the water glows slowly and usually falls just a short distance from the nozzle. When the nozzle is turned towards the closed position, it restricts the flow of the water and increases its velocity. The pressure held behind the nozzle builds and the velocity can carry the water for great distances [6].
The Venturi meter precisely calculates the volumetric flow rate of a fluid using a complete formula. This computation considers the radius of the pipeline, whether or not the measured liquid is compressible, and the total volume of fluid present. Various coefficients are added to compensate for the viscosity of the fluid, changes in the conical angles of the Venturi and other variables. When these numbers are calculated, along with the pressure measurements taken by the Venturi meter, an accurate description of the liquid flow rate can be ascertained [1,7].
A Venturi tube, of which the cross-section contracts firstly and then gradually expands, is composed of a contraction section, a throat section and a diffusion section. When the fluid flows through the throat section, the shrunken cross-section will accelerate the fluid accompanied by a pressure drop. This phenomenon is called as a Venturi effect, which will cause the fluid to occur a vacuum draw. In recent years, Venturi pipes have been widely applied in flow measurement, natural gas transmission, internal combustion engine pressurization system and industrial waste gas cleaning and dust removal [3,8]. Venturi tubes are widely used in industry due to the utilization of turbulence generated by the non-uniform structure of the convergent and divergent channel. Due to the gaining popularity of Venturi tubes in the gas and wet gas measurement applications, there are increasing studies being developed to understand its behavior in the application in order to fully benefit from its use.
Fluid mechanics has been a popular subject for laboratory illustration of classroom activities. Laboratory practice, where students design and conduct experiments in support of classroom activities, is an essential part of the educational process. It has been shown that a majority of engineering students learn best when exposed to hands-on exercises and activities [9]. Many publications exist which explain the Venturi meter in detail, and there are also several excellent YouTube videos which demonstrate its use and utility. Hence the need to provide controlled conditions in which scientific or technological research, experiments, and measurement may be performed, as well as designing, fabricating and testing of Venturi tube to understand Bernoulli's theorem [10]. This choice of using a Venturi tube for measuring the mass rate of gas and liquid can be explained by its simple design, low cost and relatively high accuracy achievable in measuring differential pressure [11].
Additional items of interest regarding use of Venturi meters that are not brought out in the case studies cited are worth noting: Venturi meters do not require horizontal installation. The static head components that may be measured as a water column at the respective upstream and throat cross

sections represent a combination of pressure head and elevation head [12]. For an installation where Venturi taps are not in the same horizontal plane an increase (or decrease) in pressure heads (compared with a horizontal installation) is exactly offset by the differing elevation heads. Thus the measured water columns for either case will be the same [13].
The aim of this study is to apply basic knowledge of fluid mechanism to develop a Bench-top Venturi that allows students study the Bernoulli's theorem by measuring the complete static head distribution along the horizontal tube. Specific objectives of this study were to: develop a benchtop Venturi tube using a locally sourced materials, determine the relationship between the volumetric flow rate or discharge of the Ventri tube and the pressure head and validate the experimental result. This work covered the development of the Venturi tube apparatus and performance of the Venturi tube in terms of Bernoulli's apparatus experimental values and theoretical values of the Venturi tube obtained using the apparatus [7,14].
In the design of this project, a review of existing text on the subject background was made in order to design and fabricate a Venturi tube apparatus to help widen practical and theoretical knowledge of Bernoulli equations in engineering materials. The cost, size and ease of operation of this machine are something to look upon. The findings of this study will help students with practical knowledge and also broaden theoretical knowledge of engineering in the tertiary institution on the application of Bernoulli theorem. It is easy to operate plus the materials used for the fabrication of this machine are sourced locally and this helps in the verification of Bernoulli theorem.

2. Methodology

The methodology uses Bernoulli's theorem and Continuity equation in the analysis of the Venturimeter. The design principle of the Venturimeter is based on the theory of discharge of a liquid flowing in a pipe. During the flow of liquid through a pipe, there is an effect known as the Venturi effect. This effect is the reduction in fluid pressure that results when a fluid flows through a constricted section of the pipe. The fluid velocity must increase through the constriction to satisfy the equation of continuity, while its pressure must decrease due to conservation of energy: the gain in kinetic energy is balanced by a drop in pressure or a pressure gradient force. An equation for the drop in pressure due to Venturi effect is governed by Bernoulli's and continuity equations.

3.1 Discharges through a Venturimeter

In this study, the performance characteristics of a Veturimeter are determined. Applying Bernoulli's theorem and Continuity equation; and according to Khurmi [15] to a Venturimeter through which some liquid is flowing as shown in Figure 3 and for completeness,

Let
p_1 = Pressure at section 1
v_1 = Velocity of water at section 1
Z_1 = Datum head at section 1
a_1 = Area of the Venturimeter at section 1
$p_2, v_2, Z_2, a_2 = \text{Corresponding values at section 2}$

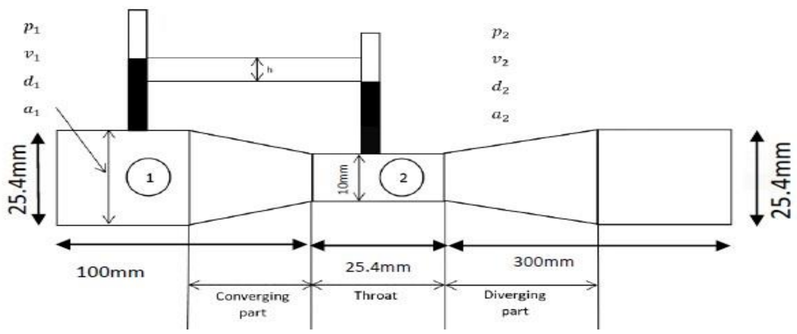

Figure 1 Venturimeter with dimensions as designed for the analysis

Applying Bernoulli's equation at section 1 and 2, we have that,

$$Z_1 + \frac{v_1^2}{2g} + \frac{p_1}{w} = Z_2 + \frac{v_2^2}{2g} + \frac{p_2}{w} \qquad 1$$

Applying the Continuity equation at section 1 and 2, since the discharge is continuous, then,

$$v_1^2 = \frac{a_2^2 v_2^2}{a_1^2} \qquad 2$$

Noting that the pipe is horizontal, then the difference between the pressure heads at sections 1 and 2 represents the Venturi head, denoted as h, hence the relationship between the velocity and the Venturi head is given as,

$$v_2 = \sqrt{2gh}\left(\frac{a_1^2}{a_1^2 - a_2^2}\right) \qquad 3$$

Having been acquainted with the discharge through a Venturimeter as,

$$Q = C\ x\ a_2\ x\ v_2 \qquad 4$$

Where C = coefficient of Venturimeter

By substituting the values of v_2 of Equation 3 in Equation 4 and simplifying the equation, we have the discharge through a Venturimeter as,

$$Q = \frac{C.a_1 a_2}{\sqrt{a_1^2 - a_2^2}}\sqrt{2gh} \qquad 5$$

In this study, the analysis of the discharge of the Venturimeter flow rig was performed with the following data: A Venturimeter with a 25.4mm diameter at inlet and 10mm at the throat is laid with its axis horizontal shown in Figure 3. During the flow, the recorded pressure head of the large section is 6.5 millimetres and that at the throat is 4.25 millimetres. Assuming the metre coefficient, C is 0.99, then: We know that the area at the inlet,

$$a_1 = \frac{\pi}{4}\ x\ \left(d_1^2\right) = \frac{\pi}{4}\ x\ \left(0.0254^2\right) = 5.07\ x\ 10^{-4}\ m^2 \qquad 6$$

And the area at throat

$$a_2 = \frac{\pi}{4}\ x\ \left(d_2^2\right) = \frac{\pi}{4}\ x\ \left(0.01^2\right) = 7.86\ x\ 10^{-4}\ m^2$$

and the discharge through the Venturimeter is given as Equation 3. 5,

$$Q = \frac{C.a_1 a_2}{\sqrt{a_1^2 - a_2^2}}\sqrt{2gh}$$

Substituting the values in the equation for Q, we have that, the discharge at the pressure head (h) of 0.00225 m is Q = 0.52 litres/s.

2.2 Design Considerations

The components used in the development of the machine were carefully selected with the aim of developing a durable and equally efficient device. The design was based on the following factors:

i. Availability of the material.
ii. Cost of the material.
iii. Size and weight.
iv. Physical appearance.
v. Resistance to corrosion.
vi. Safety
vii. Strength and durability.

2.3 Machine description

Benchtop Venturi tube consists of the converging inlet section in which the cross section of the stream decreases and the velocity with consequent increase of velocity head and decrease of pressure head.

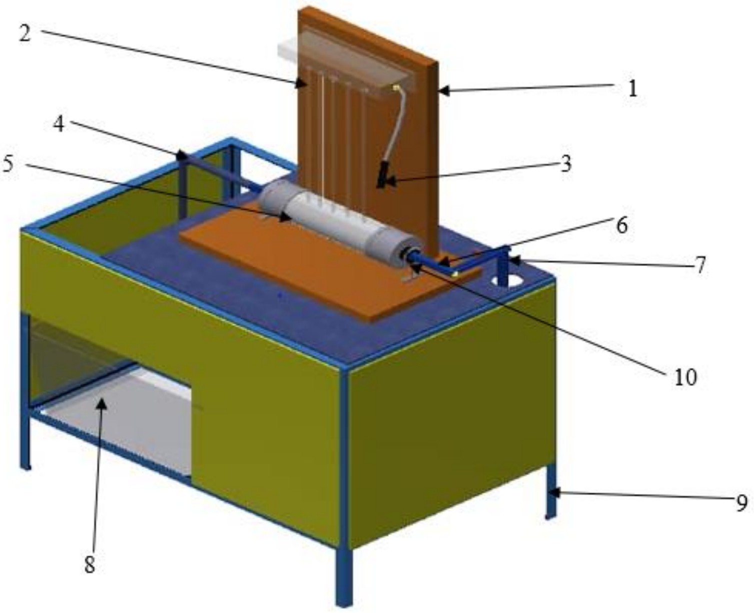

Figure 2: A Venturi standing

Item No	Part Name
1	Board top
2	Piezometers
3	Hand pump
4	Inlet pipe
5	Venturi tube
6	Control valve
7	Outlet pipe
8	Reservoir
9	Hydraulic bench
10	Connectors

2.4. Working Principle

The working principle of a bench top Venturi tube apparatus is the experimental procedures, which states as follows: clean the apparatus and make it free from dust and fill the reservoir with clean water. Allow the water to settle. Switch on the pump to supply water to the Venturi tube and adjust the control vale to have a constant water in the inlet pipe and the discharge (outlet) line. Measure the levels of water in various peizometric tubes and measure the discharge form the reservoir using a stop watch. Repeat the above steps for three runs by regulating the supply valve and calculate the pressure head, and velocity head for each runs.

3. Results and Discussion

The experimental results obtained after conducting the first experiment which involves piezometer tube reading is shown in Table 1 to Table 6.

3.1. Determination of the relationship between the volumetric flow rate or discharge of the Ventri tube and the pressure head

Table 1: Volumetric Flow Rate or Discharge of the Ventri Tube

S/N	Time (s)	Difference in head (m)	Actual volumetric flow rate (m^3/s)(10^{-4})	Theoretical volumetric flow rate (m^3/s)(10^{-4})	Square root of deference in head ($m^{0.5}$)
1	31.9	0.055	1.212	1.317	0.23
2	23.93	0.086	1.617	1.647	0.29
3	18.97	0.136	2.040	2.086	0.37
4	17.29	0.166	2.238	2.288	0.41
5	16.52	0.182	2.343	2.396	0.43
6	16.04	0.193	2.413	2.467	0.44
7	15.12	0.218	2.560	2.622	0.45

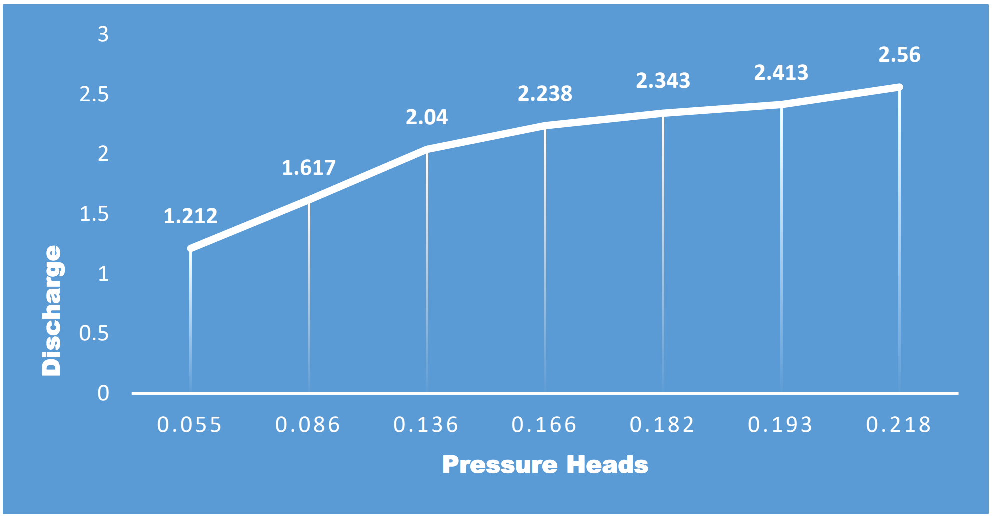

Fig. 3: Relationship between the actual discharge and pressure head

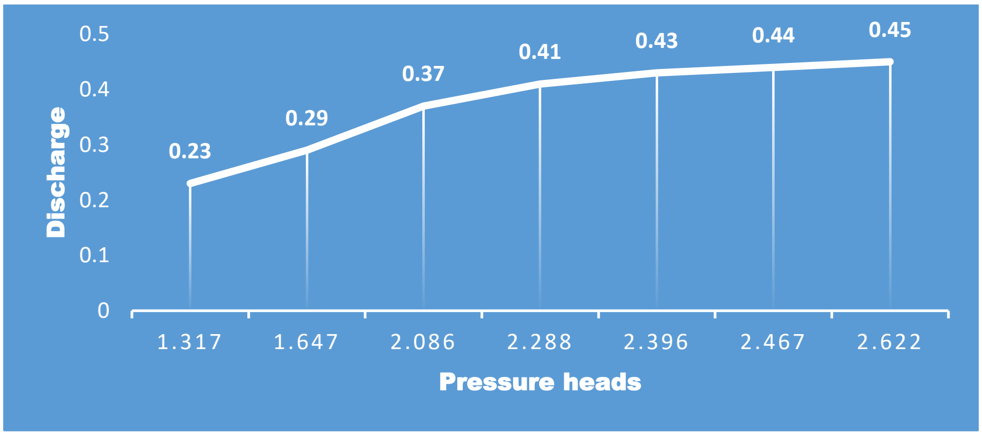

Fig. 4: Relationship between the theoretical discharge and pressure head

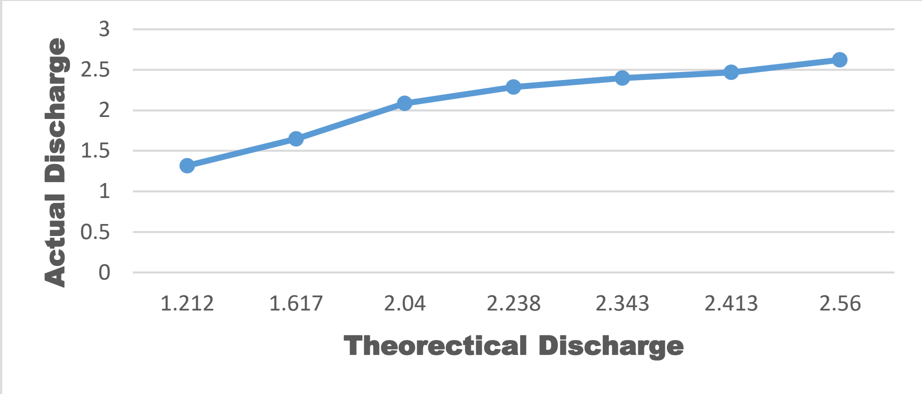

Fig. 5: Relationship between the actual discharge and the theoretical discharge

3.2. Computation Analysis of a Standard Venturi tube

The standard Khurmi [15] experimental data are as follows: A Venturimeter has an area ratio of 9 to 1, the larger diameter being 300 mm. during the flow, the recorded pressure head in the large section is 6.5metres and that at the throat is 4.25 metres. Assuming the metre coefficient, C is 0.99, the computated result of the discharge through the Venturimeter is presented as follows:

$h = h_1 - h_2 = 6.5 - 4.25 = 2.25$ m

Where

h = difference in pressure head

h1 = pressure head in the large section

h2 = pressure head at the throat

Applying the discharge equation which is given in Equation 7 as,

$$Q = \frac{C.a_1 a_2}{\sqrt{a_1{}^2 - a_2{}^2}}\sqrt{2gh} \quad (7)$$

The discharge through the metre is equal to 52 litres/s at the pressure head (h) of 2.25m (Khurmi, 15) an excel spreadsheet program was used for the computation. However, increasing the value of the pressure head produces a corresponding increase in discharge as shown in Table 2. And if these values are plotted on a graph, the result is as shown in Fig. 3 and Fig. 4 as scatter plots and 3D plot respectively.

Table 2: Actual Venturimeter discharge against the Khurmi (2006) data

SN	$h = h_1 - h_2$ (m)	Actual Venturimeteric discharge q (sec)	$h = h_1 - h_2$ (m)	KHURMI discharge q (sec)
1	0.055	1.212	1.25	39.00
2	0.086	1.617	2.25	52.00
3	0.136	2.040	3.25	62.00
4	0.166	2.238	4.25	71.00
5	0.182	2.343	5.25	79.00
6	0.193	2.413	6.25	87.00

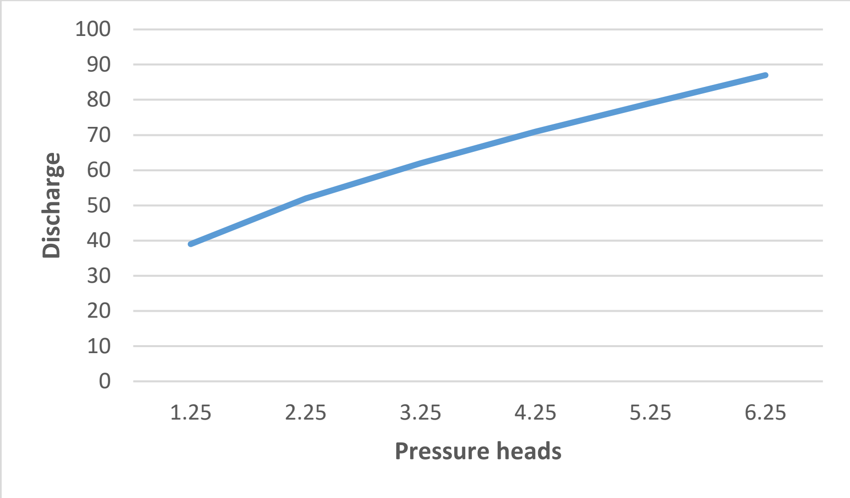

Fig. 6: Shows the relationship between the pressure head and the theoretical discharge as reported by Khurmi [15]

3.3. Validation of Results

The results of the Venturimeter flow were validated against the standard Khurmi [15] results and they were in good agreement since the trends were the same. In each case, as the pressure head increases, there was an increase in discharge in both results as shown in Table 2. This indicated that the higher the head, the higher the flow discharge as presented in Fig. 4; hence confirming the effectiveness of the Bernoulli's principles and continuity equation in the analysis of flow discharge through Venturimeter.

Thus the result of the experiment of Fig. 2 to 3 can be summarized as thus; in each case, as the pressure head increases, there was an increase in discharge in both results as shown in Table 1. This indicated that the higher the head, the higher the flow discharge as presented in Fig. 2 to Fig. 4; hence confirming the effectiveness of the Bernoulli's principles and continuity equation in the analysis of flow discharge through Venturimeter. This implied that the experiment shows that the actual volumetric flowrate is lesser than the theoretical flowrate. Volume flow increases as pressure decreases. A graph was plotted and a value for the coefficient of discharge was found from the gradient [16].

It was observed that at the Venturimeter has a fundamental principle that is based on Bernoulli's principle; when the cross sectional area of a cylindrical flow conduit is reduced, a pressure difference is created, this pressure difference is used in calculating the flow rate or discharge through a pipe [17]. The Venturimeter can accurately measure volumetric flowrate using Bernoulli's principle. In fluid dynamics, Bernoulli's principle states that an increase in the speed of a fluid occurs simultaneously with a decrease in static pressure or a decrease in the fluid's potential energy. Bernoulli's principle can be derived from the principle of conservation of energy. This states that, in a steady flow, the sum of all forms of energy in a fluid along a streamline is the same at all points on that streamline. This requires that the sum of kinetic energy, potential energy and internal energy remains constant [18].

From the Fig. 4, it could be seen that Qact rises steadily with respect to the Q theo. Therefore it can be said here that actual discharge is directly proportional the theoretical discharge. Slop of graph = 0.979, which is the coefficient of discharge which is refer to as the ratio of actual discharge to theoretical discharge [19]. A classical Venturimeter coefficient of discharge is 0.985 as described in ISO 5167-1: 1991. From the graph it can be seen that the value gotten approaches that in the ISO 5167-1, therefore the experiment can be said to be successful. The difference can be due to some errors gotten while taken the readings [5, 20].

4.0 Conclusion

The development and performance test of a benchtop Venturi tube was designed, constructed and tested. The project was successfully completed and the aims achieved. The results were analysed and compared with a standard Khurmi [3] analysis of flow discharge through Venturimeter and was in good agreement; hence confirming the usefulness of the Bernoulli's principles and continuity equation in the analysis of flow discharge through Venturimeter. The idea will be effective applied in the control and measurement of flow alone pipeline in oil field, for irrigation purposes, automotive industry, wastewater collection systems and treatment plants. The benchtop Venturi tube manufactured is portable with the capability of easy assembly and disassembly. This flow system is valuable for practical demonstration of fluid measurement and control in Fluid mechanics studies in Mechanical Engineering Laboratory. The cost is affordable due the used of locally available material; and the cost will further reduce significantly if the benchtop Venturi tube is mass produced.

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