Experimental Investigation of Flow Control Characteristics of Ball Valves

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Abstract - *This research paper summarizes the design and fabrication of the experimental setup used to determine the characteristics curve of the three-way ball valve for varying sizes of valves using a digital ultrasonic flow meter and differential pressure gauge. An attempt has been made to explain the design thinking involved in the designing of the entire setup to achieve the results. Humble efforts have been made to showcase the entire methodology, which helps to obtain a clear understanding of the concept and thus contribute to the growth of the reader's knowledge.*

***Key Words*: Fluid Mechanics, Ball Valve, Characteristic Curve, Mechanical Engineering, Instrumentation Engineering, Digital Electronics, Design Thinking**

1. INTRODUCTION

In this research paper, the reader will get to know the methodology followed, the technology used, designing, fabrication, and experimentation that will enable to obtain the characteristics curve of a three-way ball of varying sizes. It is a composition of various elements of the start-to-end procedure implemented, which are key factors to successfully obtain the desired results. The setup was made to obtain the characteristics curve and is a contribution to academia and industry in the fields of fluid mechanics, mechanical engineering, and control engineering.

1.1 What is Valve, Ball Valve, and Three-Way Ball Valve

The word valve is derived from the Latin word 'Valva', which means a moving part of a door. A valve is a device used for controlling the passage of fluid along the length of a tube, pipe, or duct by the action of opening and closing the passage.

A three-way ball valve is a type of valve that starts or stops and regulates the flow of fluid by using a hollow, perforated ball that is mounted inside the main body. The regulation is done by the movement of the ball which is done with the help of a lever connected to it.

If the hole inside the ball is in line with the flow, it determines whether the valve is open, and if it is perpendicular to the flow that determines whether the flow is obstructed by the ball.

A three-way ball valve is a multiport valve with three openings to which the pipes are connected. These ports are described as one inlet and two outlets, or one outlet and two inlets depending on the required application.

These ports in the ball help the fluids, gases, and slurries mix and divert from

- Completely shut off the flow.
- Flow coming from one inlet can be split into two different outlets.
- The flow can be made to continuously flow in one direction while blocking the outlet.

The main reason for using 3-way ball valves for industrial purposes is that 3-way ball valves can mix and divert two different fluids, which helps in changing physical and chemical properties.

1.2 Type of Flows and Material Composition

There are mainly two patterns in which the fluid in a 3-way ball valve can be made to flow.

L-type 3-way ball valve: It is also known as a diverter valve, as the flow takes place from one inlet port which is fixed, as the output of flow takes place from either of two outlet ports located at 90° from the inlet on both the left and right sides. So, in L-type flow, the inlet side is fixed, but the output direction depends on the position of the lever. The outward flow of water can be altered by adjusting the lever.

T-Type: It is a type of flow that is similar to the L-type, but here the flow takes place in either type.

1) Two inlets, single outlet

2) Two outlets, single inlet

Two inlets, single outlet: In this type of flow, the water enters from both the inlets which are in a straight line and the outlet occurs at the right angle of both the inlets. This type of flow is called a mixer flow, where two liquids can also be mixed, or their properties can be controlled.

Two Outlets, single outlet: Here the flow of water is opposite to the above-mentioned where water enters from a single inlet whereas it exits from both sides. So, the water enters and later turns 90° and diverges on both right and left sides, and thus the water exits from two ports. This is used when a single source of liquid must be divided into two storage tanks.

Material Composition: The body of a 3-way ball is made of materials like stainless steel, brass, and bronze or polyvinyl chloride (PVC); it provides resistance from corrosion.

There are many materials with which 3-way ball valves are made, but the most used materials for 3-way ball valves are stainless steel and brass. Both materials have the same performance, but for high temperatures and pressures, stainless steel is a robust material that can withstand high temperatures and pressure. There are many grades and microstructures of stainless steel that can be used to manufacture a 3-way ball valve. The most used grades are 304, 310, and 316. The most used microstructures are austenite, martensite, and duplex structures.

310-grade stainless steel is compressed with a low concentration of carbon; it is made up of 25% chromium and 20% nickel, which helps to provide resistance to corrosion. 303-grade stainless steel is compressed with a low concentration of carbon; it is an alloy made up of 18% chromium and 8% nickel.

2. CHARACTERISTIC CURVE

It is a graph, which is the representation of the relation between the two independent variables expressed in the Cartesian coordinates.

In fluid machinery, the characteristics curve can be determined for turbines, pumps, and valves by using the parameters such as power (P), head (H), discharge (Q), percentage opening (%), and efficiency (η). It is a two-dimensional graph that has the percentage of flow on the X-axis (abscissa) and has efficiency percentage on the Y-axis (ordinate).

In our case, the characteristic curve shows us the behavior and performance of the 3-way ball valve operated at different rates of openings of the isolation valve (i.e., 25%, 50%, 75%, 100%), which in other terms means the behavior of the 3-way ball valve at different flow rates. To derive a simple understanding, one can predict the behavior of the valve at a certain flow if the characteristic curve is known.

Similarly, we can formulate the characteristic curve of different sizes of valves (i.e., 2”, 2.5”, 3”, 4”) and obtain a single combined graph that will exhibit the behavior and performance of different sizes of valves in a single graph.

With the help of the curve, we can also diagnose the deviations by comparing the ideal curve and the actual curve, which helps us to determine the inefficiencies. Also, it indicates the relationship between the operating conditions and performance parameters.[3]

2.1 Uses and Classification of Characteristic Curve

Uses of Characteristic Curve

1. To obtain a graphical representation of the performance characteristics.
2. To determine the ideal efficiency using the percentage of flow.
    a. To analyze the flow and obtain an understanding of the ideal working conditions.
3. To compare the behavior of different sizes of valves in a single graph.
4. It helps in the selection of products depending on the desired performance characteristics.

Classification of Characteristic curve

1. Equal Percentage
2. Linear
3. Quick Opening

Equal Percentage: It is a type of characteristic curve that represents the change of flow rate of a turbine, pump, or valve for the percentage opening or closing of the input flow. In other words, for an equal percentage increase or decrease in the flow control parameter, there is an equal change in the flow rate as exhibited on the graph.

Linear: In this type of curve, the change occurs linearly (straight line) for every equal increment or decrement in the change of flow control; the change of flow rate is equal in amount.

Quick open: Here in this type of curve the valve, when opened is a significant surge in the flow rate which moderates and levels off, Here the valve is opened, and it is observed that there is an immediate rise in flow levels after which the flow returns to the normal level. [4]

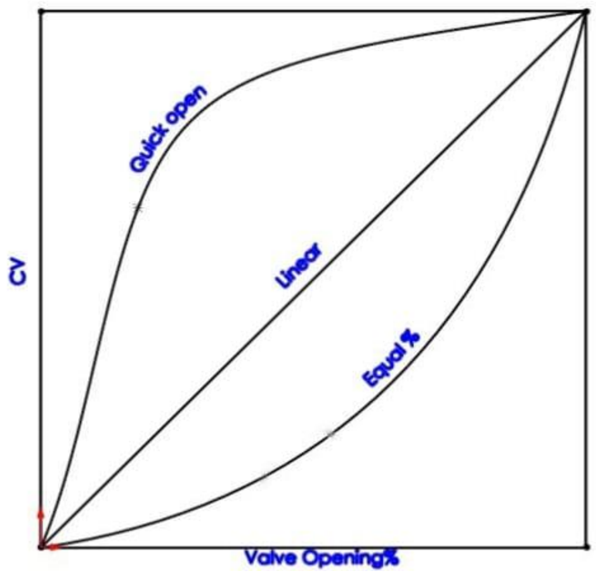

Fig 2.1.1 Types of Characteristics curve

2.2 Flow Coefficient (C_v) and Flow Factor (K_v)

Flow Coefficient (C_v): It is a flow measurement parameter that is used to measure the flow rate through a valve. It is defined as the amount of flow rate taking place in a valve in gallons per minute (GPM) with a pressure drop of 1PSI (Pound Per Square Inch). It is represented as C_v.

$C_v = Q * \sqrt{(SG/\Delta P)}$ (units in US GPM, psi).

Flow Factor (K_v): It is similar to the flow coefficient but in terms of metric units. It is defined as the flow rate of water through a valve in cubic meters per hour(m^3/hr.) at a pressure drop of 1 bar. It is represented as K_v.

$K_v = Q * \sqrt{(SG/\Delta P)}$ (units in m^3/hr., bar).

Both C_v and K_v are used for the selection of the valve depending on their flow capacity. The characteristics curve is a tool for engineers to select a valve based on their desired requirements.

Usually, in the case of valves, the C_v is represented on the Y axis and the K_v is represented on the X axis and a curve can be traced to the actual performance; this curve is a representation of the behavior characteristics of the valve. [4]

3. METERS AND EQUIPMENT FOR TESTING

1) Ultrasonic Flow Meter Specifications for a 4-inch Pipe:
   1. Pipe Size: 4 inches (100 mm) diameter.
   2. Flow Rate Range: Appropriate for the expected flow rates in the 4-inch pipe, e.g., 0 to 500 gallons per minute (GPM) or 0 to 100 cubic meters per hour.
   3. Accuracy: High accuracy, typically specified as a percentage of the measured value, such as ±1%.
   4. Fluid Type: Designed for the specific fluid in your application (e.g., liquids, gases, oil).
   5. Temperature Range: Suitable for the expected temperature range of the fluid in the pipe, e.g., -20°C to 120°C (-4°F to 248°F).
   6. Pressure Rating: Compatible with the pressure conditions of the application, specified in pounds per square inch (psi) or bars.
   7. Transducer Type: Depending on the design, it may use either clamp-on or inline transducers.
   8. Power Supply: Specify voltage and frequency requirements.
   9. Communication Protocol: If part of a larger system, specify the supported communication protocols (e.g., Modbus, HART).
   10. Environmental Conditions: Consider factors like ambient temperature, humidity, and protection against dust/water (e.g., IP65-rated).

Working Principle:

Ultrasonic flow meters use the transit-time or Doppler effect to measure the velocity of the fluid. The two main working principles are:

1. Transit-Time Principle: This method measures the time it takes for an ultrasonic signal to travel upstream and downstream between transducers. The flow velocity can be determined by comparing the transit times.
2. Doppler Principle: This method relies on the frequency shift (Doppler shift) between the emitted and received ultrasonic signals. The frequency shift is proportional to the fluid velocity, allowing for the calculation of the flow rate.

Types:

1. Clamp-On Ultrasonic Flow Meter: External sensors clamp onto the outer side of the pipe, making installation and maintenance easy without disrupting the flow.
2. Inline Ultrasonic Flow Meter: The transducers are inserted directly into the pipe, providing continuous direct measurements.

Technology/Sensor Used:

1. Transducers: Piezoelectric sensors are commonly used. They generate ultrasonic signals and receive reflected signals.

2. Signal Processing: Advanced signal processing techniques, such as digital signal processing (DSP), are employed to analyze and interpret the ultrasonic signals.

Derived Calculation Formulas:

1. Transit-Time Method:
    - Velocity of fluid (V) = Distance between transducers (D) / (Time for downstream travel + Time for upstream travel)
    - Flow rate (Q) = Cross-sectional area of the pipe (A) * Velocity (V)
2. Doppler Method:
    - Doppler frequency shift (Δf) is related to fluid velocity.
    - Flow rate (Q) = Cross-sectional area of the pipe (A) * Velocity (V)

These formulas provide the basis for calculating flow rates based on the measured parameters. Specific devices and manufacturers may have variations in their algorithms and formulas. Always refer to the manufacturer's documentation for accurate and model-specific calculation methods.

2) Differential Pressure Gauge Specifications for a 4-inch Pipe:

1. Pipe Size: 4 inches (100 mm) diameter.
2. Pressure Range: Suitable for the expected differential pressure in the 4-inch pipe (e.g., 0 to 100 psi).
3. Accuracy: High accuracy, often specified as a percentage of the measured value, such as ±1%.
4. Fluid Type: Designed for the specific fluid in your application (e.g., liquids, gases).
5. Temperature Range: Suitable for the expected temperature range of the fluid in the pipe, e.g., -20°C to 120°C (-4°F to 248°F).
6. Pressure Connection Type and Size: Compatible with the pipe's connection type (e.g., NPT, BSP) and size.
7. Mounting Type: Choose between the bottom mount, back mount, or panel mount based on installation requirements.
8. Material Construction: Constructed from materials compatible with the fluid and suitable for the environmental conditions.
9. Environmental Protection: Consider factors like weatherproof or hermetically sealed cases if the gauge will be exposed to harsh conditions.

Working Principle:

Differential pressure gauges measure the difference in pressure between two points in a system. The basic working principle involves a sensing element that responds to the pressure difference, causing a displacement or deformation that is then translated into a readable pressure value.

Types:

1. Diaphragm-type Differential Pressure Gauge: Uses a diaphragm as the sensing element. The pressure difference causes deflection, and this deflection is translated into a pressure reading.
2. Bourdon Tube-type Differential Pressure Gauge: Utilizes a Bourdon tube as the sensing element. Differential pressure causes the tube to deform, and the movement is converted into a pressure reading.

Technology/Sensor Used:

1. Diaphragm-type Sensors: Made from materials such as stainless steel or other alloys.
2. Bourdon Tube Sensors: Typically made from materials like bronze or stainless steel.

Derived Calculation Formulas:

The formula to calculate differential pressure (ΔP) is straightforward:

$$\Delta P = P1 - P2$$

Where:

- ΔP is the differential pressure.
- P1 is the pressure at the first point.
- P2 is the pressure at the second point.

This basic formula represents the pressure difference that the differential pressure gauge measures. The gauge is calibrated to provide a direct reading of this differential pressure. Always refer to the specific product documentation for any corrections or adjustments needed for accurate readings.

3.1 Methodology for Experimentation.

To test the performance of the 3-way ball valve and determine the characteristics curve, we fabricate a setup that can serve this purpose. Below is Figure 3.1.7, of the existing Francis turbine setup in which we make alterations and introduce a blank (spacer) and a Tee section to divert the flow. Also, shown in the figure we see a two-way ball valve which serves as a control valve to open and close the flow of water to the further setup.

Later, a pipe is mounted to the two-way valve which is later connected to a hub and then to the three-way ball valve (test valve). Here the hub is introduced between the pipe and the valve to facilitate testing of multiple sizes of valve in the same setup.

The ultrasonic flow meter sensor is mounted on the long pipe as shown in Figure 3.1.2, which is connected to the meter as shown in Figure 3.1.5. The differential pressure gauge has two ports (inlet and outlet), which are mounted on the inlet and outlet flanges of the three-way ball valve shown in Figure 3.1.4, which is used to find the pressure drop and individual pressure readings, which are displayed on the meter shown in figure 3.1.6. [1]

After the arrangement of the same, the setup is run for 10 minutes to achieve a steady flow condition, after which the readings are taken. The three-way ball valve is then opened at different rates of openings, such as 10, 20, and 30 until 100%, for which we note the flow rate and the pressure drop from both meters respectively. A tabular column is plotted using the following parameters: Percentage valve opening, Flow rate, and Pressure drop. Using this we plot the characteristics curve in which the x-axis of the graph is Flow Rate (Q) in mt^3/hr. and the y-axis is Pressure Drop (ΔP) in kg/mt^3 [2].

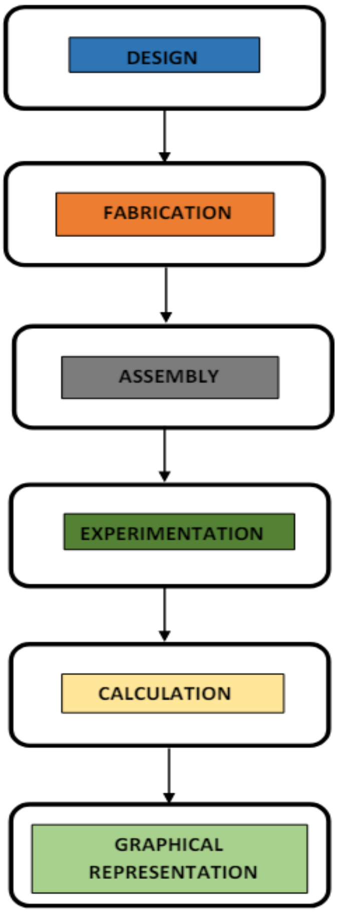

Fig3.1.1 Methodology Followed

Fig3.1.2 Ultrasonic Flow Sensor Mounted on Pipe

Fig 3.1.3 Pipe connected to 2 &3 way Valve

Fig 3.1.4 Differential Pressure gauge mounting on inlet and outlet of 3way ball valve

Fig 3.1.5 Handheld Ultrasonic flow meter.

Fig 3.1.6 Differential Pressure Guage.

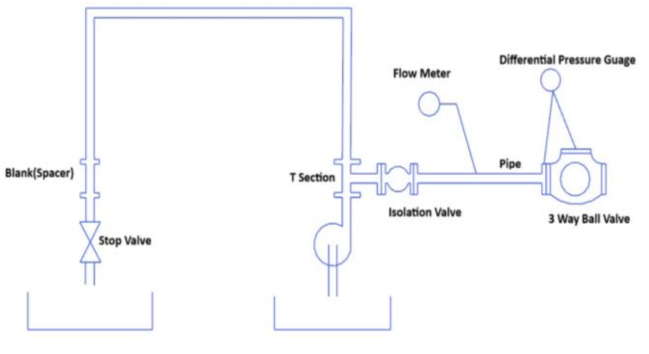

Fig 3.1.7 Line Diagram of the Setup.

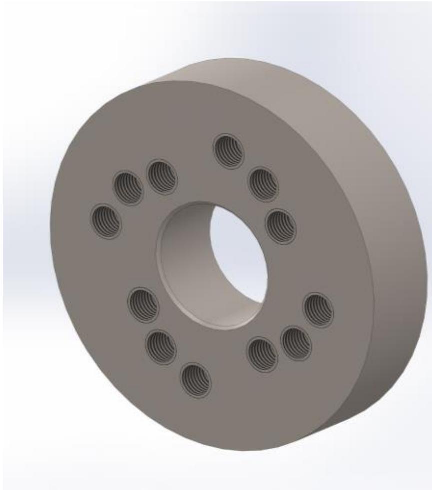

Fig 3.1.8 Hub Attachment for testing Multiple sizes of Valves (2,2.5,3 inches).

Fig3.1.9 Operator using an ultrasonic flow meter and sensors mounted on the pipe.

4. EXPERIMENTATION AND GRAPHICAL RESULTS

Table -1: Observation table for 2inch L-port Hollow ball

Observation Table			
Sl.no	Percentage Valve opening (%)	Flow Rate (Q) in mt^3/hr.	Pressure Drop(ΔP) in kg/mt^3
1.	0	0	-
2.	10	6.05	0.0016
3.	20	30.01	0.14
4.	30	41.68	0.24
5.	40	50.9	0.35
6.	50	59.93	0.47
7.	60	62.50	0.51
8.	70	64.52	0.56
9.	80	65.63	0.60
10.	90	66.76	0.63
11	100	67.33	0.65

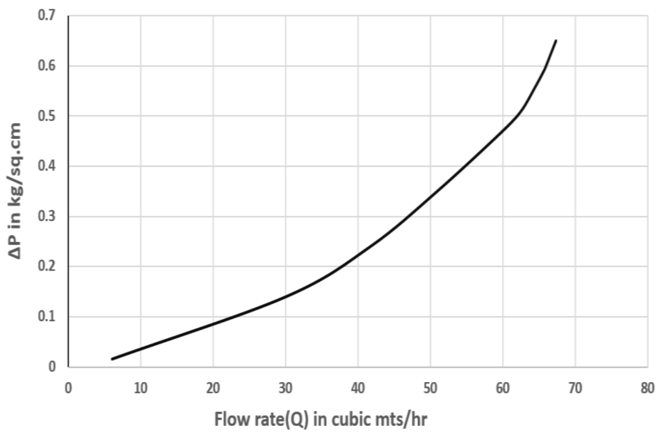

Fig 4.1 Characteristics Curve of 2" 3way L-port Ball Valve (Hallow)

Table -2: Observation table for 2inch L-port Solid ball

Observation Table			
Sl.no	Percentage Valve opening (%)	Flow Rate (Q) in mt^3/hr.	Pressure Drop(ΔP) in kg/mt^3
1.	0	0	-
2.	10	7.29	0.03
3.	20	37.27	0.22
4.	30	49.97	0.34
5.	40	56.25	0.43
6.	50	60.79	0.5
7.	60	64.04	0.55
8.	70	64.61	0.57
9.	80	65.1	0.58
10.	90	65.5	0.59
11	100	66.2	0.6

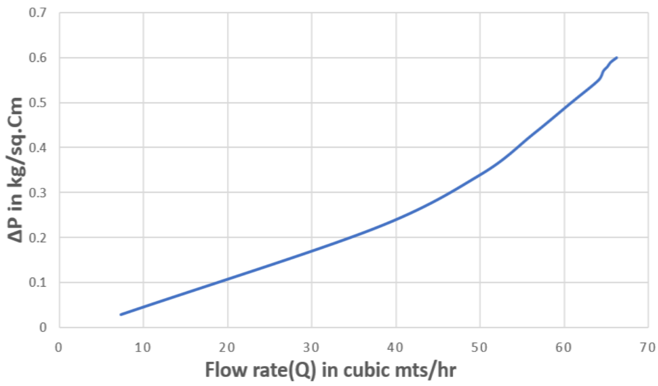

Fig 4.2 Characteristics Curve of 2" 3way L-port Ball Valve (Solid)

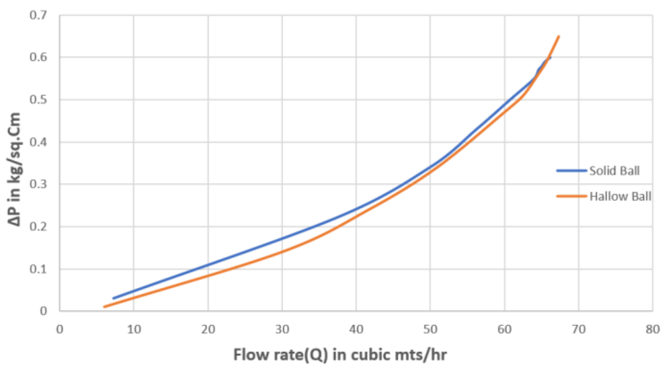

Fig 4.3 Comparison Curve of 2" 3way L-port Ball Valve

Table -3: Observation table for 3inch L-port ball valve

Observation Table			
Sl.no	Percentage Valve opening (%)	Flow Rate (Q) in mt^3/hr.	Pressure Drop(ΔP) in kg/mt^3
1.	0	0	-
2.	10	6.05	0.01
3.	20	30.01	0.14
4.	30	43.38	0.24
5.	40	59.93	0.47
6.	50	63.91	0.54

7.	60	64.52	0.56
8.	70	65.6	0.59
9.	80	65.93	0.60
10.	90	66.77	0.63
11	100	67.3	0.65

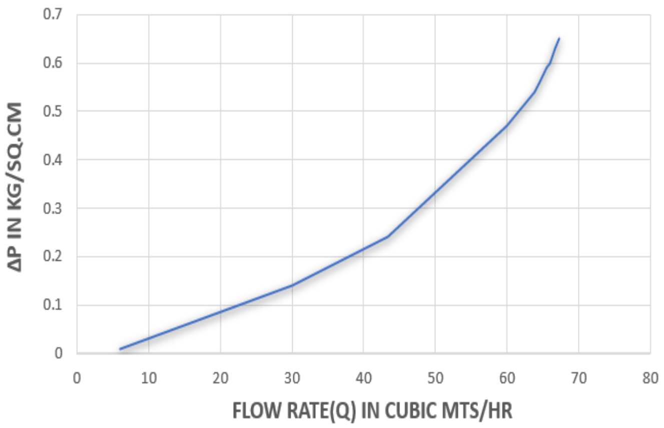

Fig 4.3 Comparison Curve of 3" 3way L-port Ball Valve

5. CONCLUSION

We derive the conclusion from the above entire paper and through the experimentation setup that as the opening rate of the valve increases, the flow rate (Q) and the pressure drop (ΔP) increase.

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