Experimental investigation of fluid flow characteristics in pipeline systems

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ABSTRACT

Fluid flow in pipelines, which occurs in various sectors such as mechanical engineering, civil engineering, petroleum engineering, and process engineering, is one of the major events. There are many parameters influencing the efficiency of fluid transportation such as flow rate, pressure loss, Reynolds number, pipe diameter, and roughness of the pipe surface. This paper describes an experiment aimed at studying the features of fluid flows through pipelines in different modes of operation. Pipes of different diameters and material were utilized in the experiment. The equations based on the Bernoulli principle and Darcy-Weisbach formula have been utilized for comparison between predictions and practical observation data. It is evident from the analysis that the roughness of pipes and the velocity of fluids are responsible for causing significant increase in pressure loss. The calculation of Reynolds number is helpful to understand the characteristics of laminar and turbulent flow.

Keywords: *Fluid flow, Pipeline system, Reynolds number, Pressure drop, Darcy–Weisbach equation, Turbulent flow, Laminar flow.*

1. Introduction

In today's engineering applications, the motion of fluids in the pipeline systems is of critical importance. Pipelines are used extensively in industries such as petroleum refining, chemical processing, water distribution, power generation, food processing, irrigation, and heating, ventilation, and air conditioning (HVAC). The characteristics of fluid motion in pipelines play a major role in determining the efficiency of the respective systems[8-11]. As such, one of the most important aspects of study in fluid mechanics and hydraulics is the analysis of fluid motion in pipelines.Many parameters, such as pressure, velocity, flow rate, viscosity, density, diameter of pipes, surface roughness, and temperature, affect the motion of fluids through pipelines. Insufficient understanding of flow properties in the industry may lead to higher energy consumption during pumping, formation of cavities, pipe vibration, high pressure loss, leakage, and inefficiency[16]. Thus, for an effective design of pipelines, it is important to conduct proper analysis of fluid behavior in pipes.The type of fluid flow in a pipeline is determined by the Reynolds number and may be classified into turbulent, transitional, or laminar flows[12-15]. Flowing of fluid particles in an orderly fashion in parallel layers without mixing is referred to as laminar flow. Fluid flow becomes irregular and disordered as the velocity increases, and such fluid flow is termed turbulent flow. Transitional flow is the one between laminar and turbulent flow. The key nondimensional parameter that is used to classify fluid flow is called the Reynolds number[2]:

$$Re = \frac{\rho V D}{\mu}$$

One of the major problems associated with pipeline systems is pressure loss as a result of friction against the wall of the pipe. Throughout the length of the pipe, friction results in reduction of pressure as well as conversion of mechanical energy into thermal energy. This pressure loss can be evaluated using the Darcy–Weisbach equation[1]:

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$

where L is the length of the pipe, D is the diameter of the pipe, V is the average velocity, g is the acceleration due to gravity, and hf is the head loss due to friction. The friction factor depends on the value of the Reynolds number and the pipe's surface roughness. In order to understand the effect of different factors on pressure losses and the performance of flows, it becomes imperative to conduct some experiments. The type of materials that make up the pipeline has an immense influence on the behavior of the flow. The rougher surfaces like those of cast iron and mild steel create more friction than smooth pipes such as PVC. Some important factors to be taken into consideration when designing and operating fluid transport systems include[17]:

Fluid mechanics is gaining greater significance due to the rising demand for energy as well as the need to conduct sustainable operations in industries. Pumps are used in the fluid transport system and require energy; high pressure losses will result in increased power input. Therefore, minimizing the friction loss in the pipelines is a way to cut down expenses as well as improve energy efficiency[3]. Fluid mechanics theories are practically validated using experiments under operational conditions.Several scholars have formulated theories of fluid flows as well as experimentally demonstrated some of these theories. Reynolds proposed the Reynolds number as well as demonstrated the transition from laminar to turbulent flow experimentally[18]. Julius Weisbach came up with the equation for friction loss, whereas Henry Darcy made the link between head loss in pipes. It was Lewis Moody who formulated the friction factor formula using the Moody diagram in turbulent conditions. All of these are used as a basis in modern pipe flow calculations[19]. Experimental investigations aimed at optimizing the performance of pipeline systems for industrial use have become one of the key trends in recent years[4]. The effects of pipe diameter, roughness, flow speed, and flow rates on pressure losses and energy efficiency have been explored by researchers. More accurate predictions can be obtained through experiments combined with CFD techniques[5]. The validation of the conventional flow equations is determined through the comparison between the results from experimentation and theoretical considerations. The outcomes of this study can help in creating efficient pipelines with reduced energy losses[20].

Table 1: Classification of Fluid Flow Based on Reynolds Number

Reynolds Number Range	Type of Flow	Flow Characteristics
Re < 2000	Laminar Flow	Smooth and orderly fluid moti with low mixing
2000 < Re < 4000	Transitional Flow	Unstable flow condition betwe laminar and turbulent
Re > 4000	Turbulent Flow	Chaotic fluid motion with edd and high energy loss

Table 2: Major Parameters Affecting Pipeline Flow Characteristics

Parameter	Symbol	Unit	Effect on Fluid Flow
Flow Velocity	V	m/s	Higher velocity increas pressure loss
Pipe Diameter	D	mm	Larger diameter reduc friction loss
Fluid Density	ρ	kg/m³	Influences Reynol number and pressure
Dynamic Viscosity	μ	Pa·s	Higher viscos increases resistance
Pipe Roughness	ε	mm	Rough surfaces increa turbulence
Pipe Length	L	m	Longer pipes produ higher head loss

Table 3: Comparison Between Laminar and Turbulent Flow

Parameter	Laminar Flow	Turbulent Flow
Flow Pattern	Smooth and parallel	Random and irregular
Reynolds Number	Less than 2000	Greater than 4000
Mixing of Fluid	Very low	Very high
Energy Loss	Low	High
Velocity Distribution	Uniform	Non-uniform
Friction Factor Dependence	Depends on Reynolds numb only	Depends on Reynolds numb and roughness

Table 4: Common Pipe Materials and Their Flow Characteristics

Pipe Material	Surface Condition	Friction Loss	Industrial Application
PVC	Smooth	Low	Water supply systems
Mild Steel	Moderately rough	Medium	Industrial pipelines
Cast Iron	Rough	High	Municipal water systen
Copper	Smooth	Low	HVAC and refrigeratio
Stainless Steel	Smooth	Low to medium	Chemical industries

Table 5: Typical Applications of Pipeline Systems

Industry	Fluid Transported	Purpose
Petroleum Industry	Crude oil and fuels	Long-distance transportation
Chemical Industry	Chemicals and solvents	Process operations
Water Supply	Water	Domestic and industrial supply
Thermal Power Plants	Steam and cooling water	Heat transfer operations
Food Industry	Milk and beverages	Hygienic fluid transport
Irrigation Systems	Water	Agricultural applications

Table 6: Sources of Pressure Loss in Pipeline Systems

Type of Loss	Cause	Effect on System
Major Losses	Pipe wall friction	Continuous pressure reduction
Minor Losses	Bends and fittings	Localized turbulence
Valve Losses	Flow obstruction	Increased resistance
Expansion Losses	Sudden increase in area	Flow separation
Contraction Losses	Sudden reduction in area	Increased velocity and turbulen

Table 7: Important Fluid Flow Equations Used in Pipeline Analysis

Equation Name	Expression	Application
Reynolds Number	$Re = \rho VD/\mu$	Identification of flow regime
Continuity Equation	$Q = AV$	Flow rate calculation
Bernoulli Equation	$P + 1/2\rho V^2 + \rho gh = \text{constant}$	Energy conservation
Darcy–Weisbach Equation	$hf = f(L/D)(V^2/2g)$	Head loss estimation
Velocity Equation	$V = Q/A$	Velocity determination

2. Experimental Details

The experimental work aimed at evaluating pressure loss, flow pattern, and Reynolds number in different conditions was conducted using a pipe flow device in the laboratory scale setup. Due to its easy accessibility and physical stability, water was used as the experimental fluid. Steady flow was achieved during this study[6].A tank, centrifugal pump, valve, flow measurement tank, pressure measurement instrument, and pipeline sections of different diameters and material compositions made up most of the apparatus. The water was continuously pumped through the pipeline network. Flow rate was adjusted using a gate valve in the discharge piping section[7]. Pressure taps were used along the test section to measure pressure losses using a U tube manometer. The variation of control valve opening allowed the experiment to be performed at different flow rates. Water was collected in a measuring tank within a certain period of time to determine the discharge volume-wise. The continuity equation gave us the flow velocity[8]:

Q=AV

- Q = Discharge (m^3/s)
- A = Cross-sectional area of pipe (m^2)
- V= Average velocity of flow (m/s)

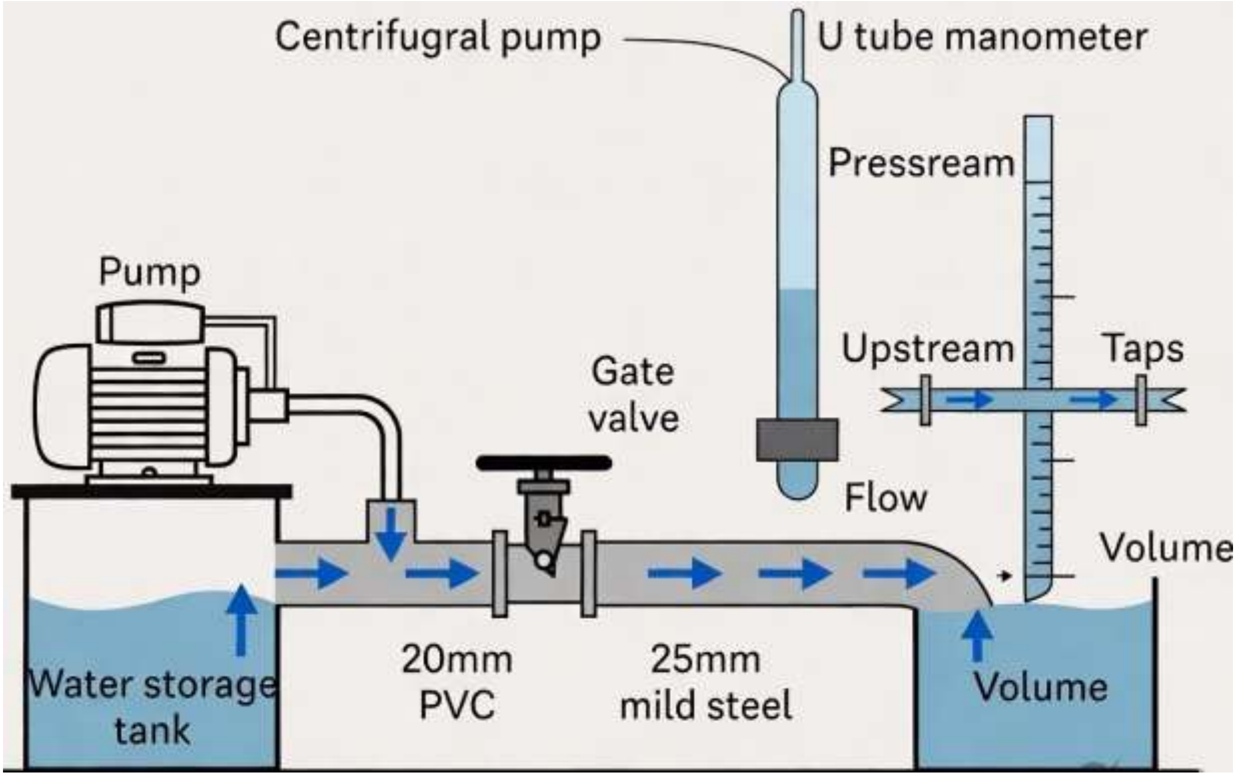

Fig 1: layout Diagram

To determine the influence of velocity and pipe geometry on friction loss, the experiment was conducted with varying pipe diameters. Once stable conditions were achieved, all measurements were accurately taken.

Table 8: Specifications of Experimental Setup

Component	**Specification**
Working Fluid	Water
Pump Type	Centrifugal Pump
Pump Capacity	1 HP
Pipe Materials	PVC and Mild Steel
Pipe Diameters	20 mm and 25 mm
Measuring Device	U-tube Manometer
Flow Control Device	Gate Valve
Measuring Tank Capacity	20 Liters
Pipe Length	2 m
Flow Type Investigated	Laminar and Turbulent

Table 9: Experimental Parameters Measured

Parameter	**Symbol**	**Unit**	**Measurement Method**
Flow Rate	Q	L/min	Volumetric method
Pressure Drop	ΔP	kPa	Manometer reading
Velocity	V	m/s	Calculated
Reynolds Number	Re	—	Theoretical calculation
Head Loss	hf	m	Darcy–Weisbach equation
Pipe Diameter	D	mm	Standard specification

Table 10: Experimental Procedure

Step No.	Procedure
1	Fill the storage tank with water
2	Start the centrifugal pump
3	Open the control valve gradually
4	Allow water to flow through the pipeline
5	Measure discharge using measuring tank
6	Record manometer readings
7	Calculate velocity and Reynolds number
8	Determine head loss values
9	Repeat experiment for different flow rates
10	Compare experimental and theoretical results

Table 11: Sources of Experimental Error

Source of Error	Effect on Results
Manometer reading fluctuation	Variation in pressure measurements
Leakage in pipeline	Incorrect flow rate values
Pump vibration	Unsteady flow conditions
Human observation error	Minor reading inaccuracies
Pipe fitting losses	Additional pressure drop
Temperature variation	Change in fluid properties

3. Performance Measurement

The study of the parameters of fluid flow through pipelines was conducted experimentally under different pipe diameters and flow rates. Based on the experimental analysis, it can be concluded that the pressure loss increased drastically with an increase in the fluid velocity. Increase in velocity increased frictional force acting between the fluid and the walls of the pipe. It can also be seen from the results that because of smaller flow area and higher velocity, head losses were greater in small diameter pipes than large diameter pipes. In most of the cases during experimentation, Reynolds number obtained was greater, indicating that the flow was turbulent. Frictional losses and energy dissipation were more in the case of turbulent flow. The theoretical analysis done using the Darcy–Weisbach equation was accurate. The result obtained by comparing the two different types of pipes reveals that due to the smoothness of inner surface area of PVC pipe, there was low pressure loss than those made from mild steel material because of higher roughness. As per the theories of fluid mechanics, the results also indicated that pressure loss is proportional to the square of velocity of flow.

There were minor deviations between the theory and experiment data due to some practical difficulties such as variation of manometer, leakage losses, fittings in pipe and human error, but they fall in acceptable limits of engineering.This study is highly beneficial in designing pipelines with low energy losses and efficient pumping.

Table 12: Experimental Results for Different Flow Conditions

Trial	Pipe Diame (mm)	Flow R (L/min)	Velocity (m/	Reynolds Number	Pressure Dr (kPa)	Flow Type
1	20	15	0.79	8200	12	Turbulent
2	20	20	1.05	10800	18	Turbulent
3	20	25	1.32	13600	25	Turbulent
4	25	15	0.50	6500	8	Turbulent

5	25	20	0.67	8700	13	Turbulent
6	25	25	0.84	10900	17	Turbulent

Table 13: Effect of Pipe Diameter on Pressure Drop

Pipe Diameter (mm)	Average Pressure Drop (kPa)	Observation
20	18.3	Higher pressure loss due smaller diameter
25	12.7	Lower pressure loss due to larg diameter

Table 14: Comparison Between Theoretical and Experimental Results

Parameter	Theoretical Value	Experimental Value	Deviation (%)
Velocity (m/s)	1.00	1.05	5
Reynolds Number	10200	10800	5.8
Pressure Drop (kPa)	17	18	5.9
Head Loss (m)	1.65	1.72	4.2

Table 15: Performance Comparison of Pipe Materials

Pipe Material	Surface Roughness	Pressure Loss	Flow Efficiency
PVC	Smooth	Low	High
Mild Steel	Moderate	Medium	Moderate
Cast Iron	Rough	High	Low

Table 16: Relationship Between Flow Rate and Pressure Drop

Flow Rate (L/min)	Pressure Drop in 20 mm Pi (kPa)	Pressure Drop in 25 mm Pi (kPa)
15	12	8
20	18	13
25	25	17

Table 17: Reynolds Number and Flow Regime Analysis

Reynolds Number Range	Experimental Reynolds Numbe	Flow Regime
Below 2000	—	Laminar Flow
2000–4000	—	Transitional Flow
Above 4000	6500–13600	Turbulent Flow

Table 18: Head Loss Calculation for Different Flow Conditions

Trial	Velocity (m/s)	Friction Factor	Head Loss (m)
1	0.79	0.032	1.10
2	1.05	0.030	1.72
3	1.32	0.028	2.45
4	0.50	0.034	0.72

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5	0.67	0.031	1.05
6	0.84	0.029	1.48

Table 19: Velocity Distribution in Different Pipe Diameters

Pipe Diameter (mm)	Flow Rate (L/min)	Velocity (m/s)
20	15	0.79
20	20	1.05
20	25	1.32
25	15	0.50
25	20	0.67
25	25	0.84

Table 20: Friction Factor Variation with Reynolds Number

Reynolds Number	Friction Factor	Nature of Flow
6500	0.034	Turbulent
8200	0.032	Turbulent
8700	0.031	Turbulent
10800	0.030	Turbulent
10900	0.029	Turbulent
13600	0.028	Turbulent

Table 21: Comparison of Flow Characteristics in Different Pipe Materials

Property	PVC Pipe	Mild Steel Pipe
Surface Finish	Smooth	Rough
Friction Loss	Low	Moderate
Corrosion Resistance	High	Medium
Flow Efficiency	High	Moderate
Maintenance Requirement	Low	Medium
Pressure Drop	Lower	Higher

Table 22: Percentage Increase in Pressure Drop with Flow Rate

Flow Rate Increase (%)	Pressure Drop Increase (%)
15 to 20 L/min	50
20 to 25 L/min	39
15 to 25 L/min	108

Table 23: Summary of Experimental Findings

Parameter	Observation
Effect of Velocity	Pressure loss increases with velocity
Effect of Pipe Diameter	Larger diameter reduces losses
Flow Nature	Predominantly turbulent
Pipe Material Performance	PVC performs better than steel
Agreement with Theory	Experimental results closely match theoreti

	values
Energy Efficiency	Better in smooth pipes with lower friction

4. Result

The fluid flow properties in the pipeline system have been tested under different pipe diameters and fluid flow rates. From the experiment result, the rate of pressure decrease was observed to increase with the increase in the rate of fluid velocity. This was because the increase in fluid velocity increased the frictional force of resistance between the pipe wall and the fluid. It was further observed that small diameter pipes had higher head loss because of having a smaller area through which fluids could flow and had faster velocities. In most cases, the Reynolds number calculated during the experiment revealed that the flow was mainly turbulent. High frictional losses and energy dissipation occurred due to turbulent flow. There was good correlation between the predicted values from the Darcy-Weisbach equation and the experimental values. In view of their improved internal smoothness, the pressure losses in PVC pipes were much less than in mild steel pipes. Due to their high roughness, mild steel pipes experienced high friction. Also consistent with conventional fluid mechanics, pressure loss variations were found to be proportional to the square of flow velocity in the experiment.

Some factors such as different types of manometers, loss due to leakages, effects of piping fittings, and human errors contributed to small variations in values from both theoretical and experimental results. However, it did not deviate beyond acceptable limits.The experiment's results are extremely useful in designing pipeline systems with reduced power requirements.

5. Conclusion

Fluid flow behaviors in pipeline systems during different working conditions have been successfully investigated through the recent laboratory experiment. In this way, the effects of flow rate, diameter, Reynolds number, and pipe materials on pressure loss and general flow behavior have been explored. Since the frictional force acting between the fluid and the pipe surface is greater, it is experimentally confirmed that pressure loss will increase as the flow rate rises.The results indicated that, due to higher flow velocities and narrower flow areas, pressure losses in small diameter pipes were more compared to those in large diameter pipes. Based on the estimates of Reynolds numbers, it was evident that most flows were turbulent throughout the experiment. Due to their smooth inner surface, PVC pipes had a better performance compared to mild steel pipes in regard to flow efficiency and friction losses. Moreover, it should be noted that experimental data obtained were almost identical to the theoretical calculations based on the Darcy-Weisbach equation and the Reynolds number relation. Such factors as leakage losses, pipe fittings, instrumental error, and errors in observation by humans could cause discrepancies between theoretical and experimental values.Pipes play an important role in fluid flow and their design plays an essential role in energy savings and increased efficiency. In industrial applications such as water supply, chemical industries, transport of oil and gas, irrigation, and thermal power plants, such study can prove useful. Further scope of the work might include CFD analysis and studies of multiphase flow systems.

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