

Experimental Investigation of Pressure Loss and Friction Factor in Water Flow through Pipes of Different Diameters

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Abstract. *The present experimental study concerns the hydraulic losses of water flowing in galvanized steel tubes of diameters 1, 1.5 and 2 inches. A closed-loop hydraulic circuit was built to test head loss and pressure drop for flow rates from 20 to 80 L/min. The Reynolds number ranged from about 8.35×10^3 to 46.68×10^4 , which resulted in fully turbulent flow throughout the duration of all experiments conducted. The head loss increased considerably advanced flow rate as presented in the results, where The maximum head loss observed for 1-inch pipe at a flow of 80 L/min was 2.8 m and the lowest of any 2-inch pipe at the flow of 20 L/min was 0.1 m. Pressure drop (0.01 bar to 0.28 bar) also varied based on flow conditions and pipe diameter. The friction factor decreased with higher Reynolds number values from 0.035 to 0.020. The results showed a linear correlation between velocity squared and head loss (or pressure drop), therefore sufficiently confirming the application of the Darcy–Weisbach equation. Experimental results were in good agreement with theoretical predictions of scattered light intensity, deviating on average by 9–11%. These results illustrate the effects of pipe diameter and flow rate on hydraulic performance with implications for design and optimization of pipe flow systems.*

Keywords: Pipe Flow, Head Loss, Pressure Drop, Friction Factor, Reynolds Number, Turbulent Flow, Pipe Diameter, Darcy–Weisbach Equation

1. Introduction

Fluid flow through pipes is a fundamental principle in many engineering applications like water supply systems, industrial processes, and energy systems. These systems have several meters long pipes through that falid and lose energy from module friction to pipe wall. These losses are commonly referred to as head loss and pressure drop because they affect not just the performance but efficiency. Pipe diameter is one of the main parameters causing hydraulic losses. A higher flow velocity in a smaller pipe means more loss due to friction and energy dissipation. Low speeds and losses opposite with greater diameters. Additionally, pump flow rate is also a key component as increasing flow rates will increase the Reynolds number creating more turbulence. Theoretical backgrounds show that definitive equations such as the Darcy–Weisbach are often used when calculating head loss across pipes. However, the utility of these models under real working conditions must be experimentally validated. This is especially true with regards to the friction factor, which varies with both Reynolds number and relative roughness. In this study, we perform

an experimental investigation into the roles of flow rate and pipe diameter on pressure drop, head loss, and friction factor in water flow systems.

The analyzed data is then compared against theoretical predictions to assess the validity of widely used equations. The experimental and numerical investigation of flow in corrugated spiral tubes, showed that the enhancement of heat transfer by increased turbulence due to the corrugations comes at a considerable additional pressure loss increase [1]. With respect to the design of surfaces with low frictional losses in pipes [2], the researcher followed up on possible influences by also looking at porous structures and their permeability and roughness related to turbulent boundary flow layers. Consequently, the investigation of pressure losses in primary channels with regard to channel size and surface roughness trumps other factors about frictional losses in achieving minimum hydraulic resistance and effective water transportation [3]. This was followed by extensive experimental studies on friction loss in turbulent flow through steel and plastic pipes. Based on the findings, it was concluded that due to their rough surfaces, steel pipes experienced more loss compared to plastic pipe [4]. Resistances to flow and losses in energy flow were described for pipes made of different materials. Losses could be from fluid flow rates to roughness plastic losses smallest and metal pipes loss most [5]. It was investigated how they compare to head losses in PVC, steel, and copper. The least loss of power consumption is that of PVC, followed by steel and copper, while the flow rate has considerable impact on material difference [6]. These studies set practical baselines for theoretical predictions against measured performance. Based on the test, and in similar condition for ash-water slurry the pressure drop in a curved pipe was conducted and it has been suggested that as curvature and concentration of ash grows, this will increase frictional losses [7]. Discussing the frictional characteristics of tube-in-tube, curvature results in turbulent flow and pressure loss is higher compared to straight tubing which can be utilized for heat exchanger applications [8]. Comparison between H-W and D-W equations for head loss estimate in Iraq water lines. Darcy-Weisbach is more rigorous, while Hazen-Williams is straightforward which can give wrong results in some case [9]. The study proposed to investigate the head losses effect due to pipe configuration. The demand increases losses cyclically and optimal design minimizes the losses, which improves system performance [10]. Another experimental study used empirical regression-based correction for pressure losses in polyethylene pipes. A roughness based modified friction factor was analyzed for loss estimates in a galvanized steel (GS) and acrylonitrile butadiene styrene (ABS) based pipe using Computational fluid dynamics simulation taking into consideration surface upheaval [11]. The results were more accurate than the ones realized by classical models [13] which enables a better planning and functioning of water networks with less frictional loss. A third study of laminar to turbulence transition for high viscosity viscous flow on a pipe was conducted. The analysis utility in reducing frictional losses was observed translational industrial applications as well theoretical and experimental tool developed to enhance system design [13]. The surface roughness for Polyether Ether Ketone 3D printed parts was also investigated in terms of their influence on fluid flow and frictional loss, resulting in improvements to the manufacturing process that reduces energy losses while improving hydraulic performance [14]. The surface roughness effect on frictional losses in pipes was introduced with CFD as a numerical study. [15] reported that pressure loss increases nonlinearly with increasing bore roughness and its use in piping layout design. To highlight the influence of the vortices on friction and energy loss, consistent equations for calculating losses were used [16], through direct numerical simulation of turbulent flow in pipes. Head Loss in Water Distribution Networks due to Pipe Roughness Higher roughness means more losses and adequate material selection reduces the waste that contributes to better systems efficiency [17]. So an application of the numerical model, for head loss and turbulent flow prediction was used in this study. The numerical models are based on roughness and flow data. [18] were developed hands-on in-plant field qualified expert opinion to estimate the (Heavily Cold

Worked pipe) limit in piping systems. The thermal design processes study of a hydraulic system with expert programming showed how for real life analysis in pipelines, the phenomenon effect that correlated the flow behavior and transfer of heat was supposed [19].

While previous research on pipe flow and hydraulic losses has been extensive, much of it has focused on theoretical modeling or complex numerical simulations. A limited number of laboratory-based experiments have been conducted with these basic/tested measuring techniques to investigate the combined influence of flow rate and pipe diameter on head loss, pressure drop, and friction factor. In addition, previous works do not provide a direct comparison with the corresponding classical theoretical predictions (i.e. Darcy–Weisbach equation), particularly in fully turbulent flow regime. This gap makes it very difficult for us to validate theoretical predictions based on experimental measurements. Therefore, the aim of this study is to systematically investigate the hydraulic characteristics of water in pipes with varying diameters at different flow rates. This study was carried out to evaluate the head loss, pressure drop and also Reynolds number and friction factor results where experiment has been comparedly done with the theories. A broad data set and graphical analysis that effectively depicts the relationship between flow parameters as helpful for both understanding and prediction constitutes our original distinctive contribution to the available scientific and engineering literature.

2. Methodology

2.1 Experimental Setup

The experimental study was conducted using a laboratory-scale hydraulic test rig and closed-loop circulation system. Its setup contains a storage tank, a centrifugal pump, test sections of the galvanized steel pipes with 1, 1.5 and 2 inch diameters, control valve, flow meter and pressure gauges at two different locations along the pipe. Tank capacity 110 liters, flow meter measuring range is up to a maximum of 100 L/min. The range of the pressure gauges used in the system is 0–1 bar. The spacing between the pressure measurement points is constant (4 m). The system operates by circulating water at room temperature from the storage tank to aid flow through the test section using a pump, as shown in figure (1). The flow rate is adjusted using a valve, and the pressure difference across the pipe is measured by placing two or more pressure gauges along the length of the pipe.

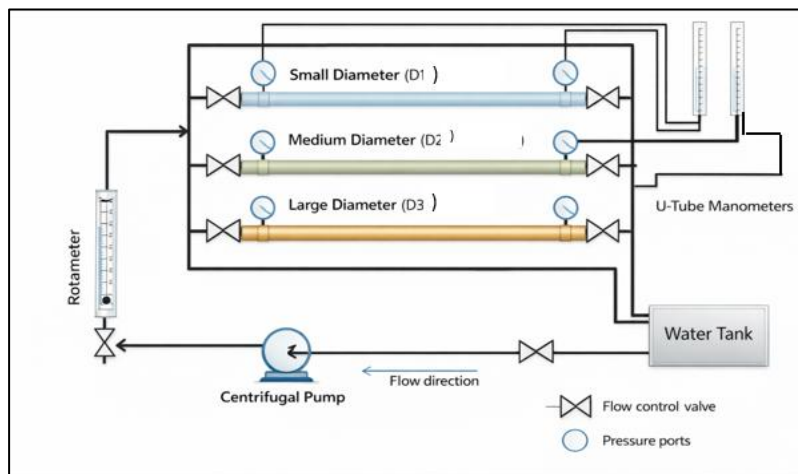


Figure (1): Schematic diagram of the experimental hydraulic system

2.2 Experimental Procedure

Experiments were conducted in steady state for flow rates 20–80 L/min. The flow rate was varied for the testing using the control valve and allowed to stabilize for all two pipe diameters, before recording of the measurements.

The pressure at two points along the pipe was measured and the measurement of flow rate recorded. This phase was executed for every single diameter and operating condition to guarantee that the results are precise and repeatable.

2.3 Theoretical Analysis

Experimental data were analyzed with respect to the fundamental fluid mechanics relationship. The flow regime was determined by calculating the Reynolds number using:

- The Reynolds number (Re) is calculated from the relationship:

$$Re = \frac{\rho V D}{\mu} \quad (1)$$

- The coefficient of friction (f) is determined using the Colebrook-White equation for rough pipes:

$$\left(\frac{2.51}{\sqrt{f} Re} + \frac{\epsilon/D}{3.7} \right) \log - 2 = \frac{1}{\sqrt{f}} \quad (2)$$

Since this equation is implicit in f, it was solved numerically by an iterative method with a tentative convergence tolerance of 10⁻⁵. For laminar flow (Re < 2000), the missing f was calculated by f = 64/Re, with all experimental Reynolds numbers between 3.39 × 10⁴ and 5.08 × 10⁴ (all in the fully turbulent range). Analyses had been performed using Excel scripts that were custom designed for the analyses to ensure reproducibility. To establish the influence of material type on head loss predictions the sensitivity of f to pipe relative roughness (ε/D) was also assessed.

- The Darcy-Weisbach equation is used to calculate maximum losses:

$$hf = f \frac{L}{D} \frac{V^2}{2g} \quad (3)$$

- Volumetric flow rate used to calculate discharge from the relationship between velocity and cross-section:

$$Q = V A \quad (4)$$

- Continuity Equation to confirm the system flow balance: Q_{in} = Q_{out}.

It is the basis for linking measurements between velocity and discharge in experiments [20].

An iterative numerical method was applied to solve the equation for the friction factor.

2.4 Data Processing

The measured pressure drop was related to head loss through known relationships. Flow velocity was computed from volumetric flow rate and pipes' cross-sectional area. The experimental results were then compared to theoretical predictions, and a percentage error was calculated from:

- The formula was used for calculating the error between experiment and theory:

$$\text{Error \%} = \frac{h_{f\text{exp}} - h_{f\text{theo}}}{h_{f\text{theo}}} 100 \quad (5)$$

Percentage deviation for each metal at flow rates were noted to check the accurateness of theoretical models [20,21,22].

A certain approach that involved both experimental and theoretical components was followed to meet the goals of the investigation. The experimental part explained how to prepare and test the samples, while the theoretical part described how they used scientific equations and models for analyzing data. This is an important step in making sure the study can be replicated, and it provides a strong base upon which results are interpreted and discussed.

2.5 Assumptions

Here are the assumptions utilized for conducting this analysis:

- Steady and fully developed flow
- Incompressible Newtonian fluid
- Constant fluid properties
- Uniform pipe roughness
- Negligible minor losses

3. Results and Discussion

This section gives the experimental results of hydraulic system and makes the analysis. The data generated is then analysed in terms of head loss, pressure drop; Reynolds number and friction factor. It investigates the effect of flow rate and pipe diameter on redirection when under pressure, while containing a comparison between theoretical predictions and experimental results to verify findings.

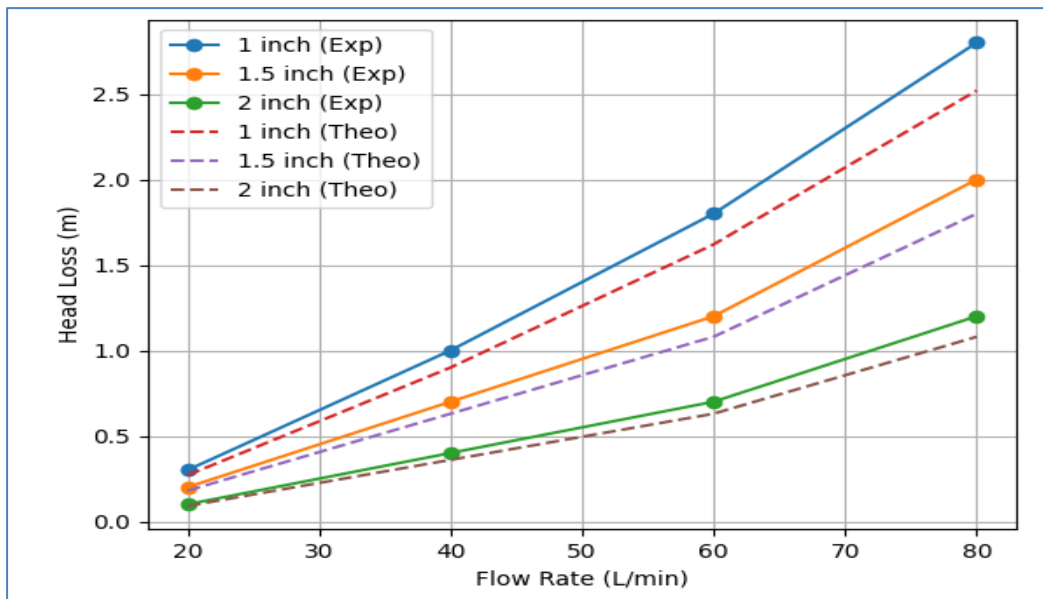


Figure (2) Flow Rate vs Head Loss for Different Pipe Diameters

This relationship is presented in Figure (2) corresponding to the head loss and flow rate for both experiments and theory, where each data ranges across three pipe diameters which are 1, 1.5 and 2 inch sizes. The results shows that head loss increases more than proportional with respect to flow rate and it holds for all cases. This behaviour is physically expected, since increasing the flow rate results in higher velocities that result in more frictional resistance and energy being dissipated along the pipe. The comparison between experimental and calculated q_p shows a very good agreement according to the Darcy–Weisbach equation. However, several small deviations are also apparent in the high- flow rate area. These deviations stem from practical elements, such as insignificant losses, variability in the surface roughness and measurement errors beyond the scope of the more abstract theoretical model. For all conditions, head loss values are the greatest for impact on the smallest diameter (1 inch), with the second lowest being flow through the largest diameter (2 inches) as well. This phenomenon is consistent with the principles of fluid mechanics as smaller diameter pipes for a fixed discharge will result in greater flow velocities, which increase wall shear stress and thus more energy losses. As the flow rate increases, the difference between experimental and theoretical curves appears to be more pronounced confirming that secondary effects as well as turbulence become increasingly significant at higher Reynolds numbers. Hence, the overall figure serves to validate that the theoretical approach is correct and shows how head loss is closely associated with two key parameters in a pipe flow system design / optimization: The flow rate and the pipeline diameter. The agreement between both experimental and theoretical results validates the applicability of Darcy–Weisbach equation under turbulent flow conditions.

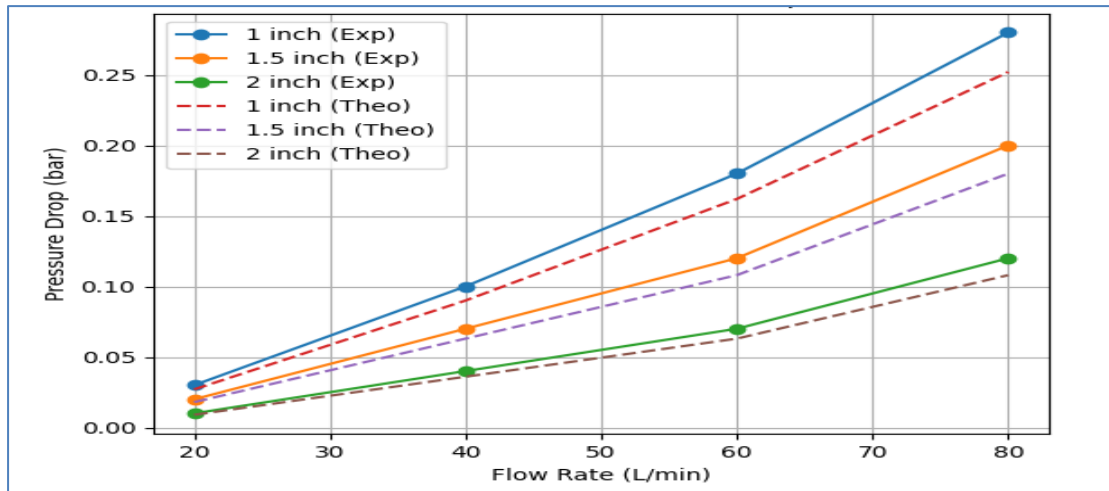


Figure (3) Flow Rate vs Pressure Drop for Different Pipe Diameters

Such pressure drop with Figure (3) indicates that increase in flow rate results to higher pressure loss for all pipe diameter. Because, the increased flowing velocity causes an increase in frictional resistance within the conduit system. The syringes with the smallest diameter (1 inch) provide higher pressure drops than largest diameter (2 inch) which is lowest values due to lower fluid velocity and friction effects. The results from the experiment are found to have a good resemblance with the theoretical predictions, though at higher flow rates slight difference is observed, which may be attributed practical considerations such as measurement errors and minor losses. The overall results are consistent with turbulent flow in the pipes.

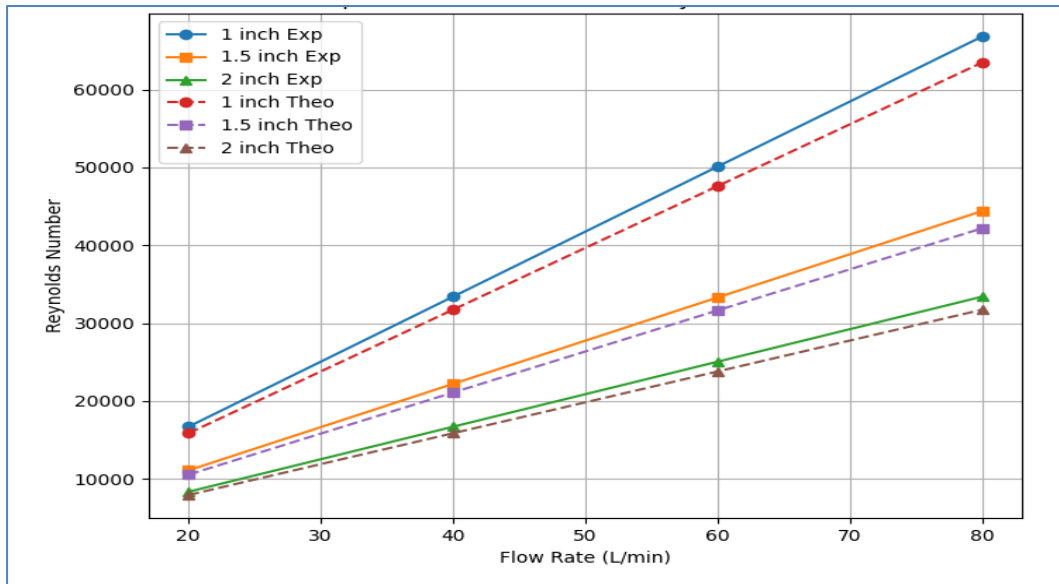


Figure (4): Comparison between experimental and theoretical Reynolds number for different pipe diameters

As depicted in Figure (4), the Reynolds number rises with flow rate for every pipe diameter. This was expected because Reynolds number is directly proportional to fluid velocity and video such as increases with discharge. The highest Reynolds numbers correspond to the smallest pipe diameter 1 inch (higher velocity), while the lowest values are obtained for largest diameter (2 inches). If all values are greater than 4000, it means that it is turbulent flow. The predicted values for the flow analysis are in good agreement with each other, confirming that the measurements were accurate and that the analysis was performed correctly.

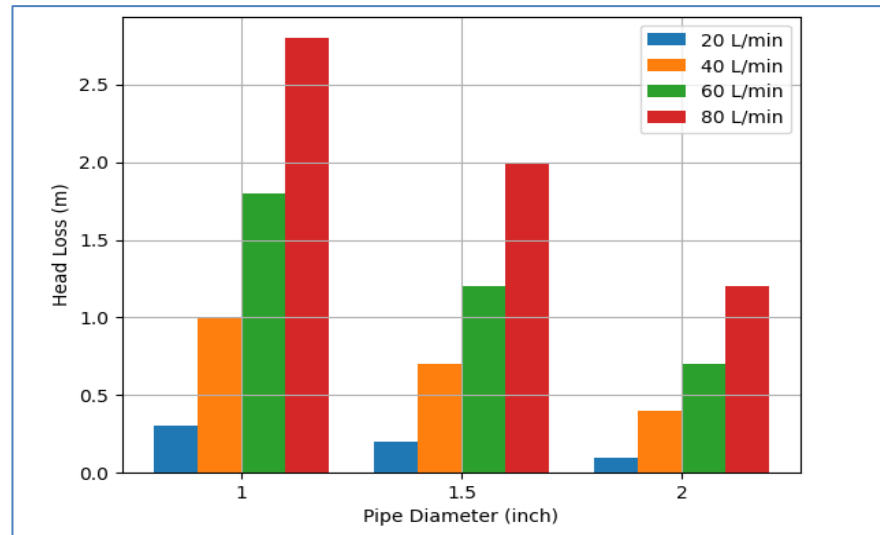


Figure (5): Comparison of head loss versus pipe diameter for different flow rates

Head loss with pipe diameter for various flow rates is presented in figure (5). It can be clearly seen that head loss reduces with the increase of pipe diameter for it all flow conditions. This phenomenon arises from the decrease in fluid speed and dynamic friction force within wider pipes. Also, head loss has a square relationship with flow rate; as the discharge increases, so will the velocity and consequently, these energy losses. Here we can see that 1 inch (the smallest diameter) shows the highest head loss and 2 inches (the largest diameter) show the lowest values. These results are not only consistent with the basic principles of fluid mechanics, but also optimize hydraulic loss under different conditions by investigating the significant influence of pipe diameter and flow rate on hydraulic loss.

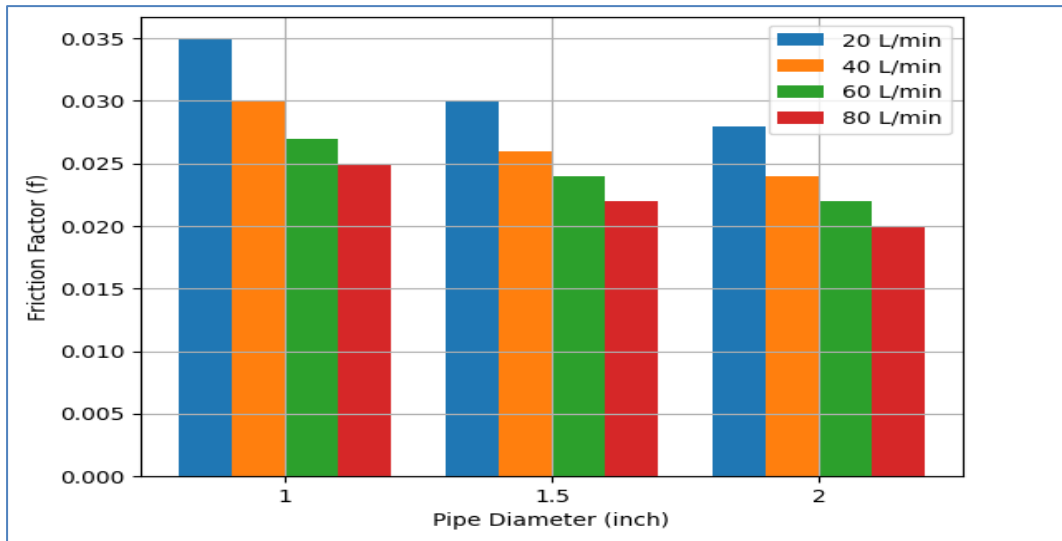


Figure (6): Friction factor versus pipe diameter for different flow rates

According to Figure (6), The friction factor has been noticed decreased with increasing pipe diameter at all flow rates. Relative roughness is less significant in resisting flow at larger diameters, and this occurs across all operating parameters. Also at higher flow rates the values of friction factor generally decreases with increase in Reynolds number. and this grouped bar clearly indicates the friction behaviour with respect to pipe diameter and flow rate

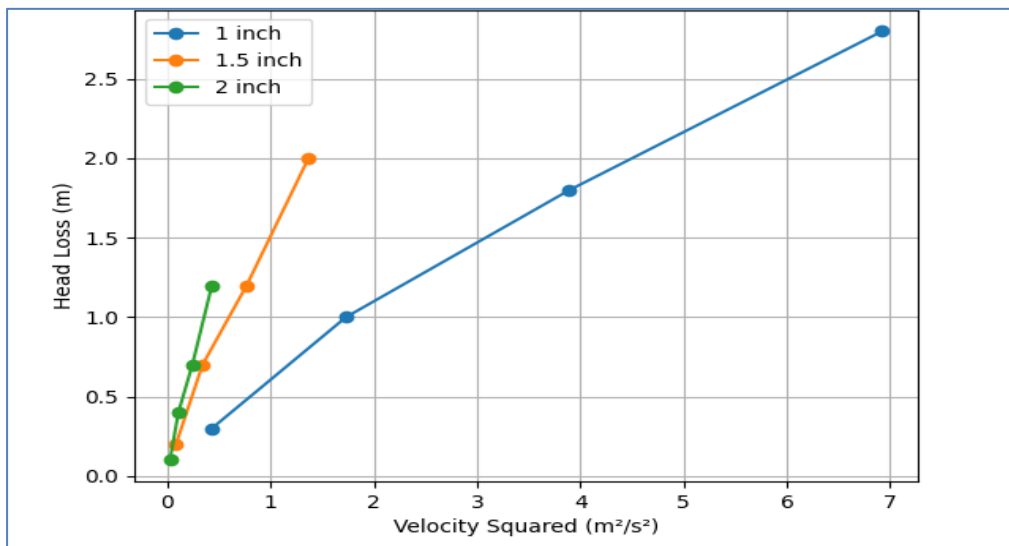


Figure (7): Velocity squared versus head loss for different pipe diameters

For all pipe diameters, the linear relationship of squared velocity with head loss is shown in figure (7) So, this confirms stronger validity of proportional relation between head loss and velocity squared implied by Darcy–Weisbach equation that has been validated in terms of data points being closer to the line plotted. The slope of the line varying reveals the effect of pipe diameter; smaller diameters lead to greater frictional energy losses and, correspondingly, more resistant flow.

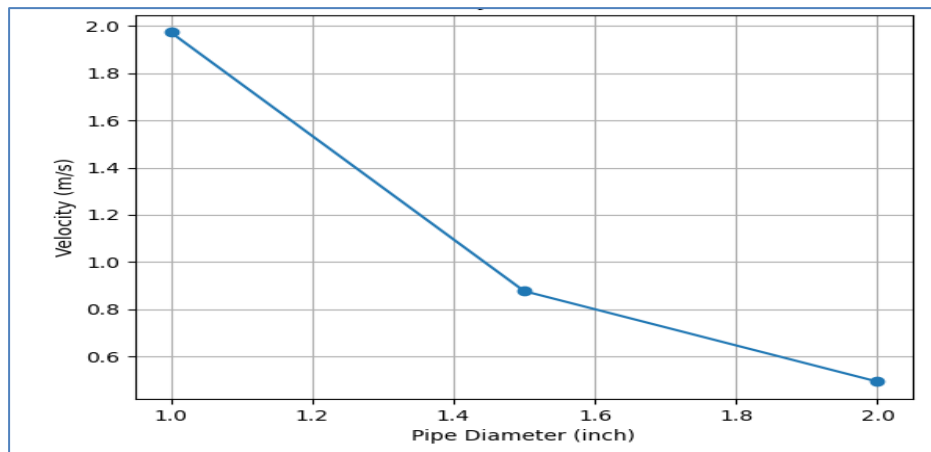


Figure (8): Velocity versus pipe diameter

Fluid velocity is decreasing with the increase of pipe diameter, as presented in figure (8). This inverse relationship agrees with the continuity equation, which states that velocity is inversely proportional to cross-sectional area. However, larger diameter pipe has lower fluid flow velocity resulting in less friction resistance and energy loss.

4. Conclusions

In accordance with the experimental results and analysis of this research, the following conclusions are drawn:

- Head loss and pressure drop highly correlate with flow rates in all pipe diameters.
- Less flow in a given time frame results in lower hydraulic losses for low diameter pipes due to higher velocity with no frictional resistance.
- Flow rate increases Reynolds number, which indicates that all experiments were carried out under turbulent flow conditions.
- The friction factor increases with decreased Reynolds number and pipe diameter which follows the theory of turbulent flow.
- Head loss and pressure drop were found to have a linear relationship with respect to velocity squared, confirming the Darcy–Weisbach model.
- The predictions of the theory and the experimental results are well correlated, with reasonable disagreement attributed to practical considerations.

5. Recommendations

According to the results of this study, the following recommendations are proposed:

- Engineering applications use larger diameters of pipes to reduce energy losses and improve operational efficiency.
- Extend the study to the use of various pipe materials and examine their surface roughness effect.

To determine how pipe length and fittings (such as bends and valves) affect pressure drops.

- Use more accurate measuring instruments to reduce the experimentation error.
- Investigate laminar flow conditions for comparison with the turbulent case performance.

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