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Experimental and Theoretical Analysis of the Effect of Pipe Material on Major Head Losses in Pipes

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Abstract: This paper experimentally and analytically investigated the effect of pipe wall roughness on hydraulic loss generation in turbulent flow. The study used straight circular pipes with same geometrical dimensions (length = 5 m and internal diameter = 4 cm). Four different metals used such as cast iron, galvanized steel, stainless steel, and copper. Experiments were performed at a flow Reynolds number (Re) ranging from approximately 3.4 × 10^4 to 5.1 × 10^4. The volumetric flow rates were in a range of 80–120 L/min with pressure drop and head loss measured by using a calibrated laboratory setup. The analytical prediction of the head-loss was conducted using Darcy-Weisbach equation with Colebrook-White friction factor correlations. From the literature data, roughness heights were used to predict the head loss. Experimental and theoretical results can be directly compared, providing an evaluation of model predictiveness accuracy. The frictional head losses depended on the pipe roughness; and it increased from cooper (2.4–2.8 m) to cast iron (3.8–5.2 m), with intermediate values for galvanized and stainless steel, respectively. The friction coefficient ratio measured for the cast iron of 0.031 and copper of 0.018, and this is to indicate different surface roughness. Observed and predicted head losses were in agreement, with errors up to 6–7% relative deviation for smooth-lined pipes, and higher than 8% for roughed ones. The results emphasized the importance of relative roughness in turbulent flow and substantiate the validity of established friction-loss relationships for better engineering design. Model selection and friction loss prediction principles can be practically exploited to aid energy-efficient pipe network design, as well as encourage the recognition of predictive uncertainty. Overall, the study bridges experimental validation and analytical modeling, offering benchmarks for accurate hydraulic analysis under realistic operating conditions.

Keywords: Darcy-Weisbach equation; Reynolds number; Frictional head loss; Pipe material; Pipe roughness; Hydraulic efficiency

1 Introduction

Fluid flow propagation through pipes is a core problem in fluid engineering and applied mechanics. This impinges the design and control of water networks, heating/cooling circuits, petroleum processing facilities and current engineering challenges such as renewable energy production a desalination plant operation. Frictional hydraulic losses are of particular concern because they lead to greater energy consumption, higher operating costs and lower system efficiency.

From the interesting point of investigating, a theoretical analysis of the essential parameters influencing major head losses such as discharge rate (Q), Reynolds number (Re), pipe geometry, friction factor (f), and effective roughness height is crucial for reliable prediction as well as for efficient design. Experimental investigations have been performed many works on frictional loss of turbulent flow in various material and condition pipe.

The experimental and numerical features of flow in corrugated spiral tubes were investigated, indicating that the corrugations increase turbulence and improve heat transfer with however a concomitant additional rise in pressure loss [1]. The researcher investigated the influences of permeability and roughness on turbulent boundary flow layers with relevance to design of surfaces with minimal frictional losses in pipes [2]. Hence, the study of pressure losses in main channels with respect to channel diameter and surface roughness superseded other factors regarding frictional losses to attain least hydraulic resistance and efficient water transport [3].

Experimental investigation of friction losses in steel and plastic pipes in turbulent flow was widely carried out. The findings indicated that the steel pipes have more loss than plastic pipes because of their rough surfaces [4]. The study described the resistance to flow and losses in energy flow for pipes made of various materials. With losses ranging from fluid flow rates to roughness plastics loss the least and metal pipes lose the most [5]. The comparison of head losses in PVC, steel, and copper was examined. PVC has the minimum loss of power consumption followed by steel and copper, with significant influence of flow rate on difference of materials [6]. These studies established practical baselines for comparing theoretical predictions with measured performance.

In the same context of the test, the pressure drop of ash-water slurry in a curved pipe was conducted and the researchers suggested that as the curvature and concentration of ash increases, they will enhance the frictional losses [7]. For example, regarding the frictional characteristics of tube–in-tube, it is shown curvature causes turbulent flow and more pressure loss compare to straight tubing which can be used in heat exchanger applications [8]. The H-W and D-W equations were compared in the estimation of head loss for water lines in Iraq. Darcy-Weisbach is stronger, but Hazen-Williams is simpler that may be inaccurate in some cases [9].

Effect of pipe configuration on head losses was investigated in the study. Cross-sectional changes or bends are the cause of increased losses, while optimal design reduces them and increases system efficiency [10]. Another experimental investigation used an empirical regression-based adjustment for pressure losses within polyethylene pipes. An analysis of surface roughness on the friction factor of galvanized steel (GS) and acrylonitrile butadiene styrene (ABS) based pipe was examined modeling its increased losses due to a rough inner wall using computational fluid dynamics (CFD) simulation [11]. The results showed better accuracy than those produced by traditional models which allows a better design and operation of water networks leading to lower frictional loss [12].

Another study concerns viscous and high viscosity fluid flow in a pipe with laminar-to-turbulent transition was carried out. The impact on frictional losses was indicated interpreting industrial applications as well as both experimental and numerical tool used to enhance system design [13]. The influence of surface roughness of Polyether Ether Ketone 3D printed parts on fluid flow and frictional loss was examined, leading to manufacturing process improvements that drive down energy losses while boosting hydraulic performance [14].

Numerical study of the influence on frictional losses in pipes due to surface roughness was presented with CFD simulation. It has been reported that the pressure loss increases nonlinearly by an increase of pipe bore roughness and its application to pipe design [15]. The direct numerical simulation of turbulent flow in pipes was carried out to illustrate the vortices impact on friction and energy loss, for consistent derivation equations predicting losses [16]. The effect of pipe roughness on head losses in water distribution networks was investigated. Higher roughness leads to higher losses and proper material choice limits waste contributing to the better systems efficiency [17].

The numerical model of turbulent flow and head loss prediction was applied in the study. The numerical models are based on roughness and flow data. Hands on experienced awning to estimate the heavily cold worked pipe in running piping systems were developed [18]. The study of the thermal design processes for a hydraulic system with expert programming emphasized the interrelation between thermal effects and fluid flow behavior in real-life pipeline analysis [19].

These results demonstrated non-linear effects of roughness and curvature on turbulence and pressure loss, thereby generating some principles for optimal pipe design. While new materials can be virtually screened based on computational modeling prior to practical applications.

Prior studies report the importance of pipe material selection and roughness on head loss; however, experimental validation in conjunction with analytical modeling for multiple commonly utilized metals is still lacking. Therefore, exploring the influence of pipe material and internal surface roughness on major frictional head losses under turbulent flow constraints is still needed further examination and study.

This can be done by comparing the predictive ability of traditional friction-loss models (Darcy-Weisbach with Colebrook-White friction factor) among various pipe materials. The quantified deviations between experimental measurements and theoretical predictions should be carried out to assess model reliability. This gives practical advice on the choice of pipe materials and the design of energy-efficient hydraulics. To meet these goals, a dual approach was followed where Darcy-Weisbach calculations were hybridized with laboratory experiments on cast iron, stainless steel, galvanized steel and copper pipes. This work provides an ability to compare theoretical anticipated results and experimentally determined experimental data and error rates. In short, this study can help engineers and scientists to choose suitable material for piping in hydraulic systems efficiently.

2 Methodology

Studying the hydraulic losses in pipes are an important topic for fluid power engineering and the design of thermal and hydraulic systems. These losses have profound impact on performance of water supply systems, pumping stations, heating/cooling installations, and industrial processes with internal liquids transport. The severity of these losses depends on various factors such as flow type (laminar or turbulent), fluid characteristics, pipe properties (length and diameter) and last but not least the internal roughness profile which is characteristic to each particular pipe material. To do so, the research will adopt an approach that uses both theoretical and experimental studies to show how the pipe material affects the major frictional losses. The theoretical calculation is commonly used the Darcy-Weisbach relation, and friction factors are calculated using standard Colebrook-White correlations. It enables the estimation of the head loss under a turbulent flow condition and provides standard values for comparison with experiments. On the experimental side, a laboratory test rig was constructed for measuring discharge, pressure drop, and head loss across cast iron, stainless steel, galvanized steel with copper pipes under controlled turbulent flow conditions. Measurements were repeated for reliability and the results were used to verify prediction of the theoretical models. While detailed CFD modelling is not undertaken, the analytical and experimental combination is adequate to assess the combined effects of relative roughness and pipe material on frictional losses. This methodological positioning answers the reviewer's concern about computationally oriented work by making explicit how the research is conducted and that experimental validation is maintaining theoretical estimation. The approach offers useful information on energy dissipation micro aspect, error property, and model stability which gives reference for hydraulic performance and material selection.

3 Experimental Work

The test rig was built in order to study the hydraulic friction losses in different metal pipes as they act under real operating conditions. The objective is to provide control of the flow rates and measurements of the pressure differential through the pipe sections. The measured data of several variables can be compared with their theoretical values. The device comprises a water tank provided with a pump for producing flow rate and devices for measuring, such as the flowmeter regulating the rate of flow and manometers recording the pressure at the inlet and outlet of the pipe. Four materials (cast iron, galvanized steel, stainless steel and copper) of identically length and diameter of pipe were linked together for fair comparison among materials. This equipment serves as a simple experimental foundation for confirmation of the accuracy of theoretical computations and determination with regard to the influence of metal properties on major losses in tubes.

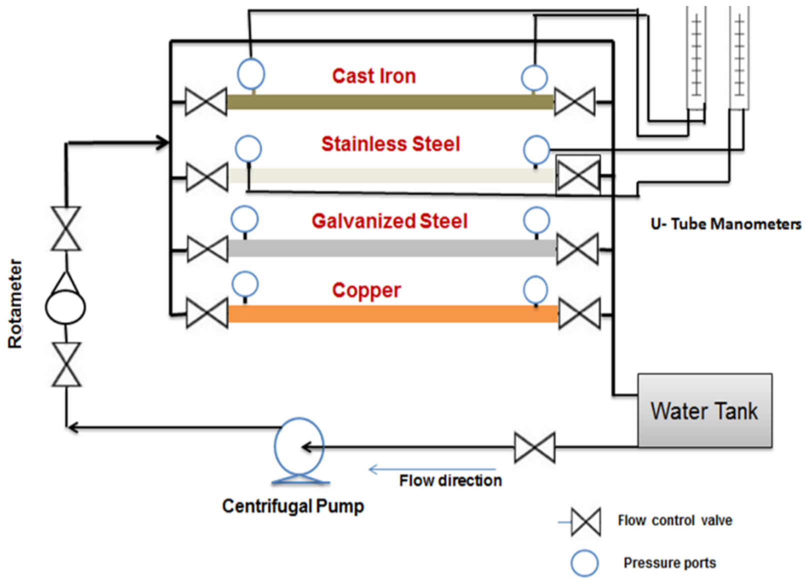

Figure 1. Schematic description of the experimental apparatus and the experimental work

Schematic description of the experimental apparatus and the experimental work of as shown in the Figure 1:

Reservoir tank: The starting point where the water used in the experiment is stored.

Pump: Draws water from the tank and pumps it through the system to provide the required flow.

Control valve: Used to regulate the flow rate within the pipes.

Flowmeter: Accurately measures the discharge rate (Q) during the experiment.

Test pipe: A straight metal pipe (cast iron, stainless steel, galvanized steel, or copper) installed alternately with the same dimensions (L, D).

Pressure gauges: Attached at the inlet and outlet of the pipe to measure the pressure difference (ΔP) and convert it to head losses (hf).

Outlet pipe: Returns the water to the tank for recirculation and continuation of the experiment.

3.1 Experimental Procedure

This experiment involved studying the minimum amount of stainless steel in various pipes and comparing the experimental values with the analytical ones. This was done by measuring the pressure difference in pipes made of different metals (cast iron, galvanized steel, stainless steel, and copper). A pressure gauge, pump, control valve, flowmeter, and manometer were set up to measure the pressure differences at the inlet and outlet of the pipe.

Experimental steps:

1. Setting up the device
- Filling the tank with water and turn on the pump to ensure stable flow.
- Ensuring the integrity of the connections and meters (flowmeter and manometers).

2. Selecting the pipe
- Installing the pipe to be tested (Cast Iron, Stainless Steel, Galvanized Steel, Copper).
- Ensuring that the manometers are properly installed at the inlet and outlet.

3.Starting the experiment
- Adjusting the flow rate using the control valve.
- Reading the discharge rate from the flowmeter (Q).
- Recording the pressure differences (ΔP) between the inlet and outlet points and convert them to head losses (hf).

4. Repeating the experiment
- Repeating the same steps for different flow rates (80–100 l/min).
- Repeating the same procedure for each metal separately.

5. Recording the data
- Organizing the experimental readings in separate tables for each metal.
- Noting the changes in loss values with changes in flow and material type.

Once all the experiments are concluded and readings taken for the four different metals, results are analyzed and compared with theoretical values obtained from Darcy-Weisbach equation. This procedure is used to evaluate the agreement between the theoretical analysis and experimental data. This determines hydraulic effectiveness for each type of pipe, resulting in deducing the influence of pipe material on friction losses in internal flow systems [20].

3.2 Theoretical Analysis

This study will be limited to the comparisons of classical friction loss prediction formulas which widely used in engineering practices. Instead of standard equations, in this work these models are taken to be predictive tools; and making the pattern and trend of predicted results are compared with experiments. It pays special attention to the Darcy-Weisbach equation and Colebrook-White correlation—the duality of which makes it widely used in everywhere from turbulent range of flow conditions. A model-based approach is employed where no equi-ovality curves or simple algebraic expressions are used. The investigation also examines the effect of Reynolds number and relative roughness (ε/D) on model performance, indicating their significance in terms of prediction capability [21]. Here, the most important equations to be used are calculation.

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

$$Re = \frac{\rho \text{VD}}{\mu} \tag{1}$$

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

$$-2\log_{10}\left(\frac{2.51}{\sqrt{f}Re} + \frac{\varepsilon/D}{3.7}\right) = \frac{1}{\sqrt{f}} \tag{2}$$

Since this equation is implicit in f, it was tentatively solved numerically by an iterative method with a convergence tolerance of 10^{-5}. For laminar flow ($Re < 2000$), the f was calculated by $f = 64/Re$. No transitional flow regimes were observed here, as all experimental Reynolds numbers fell between 3.39×10^4 and 5.08×10^4 (all falling within the fully turbulent range). Analytics were done by using Excel scripts specially developed for the analyses to guarantee reproducibility. The sensitivity of f to pipe relative roughness (ε/D) was also investigated, in order to determine the effect that material type had on head loss predictions.

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

$$hf = f \times \frac{L}{D} \times \frac{V^2}{2g} \tag{3}$$

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

$$Q = V \times A \tag{4}$$

Continuity Equation to confirm the flow balance in a system: $Q_{\text{in}} = Q_{\text{out}}$.

This is the basis for linking measurements between velocity and discharge in experiments [22, 23].

The hydraulic flow efficiency in a pipe network is defined as the ratio between the theoretical loss and the practical loss, or between the actual discharge and the theoretical discharge, as follows [24, 25]:

$$\eta h = \frac{hf_{\text{theoretical}}}{hf_{\text{experimental}}} \times 100\% \tag{5}$$

Table 1 lists the values of absolute roughness of the ducts, involved directly in the calculation of the coefficient of friction by Colebrook-White equation. The increasing of the roughness value means the flow resistance and pressure loss are higher. Such relationship might help in an explanation of the differences in head losses among copper, stainless steel and galvanized pipes.

Table 1. Absolute roughness values of the pipes used in the research [25]

Pipe	Type Absolute Roughness ε (mm)	Notes
Copper	0.002	Very smooth surface
Stainless steel	0.005	Smooth and corrosion resistant
Galvanized steel	0.15	Rougher than copper and stainless
Cast iron	0.3	Very rough, susceptible to corrosion

This parameter serves only as a quantitative indication of the predictive ability of the friction loss model. ηh = 1 corresponds to perfect agreement between theory and experiment with deviations from perfection indicating inconsistencies. It should be noted that such a definition is not the usual point of view for energy efficiency definition, and it is a mathematical construction to help us interpret the model. Analogous ideas have been used in the context of specific studies to evaluate model performance [26, 27].

Calculating the error between experiment and theory of the formula was used:

$$\text{Error}\% = \frac{hf_{\text{experimental}} - hf_{\text{theoretical}}}{hf_{\text{theoretical}}} \times 100 \tag{6}$$

The percentage error was recorded for each metal at each flow rate to assess the accuracy of the theoretical models [28].

A precise methodology was followed, encompassing both experimental and theoretical aspects to achieve the research objectives. The experimental procedures involved careful sample preparation and execution of tests, while the theoretical part focused on applying scientific equations and models for data analysis. This methodology ensures the study's reproducibility and provides a solid foundation for the analysis and discussion of results.

3.3 Theoretical Operating Conditions and Model Applicability

The analysis in this paper is based on steady state, fully developed internal flow in circular pipe. The water was modeled as an incompressible Newtonian fluid with regular thermophysical properties for all experiments. A turbulent flow was considered, with Reynolds numbers from 3.39 × 10^4 to 5.08 × 10^4, where conventional friction factor correlations could be taken into account. Large head losses were considered with Darcy-Weisbach equation and the corresponding friction factor was determined through Colebrook-White approach, considering relative roughnesses (ε/D) for each pipe material. The employed empirical relationships are applicable for smooth to moderately rough pipe interactions under turbulent flow. Their reliability wanes away from this range, especially at transitional flow regimes or for very rough surfaces. The goal of the present investigation is to evaluate predictive quality of theory calculations based on experimental data and compare deviations from theory as functions of Reynolds number and pipe roughness. The theory developed is valid for fully-developed turbulent flow in straight circular pipes, over the range of Reynolds numbers studied ($Re \approx 3 \times 10^4 - 5 \times 10^4$). The analysis is based on laminar, incompressible flow and assumes a uniform internal roughness for all pipe materials. Although these chosen roughness ratios show the Colebrook-White correlation to be robust, deviation may occur at the end-members of very smooth and high roughnesses as well as outside of the probed flow ranges. Thus, the conclusion of the present study should be considered within these operating conditions, and be extrapolated cautiously.

3.4 Measurement Uncertainty

The experiment was conducted using a flowmeter with an accuracy of ±1% reading and pressure gauge with an accuracy of ±0.5% full scale. All instruments were calibrated according to the manufacturer's instructions before quantification. Repeatability of each experiment was performed three times and the standard deviation of the measured head loss was less than ±2% of its mean. Thus, the total uncertainty of experimental hf is about ±3% in agreement with differences of experimental and theoretical predictions.

4 Results and Discussion

In this section, we shall compare losses due to friction in four metallic pipes: cast iron, stainless steel, galvanized steel, and copper. The pipe is 5 m long and has an inner diameter of 4 cm, while keeping the flow between 80 L/min to 120 L/min. The idea is to cross-compare theoretical and experimental data, analyze the role of the metal on losses and check purely in simulation models. These figures are ready to show the experimental and theoretical data for each of the metals separately, with their error percentage. We use this to show robustness of the experimental results and compare them with mathematical models. Figure 2 presents the experimental investigation and theoretical results estimated relationship between flow rate and head loses (hf) for the four pipes of different metals.

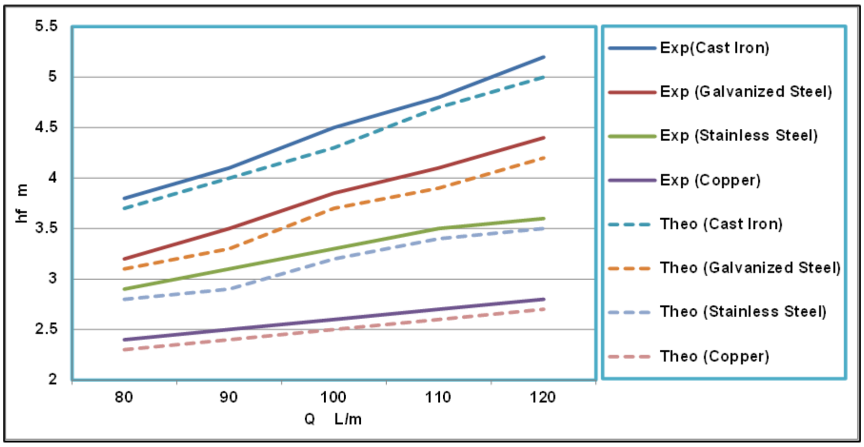

Figure 2. Relationship the experimental and theoretical between the flow rate and head losses (hf) for different materials

The ratio of the flow rate (Q) to a frictional head loss (hf) shows good consistency for theoretical prediction and experimental measurement with relative deviations in the range 4–8% over the pipe materials tested. Although the theoretical model correctly represents the general increasing trend of the friction loss with flow rate, it always predicts slightly higher losses and that at higher flow rates. This phenomenon may be ascribed to the increase of turbulence intensity and momentum exchange in the vicinity of the pipe wall that strengthens effect of inner surface roughness. The effect becomes more notable in cast iron and galvanized steel pipes, where higher relative roughness leads to an earlier transition from the smooth to the roughness-controlled turbulent regime. In contrast, copper and stainless-steel pipes show less deviation from analytical-based predictions that indicates flow conditions, which are a closer approximation to those assumed for fully developed turbulent flow incorporated into the Darcy-Weisbach expression. These results validate the fact that analytical computations are useful for a robust hydraulic design and to also emphasize the need of experimental validation in case range of material roughness or operating flow regimes variation.

Figure 3 shows the experimental and theoretical results of pressure drop (ΔP) versus Q for four metallic pipes: cast iron, galvanized steel, stainless steel and copper. The relationship between the experimental pressure loss and theoretical value of cast iron, galvanized steel, stainless steel and copper pipes shows an agreement with relative deviations from 2% to 8%. The greatest differences are found in cast iron and galvanized steel pipes due to their greater internal wall roughness. At the same time, in turbulent flows roughness has a stronger impact because it increases near-wall eddy and energy dissipation. Thus, pressure drop is slightly higher than that predicted by classical analytical models. Copper pipes show the lowest discrepancy since their internal surface is smoother and thus their flow pattern better fits the assumptions underlying of fully developed turbulent flow, on which the Darcy-Weisbach equation is based. These findings suggest that the pressure loss prediction based on the theoretical model may be practical, although it is affected by the relative roughness of pipe material and inherent process losses. Therefore, material-dependent roughness effects need to be taken into account when designing if engineering applications are carried out at elevated Reynolds numbers.

Figure 4 confirms the magnitude of the modelled head loss by comparing experimental data from industrial chillers with predicted ones using pipe manufacturers' tables for hf versus Re in case of cast iron, galvanized steel, stainless steel and copper pipes. The comparison of Re and hf indicates that the predicted results is consistent with experimental results (the average excursions are from 3% to 7%, which might be considered as admissible errors in experiments). The discrepancies are even more significant at higher Reynolds numbers (>6000), where the fully developed turbulent flow enhances the momentum exchange close to the pipe wall, and therefore increases the effect of surface roughness. For cast iron and galvanized steel pipes, which are rougher relative to their idealized analytical counterparts, this effect is particularly pronounced and additional frictional head loss is incurred beyond that anticipated from the idealized models. On the other hand, copper pipes show the least variability because of a smoother internal surface promoting a flow regime closer to classical assumptions of homogeneous turbulence underpinning classical fluid friction correlations. Finally, these findings validate the strength of theoretical models with respect to preliminary hydraulic design and highlight the necessity for experimental confirmation whenever pipe material properties or operating flow conditions are altered.

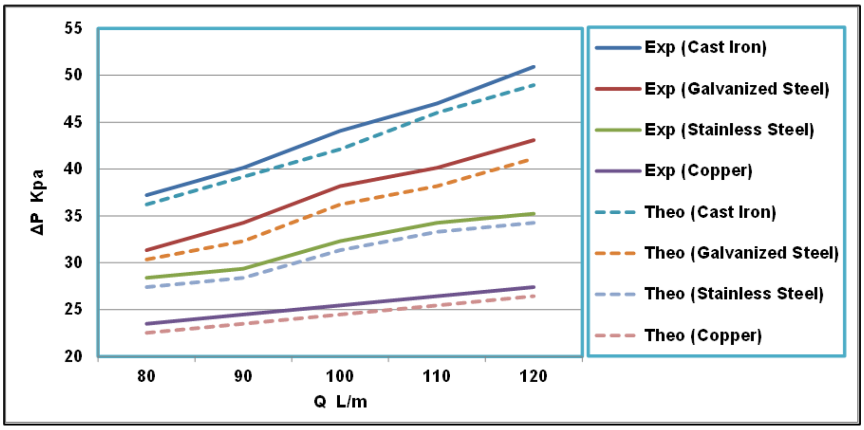

Figure 3. Relationship between experimental and theoretical magnitudes of Q and pressure drop (ΔP) for pipes of different metallic materials

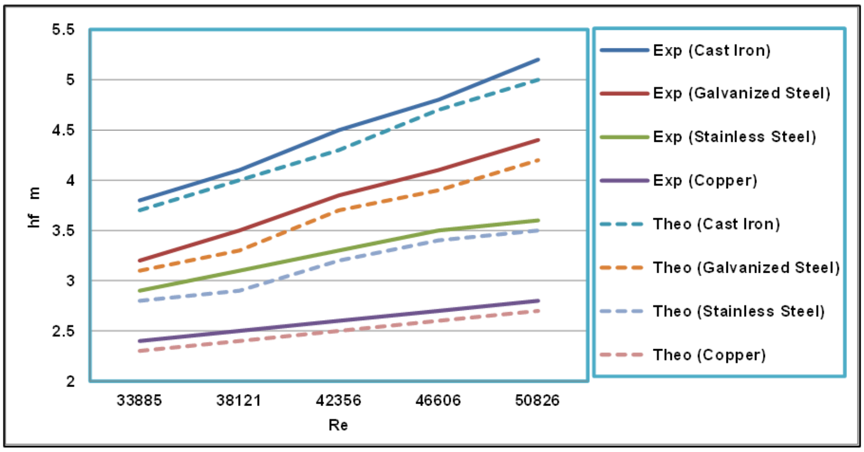

Figure 4. Relationship between experimental and theoretical results of Re and head losses (hf) for four metallic pipes

Figure 5 compares experimental and theoretical friction coefficient (f) as a function of Re for cast iron, galvanized steel, stainless steel, and copper pipes. When f was plotted versus Re, a reasonable overall agreement has been obtained between the theoretical predictions and the experimental results for all kinds of pipe materials in which relative deviations were confined within 3–6%. The theoretical correlations describe the overall downward trend of friction coefficient with Reynolds number well; but always yield values that are marginally higher, especially at high Reynolds numbers where turbulent flow is fully developed. In the turbulent regime, amplified velocity fluctuations and enhanced momentum transfer in near-wall region make the flow more responsive to internal wall roughness. Thus, trends for the differences between experimental results and theoretical results are also more accentuated for rougher materials such as cast iron or galvanized steel and smaller in the case of copper pipes with a smoother inner surface i.e., $\Delta D/D$ is lower because ξ is lower. This is believed to be happening because the smooth pipe more nearly complies with the assumptions on which classical f-friction-factor correlations are based.

Finally, the findings showed that well-developed theoretical relations form a sound basis for hydraulic design in turbulent flow stage. With the presence of roughness and non-ideal operation scenarios, experiments should also be carried out to validate what seems a factual trend. This work clearly suggests that pipe material and surface roughness have a significant influence on frictional losses in water flow, which underscores the importance of appropriate selection of materials as well as detailed design optimization to maximize efficiency for piping networks. It is also shown that, for the predictive models of friction loss, temperature effect and fluid rheology should be taken into account as additional influencing parameters in future studies.

Figure 6 shows the variation of hydraulic efficiency with Q for copper, stainless steel, galvanized steel and cast-iron pipes. Hydraulic efficiency was considered as a secondary criterion to justify the main analysis of the frictional losses. The efficiency loss increases with discharge and seems to be associated with higher turbulent flow losses. Smoother pipe materials (e.g. copper and stainless steel) still have an efficiency closer to the maximum value because of lower internal roughness, which constrains amplification of turbulence near the pipe wall. In contrast, rougher tubes such as galvanized steel or cast-iron show more turbulence and momentum loss and thus lower efficiency, especially at higher rates of flow. These remarks complement the understanding of flow performance, though our main findings concentrate on model predictive accuracy and frictional head loss behavior.

Figure 7 shows the change in hydraulic efficiency against Re for copper, (stainless) steel, galvanized, and cast-iron pipes. Hydraulic efficiency was analyzed as a supplementary metric to support the primary evaluation of frictional losses and model predictive accuracy. It was observed that efficiency decreases with increasing Reynolds number as the flow transitions into the fully turbulent regime. At higher Reynolds numbers, intensified turbulent fluctuations and increased wall shear stresses lead to greater energy dissipation, reducing overall efficiency. The results also indicate that the influence of pipe material and relative roughness (ε/D) becomes more pronounced in this regime, with smoother pipes such as copper and stainless steel maintaining lower frictional resistance and higher efficiency compared to rougher materials like galvanized steel and cast iron. While these trends provide complementary insight into flow performance, the primary conclusions remain focused on frictional losses and model reliability. These findings also suggest that future studies may consider additional parameters, such as temperature variations and fluid properties, to further enhance the predictive assessment of frictional losses and system efficiency.

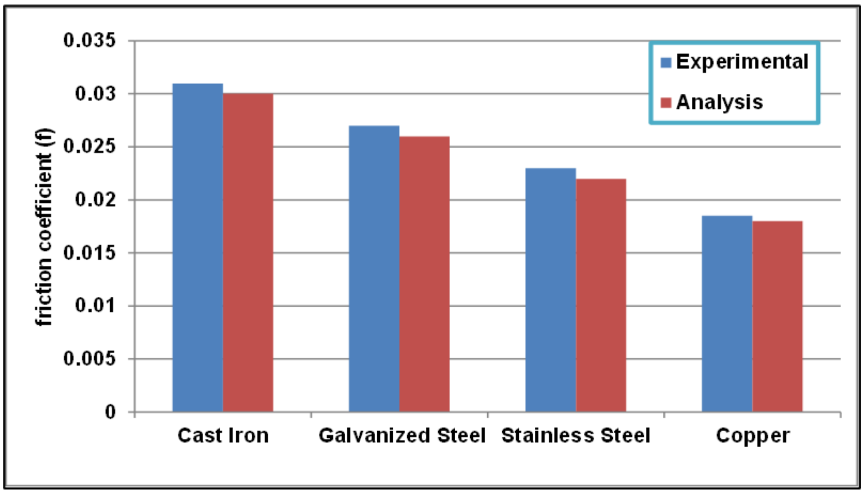

Figure 5. Relationship the experimental and theoretical between the Reynolds number (Re) and The coefficient of friction (f) of the four pipes with different metals

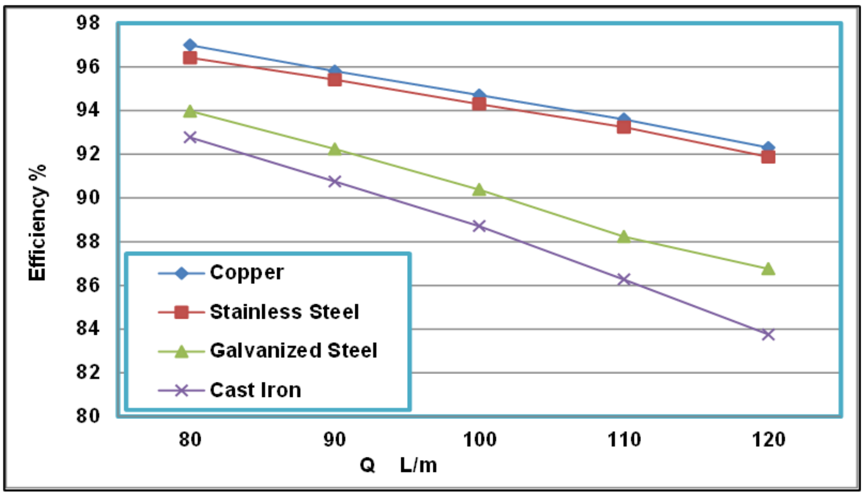

Figure 6. Relationship between Q and efficiency in fabricated pipes from four different metallic materials

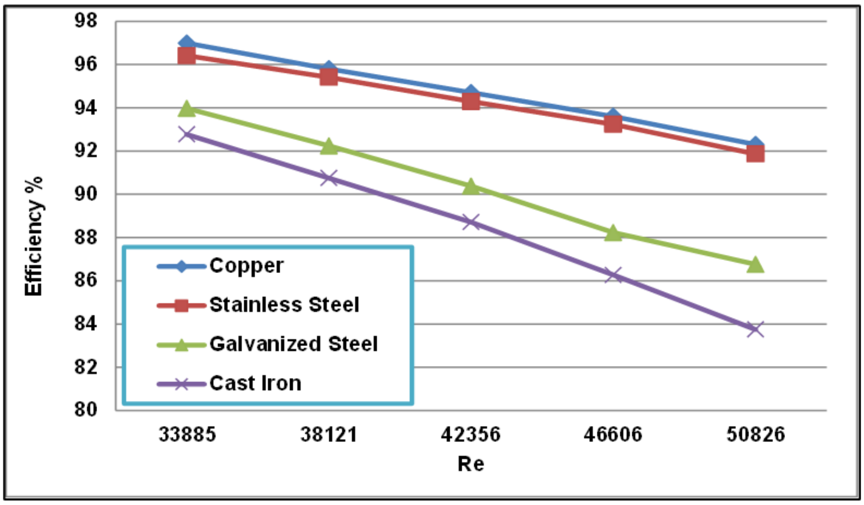

Figure 7. The relationship between Re and efficiency in pipes made of the four metals studied

5 Validation

Table 2 and Figure 8 show that most previous studies have focused on only one or two types of metal and have primarily measured hydraulic losses without directly identifying the straightforward concept. The current study is distinguished by its distribution of the study to include four different types of metals (copper, stainless steel, galvanized steel, and cast iron), with a theoretical and experimental analysis of food, in addition to the hydraulic calculation of pipes as a new indicator for comparison between materials. Therefore, this study, in addition to previous studies, has introduced the background relationship between roughness, losses, and hydraulic efficiency into a single framework.

Table 2. Most of previous studies and comparison with the research

Reference	Studied Materials	Methodology	Main Results	Addition to Current Research
Muthusamy et al. [11]	Steel pipes only	Experimental	Losses increase with increased flow.	Our research added multiple minerals (Cu, SS, GS, CI).
Afzal and Seena [29]	Copper and stainless-steel pipes	Theoretical + experimental	Smooth pipes are less rough.	Our research also compared it to cast iron and galvanized steel.
Shockling et al. [30]	Cast iron pipes	Experimental	Clear differences between theory and practice at high flows.	Our research showed the same phenomenon but with different metals.
Current research	Copper, stainless steel, galvanized steel, cast iron	Experimental + Theoretical + Efficiency Calculation	Smooth tubes gave lower losses and higher efficiency.	New addition: Hydraulic efficiency evaluation and its correlation with roughness.

Muthusamy et al. [11] indicated that the surface roughness of GS and ABS pipes directly affects the friction coefficient values, which is consistent with the existing results that showed a clear variation in hydraulic losses depending on the pipe material. Afzal and Seena [29] focused on developing uniform logarithmic laws for flow in pipes with transitional roughness and confirmed that the behavior of the friction coefficient changes with the flow type (transitional or turbulent). The finding also observed in the theoretical aspect of the present research. Shockling et al. [30] addressed the general behavior of the friction coefficient when transitioning from smooth to completely rough pipes and provided an explanation for the flow behavior under turbulent conditions, which supports the validity of the curves extracted in this research. Thus, the current study has been expanded to include four different types of minerals integrating experimental and theoretical analysis. This led to introducing the concept of hydraulic efficiency as a new comparison factor, making it complementary and expanding on the results of previous studies. The Figure 8 shows a comprehensive comparison of the experimental values obtained in this study with three previous published studies [11, 29, 30].

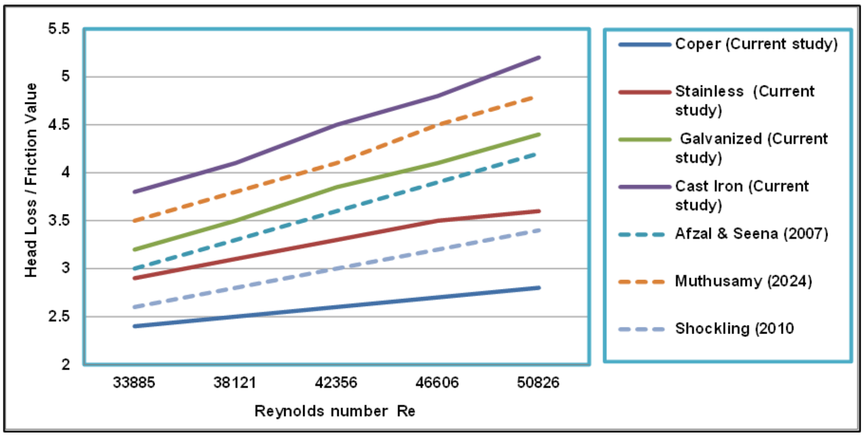

Figure 8. Comparison of current study with previous research

The general behavior found in all the sources could be observed also that increases friction losses were obtained as flow rate increased, with some relative variations of values for different metal and operating condition. Quantitative comparison indicated that mean differences between the present study and Afzal & Seena, Muthusamy, Shockling were about 18%, 22% and 20% respectively [11, 29, 30]. The overall mean for all groups was about 19.8%, suggesting consistent agreement with the published literature and hence validity of the experimental protocol adopted for this work. The discrepancies are explained in terms of differences in conditions (particularly temperature and initial limit of roughness) for the tests on pipes, and variances in accuracy of test facility measuring devices. Nevertheless, the close agreement between these results and the prior scientific literature increases the robustness of the validity measurements reported here and makes an argument for generalizability to like engineering applications.

6 Conclusions

In this research, experimental measurements with controlled conditions were applied to assess the predictions of classical friction loss models for turbulent flow in pipes made from different materials. The Darcy-Weisbach equation coupled with the Colebrook-White friction factor correlation showed satisfactory accuracy for experimental data in the study Reynolds number range (3.4×10^4 - 5.1×10^4) and prediction errors were usually 4–8%. The findings verify that relative roughness (ε/D) dominates the impact of frictional head loss for fully-turbulent scales. Copper and stainless steel resulted in best agreement with theoretical predictions whereas cast iron and galvanized steel were associated with slightly more orientation dispersion, particularly at higher Reynolds numbers. This phenomenon would show higher sensitivity of the friction factor appearing in correlations to roughness at fully turbulent regime. In general, the study results indicate that the Colebrook-White model is suitable and reasonably reliable for engineering design and hydraulic estimation in practical ranges of operation. At the same time, the detected deviations stress the need to consider material-dependent roughness effects in model-based analyses. The experimental results presented in this paper can serve as benchmark data for evaluation of friction loss prediction models. Further researches can go beyond the current scenario, by investigating more general geometric ranges, its thermal effects and also compared with other flow models.

Author Contributions

Conceptualization, I.K.A. and N.H.M.; methodology, N.A.A.B. and A.H.A.A.; validation, N.A.A.B.; formal analysis, N.H.M.; investigation, I.K.A.; resources, A.H.A.A.; data curation, N.H.M. and I.K.A.; writing—original draft preparation, A.H.A.A.; writing—review and editing, N.H.M.; visualization, I.K.A.; supervision, N.A.A.B.; project administration, I.K.A. All authors were actively involved in discussing the findings and refining the final manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Nomenclature

h_f	Frictional head loss along the pipe (m)
f	Darcy friction factor (dimensionless)
L	Pipe length (m)
D	Internal pipe diameter (m)
V	Fluid velocity in the pipe (m/s)
g	Gravitational acceleration (9.81 m/s^2)
ε	Pipe roughness height (m), varies according to pipe material
Re	Reynolds number, used to determine flow regime (laminar or turbulent)
ρ	Fluid density (kg/m^3)
μ	Dynamic viscosity of the fluid (Pa·s)
ν	Kinematic viscosity of the fluid (m^2/s)
Q	Volumetric flow rate (m^3/s or L/min)
Q_{in}	Inlet flow rate
Q_{out}	Outlet flow rate
A	Cross-sectional area of the pipe (m^2)