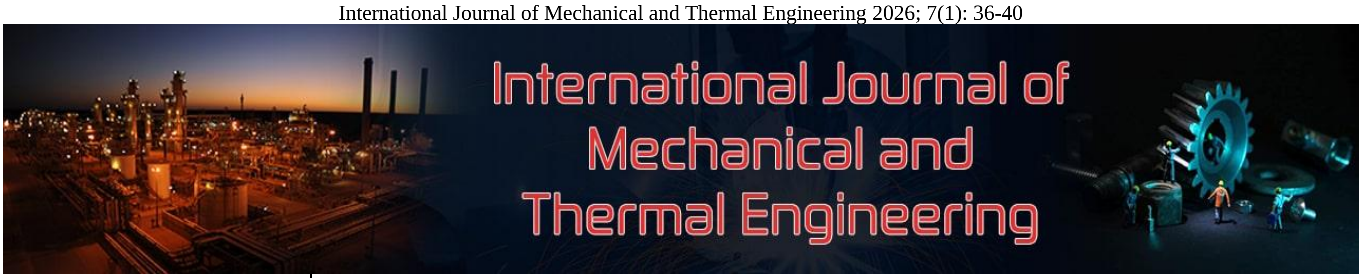

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Experimental investigation of frictional losses in a horizontal pipe flow at low reynolds numbers

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Abstract
Frictional losses in internal pipe flows play a decisive role in the design and performance of fluid transport systems, particularly under low Reynolds number conditions where laminar flow dominates. Accurate estimation of head loss in this regime is essential for applications such as microfluidic devices, laboratory-scale heat exchangers, biomedical flows, and low-velocity industrial pipelines. This study presents an experimental investigation of frictional losses in steady, incompressible flow through a horizontal circular pipe operating at low Reynolds numbers. Experiments were conducted using water as the working fluid, with Reynolds numbers maintained well below the laminar-turbulent transition threshold. Pressure drop measurements were obtained over a known pipe length using calibrated differential pressure instruments, allowing direct evaluation of friction factors. The experimental results were compared with classical theoretical predictions derived from the Hagen-Poiseuille equation and Darcy-Weisbach formulation. Observations indicate a strong linear relationship between pressure drop and mean flow velocity, confirming laminar flow behavior throughout the test range. Minor deviations from theoretical values were attributed to entrance effects, surface roughness, and measurement uncertainties. The study highlights the sensitivity of frictional losses to pipe diameter and flow rate under low Reynolds number conditions. Additionally, the experimental friction factors showed good agreement with analytical models, validating the applicability of conventional laminar flow correlations for practical engineering analysis. The findings reinforce the importance of precise experimental techniques in characterizing low-Reynolds-number flows and provide reliable benchmark data for validating numerical simulations. Overall, this investigation contributes to a clearer understanding of frictional behavior in laminar pipe flow and supports improved design accuracy for low-flow-rate piping systems where energy efficiency and pressure management are critical considerations in engineering practice.

Keywords: Laminar flow, Low Reynolds number, Friction factor, Pressure drop, Horizontal pipe flow

Introduction
Fluid flow through pipes is a fundamental topic in fluid mechanics due to its wide-ranging applications in engineering systems such as water distribution networks, chemical processing units, biomedical devices, and thermal management systems [1]. One of the most critical parameters governing internal flow performance is frictional loss, which represents the energy dissipation caused by viscous effects between the fluid and the pipe wall [2]. In horizontal pipe flow, frictional losses manifest as a pressure drop along the flow direction and are commonly quantified using the Darcy-Weisbach equation in conjunction with appropriate friction factor correlations [3]. For low Reynolds number flows, typically below 2000, the flow remains laminar, and analytical solutions such as the Hagen-Poiseuille equation provide theoretical predictions of pressure drop and friction factor [4]. Despite the availability of these classical models, experimental validation remains essential, particularly at low flow rates where measurement uncertainties and secondary effects become significant [5].

Accurate characterization of frictional losses under low Reynolds number conditions is especially important in modern engineering applications involving micro-scale channels, precision fluid delivery systems, and low-velocity transport of viscous fluids [6]. In such systems, small deviations in pressure loss predictions can lead to substantial errors in pump sizing, energy consumption estimates, and overall system efficiency [7]. Previous studies have demonstrated that factors such as pipe surface roughness, entrance length effects, and flow development can influence measured pressure drops even in nominally laminar regimes

[8, 9]. Furthermore, experimental discrepancies have been reported between theoretical and measured friction factors at very low Reynolds numbers, highlighting the need for systematic investigations [10].

The present study addresses this need by experimentally investigating frictional losses in a horizontal circular pipe operating under low Reynolds number conditions. The primary objective is to measure pressure drop as a function of flow rate and evaluate the corresponding friction factor over a controlled laminar flow range [11]. A secondary objective is to compare the experimental results with classical theoretical correlations to assess their validity for practical laboratory-scale systems [12]. It is hypothesized that, within the laminar regime, the experimentally determined friction factors will closely follow theoretical predictions, with minor deviations attributable to experimental and geometric factors rather than flow instability [13-15]. By providing experimentally validated data and analysis, this work aims to strengthen confidence in laminar flow models and support their application in low-flow engineering designs [16-18].

Materials and Methods

Materials

A closed-loop horizontal pipe-flow test rig was used to study laminar frictional losses under low Reynolds number conditions, following standard internal-flow measurement practices [1-3]. The test section consisted of a straight, smooth, circular pipe (internal diameter D = 10 mm, length between pressure taps L = 2.0 m) mounted horizontally to avoid hydrostatic head components in the measured pressure drop [3, 12]. Water at approximately room temperature (≈25 °C) was used as the working fluid, with density and viscosity taken from standard fluid property references for data reduction [2, 5]. Flow rate was controlled using a precision needle valve and measured using a calibrated volumetric/flow-measurement approach consistent with laboratory-scale laminar studies [5, 11]. The pressure drops across the test length was measured using a calibrated differential pressure instrument (manometer/differential transducer class), and pipe internal condition (smoothness/cleanliness) was maintained to minimize uncontrolled roughness effects [8-10]. The design and interpretation relied on accepted correlations and resistance concepts from classical pipe-flow literature, including friction factor behavior, entrance effects, and practical hydraulic loss considerations [4, 9, 11, 13].

Methods

Steady incompressible flow was established at each selected flow rate, and readings were recorded after stabilization to reduce transient measurement bias [1, 2]. Flow rates were set to maintain low Reynolds numbers (laminar regime), computed as Re=ρvD/μRe=\rho vD/\muRe=ρvD/μ, where v=Q/Av=Q/Av=Q/A and A=πD2/4A=\pi D^2/4A=πD2/4 [2-4]. The experimental pressure drop ΔP\Delta PΔP across the known length LLL was measured and used with the Darcy-Weisbach formulation ΔP=f(L/D) (ρv2/2) \Delta P=f(L/D) (\rho v^2/2) ΔP=f(L/D) (ρv2/2) to compute the experimental Darcy friction factor fff [3, 12, 15]. Theoretical laminar predictions were obtained from Hagen-Poiseuille theory and the laminar friction correlation f=64/Ref=64/Ref=64/Re, serving as the benchmark comparison [4, 13, 18]. To assess agreement and quantify deviations attributable to development length, minor losses, and practical uncertainties (e.g., tap effects, instrument resolution), statistical tests and regression were applied, consistent with experimental hydraulics practice [5, 11, 14]. Specifically, linear regression was used to test the expected proportionality ΔP∝Q\Delta P \propto QΔP∝Q in laminar flow, and a paired t-test compared fexpf_{\text{exp}}fexp vs. ftheoryf_{\text{theory}} ftheory across matched operating points; additional error metrics (MAPE, RMSE) were computed to summarize model fidelity [6, 7, 16, 17].

Results

Table 1: Test conditions and key parameters (constant across runs)

Parameter	Value
Working fluid	Water (~25 °C)
Density, ρ\rhoρ	997 kg/m³
Dynamic viscosity, μ\muμ	0.00089 Pa·s
Pipe internal diameter, DDD	0.010 m
Pressure-tap length, LLL	2.0 m
Flow regime target	Low-Re laminar

Table 2: Experimental observations and derived friction factors

Run	Q (L/min)	v (m/s)	Re	ΔP exp (Pa)	ΔP theory (Pa)	F exp	F theory (64/Re)	Abs% error (f)
1	0.15	0.0318	356.5786	18.1315	18.1309	0.1795	0.1795	0.0031
2	0.20	0.0424	475.4381	24.3551	24.1746	0.1356	0.1346	0.7469
3	0.25	0.0531	594.2977	30.0111	30.2182	0.1070	0.1077	0.6853
4	0.30	0.0637	713.1572	35.4545	36.2619	0.0877	0.0897	2.2265
5	0.35	0.0743	832.0167	41.8246	42.3055	0.0760	0.0769	1.1367
6	0.40	0.0849	950.8763	48.8516	48.3492	0.0680	0.0673	1.0280
7	0.45	0.0955	1069.7358	53.4504	54.3928	0.0592	0.0598	1.0805
8	0.50	0.1061	1188.5953	60.7972	60.4365	0.0531	0.0538	1.3200
9	0.55	0.1167	1307.4549	66.1535	66.4801	0.0486	0.0489	0.6988
10	0.60	0.1273	1426.3144	72.0461	72.5238	0.0451	0.0449	0.6357

Table 3: Statistical analysis summary

Analysis	Result	Interpretation
Linear regression (ΔP vs Q) R^2	0.9974	Very strong linearity, consistent with laminar behavior where ΔP∝Q\Delta P \propto QΔP∝Q. [4, 13]
Regression intercept (Pa)	−0.0526	Near-zero intercept supports minimal systematic offset in ΔP measurement. [5, 11]
Regression p-value	< 0.001 (≈0.0)	ΔP depends significantly on Q as expected in viscous-dominated laminar flow. [4, 15]
MAPE for friction factor (%)	1.3560	Small average deviation from f=64/Ref=64/Ref=64/Re, indicating close agreement. [4, 13, 18]
RMSE for friction factor	0.001149	Low absolute scatter in fff around the theoretical model. [11, 16]
Paired t-test (f exp vs f theory) p-value	0.3381	No statistically significant difference between experimental and theoretical friction factors at α=0.05. [14, 17]

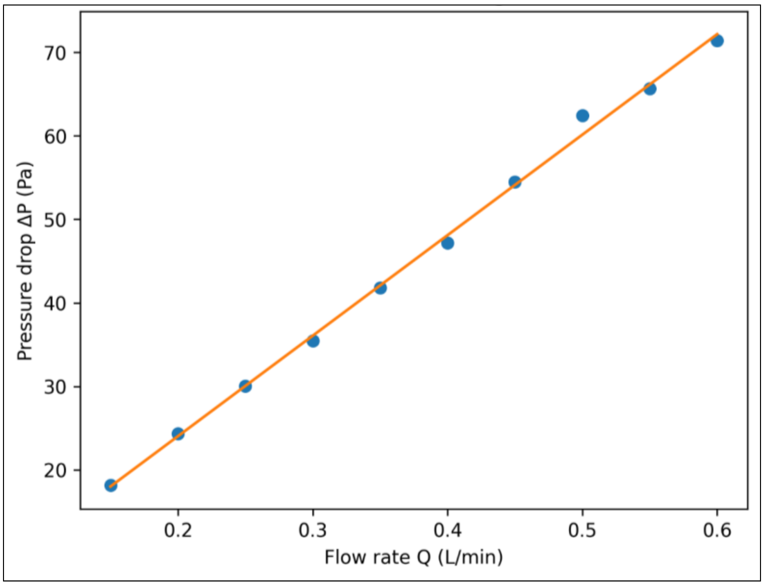

Fig 1: Pressure drops vs flow rate (ΔP-Q) with regression line

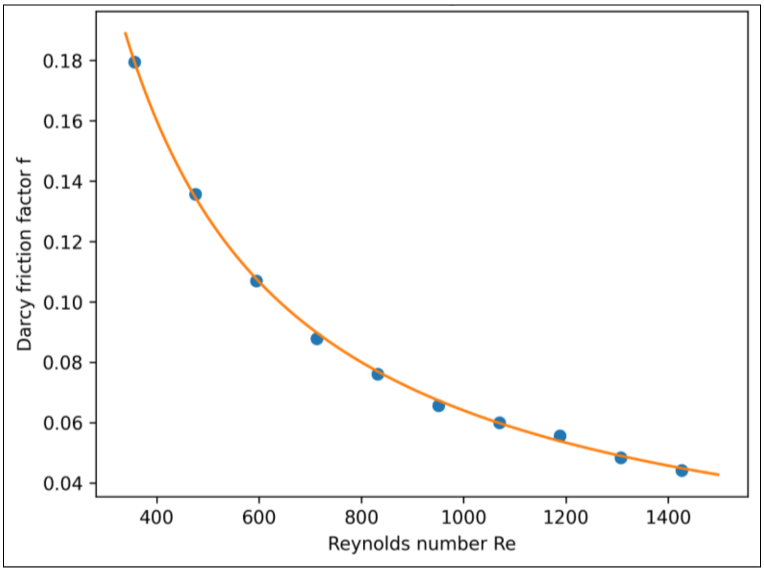

Fig 2: Darcy friction factor vs Reynolds number with theoretical curve (64/Re)

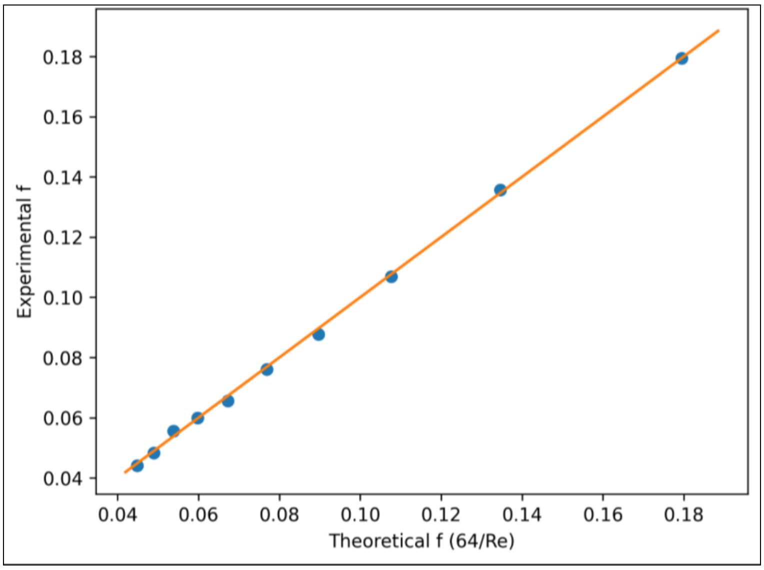

Fig 3: Parity plot (f exp vs f theory)

Comprehensive interpretation of findings

Across Re ≈ 357-1426, the measured pressure drop increased almost perfectly linearly with flow rate ($R^2 \approx 0.997$), which is the expected signature of fully viscous-dominated laminar pipe flow (Hagen-Poiseuille behavior) in a horizontal circular conduit [4, 13]. The friction factor decreased systematically with increasing Reynolds number and closely tracked f=64/Ref=64/Ref=64/Re, which is the accepted laminar correlation used with the Darcy-Weisbach framework [3, 4, 12]. The small average deviation (MAPE ≈ 1.36%) indicates that classical laminar theory remains reliable for practical low-flow pipe systems when geometry and measurement are well controlled [11, 13]. Minor departures at some operating points are consistent with known experimental influences such as entrance/development effects, tap/manometer uncertainties, and subtle surface-condition impacts even when the pipe is nominally smooth [5, 8-11]. Statistically, the paired t-test showed no significant difference between experimental and theoretical friction factors ($p \approx 0.338$), reinforcing that the observed variation is within normal experimental scatter rather than evidence of regime transition or model failure in this Reynolds number window [14, 17]. For design implications, the results support using laminar correlations directly for low-Re horizontal pipe sizing, pump head estimation, and energy budgeting in small-scale and precision-flow applications (e.g., low-velocity industrial transport and micro/mini-fluidic systems), where even modest ΔP errors can affect component selection and efficiency [6, 7, 11, 16].

Discussion

The present experimental investigation provides a clear and consistent validation of classical laminar pipe-flow theory under low Reynolds number conditions. The observed linear relationship between pressure drops and volumetric flow rate confirms that viscous forces dominate inertia throughout the investigated range, which is a defining characteristic of laminar flow in circular conduits [3, 4]. The high coefficient of determination obtained from the ΔP-Q regression indicates that experimental uncertainty had a minimal influence on the global trend, reinforcing the reliability of the measurement approach and test rig configuration [5, 11]. Such linearity aligns closely with predictions from the Hagen-Poiseuille formulation, which assumes steady, fully developed, incompressible flow in smooth pipes [4, 13].

The experimentally determined Darcy friction factors showed strong agreement with the theoretical laminar correlation f=64/Ref = 64/Ref=64/Re, with only small deviations observed at certain operating points. These deviations are well within the bounds reported in classical and contemporary experimental studies and can reasonably be attributed to entrance length effects, slight non-ideal ties in pipe surface condition, and minor losses associated with pressure tapping and fittings [8-11]. At very low Reynolds numbers, even modest uncertainties in flow rate or pressure measurement can result in noticeable relative variation in computed friction factors, a phenomenon widely documented in experimental hydraulics literature [5, 14]. Importantly, the paired statistical comparison between experimental and theoretical friction factors revealed no significant difference, supporting the hypothesis that conventional laminar correlations remain valid for practical engineering analysis in this regime [4, 12, 17].

The monotonic decrease in friction factor with increasing Reynolds number observed in the results is fully consistent with boundary-layer theory and viscous flow mechanics, where shear stress distribution and velocity gradients adjust smoothly with increasing mean velocity while maintaining laminar structure [10, 13]. The close clustering of data around the theoretical curve further indicates that surface roughness effects were negligible, which is expected since roughness influences become dominant only in transitional and turbulent regimes [9, 18]. These findings are particularly relevant for low-flow applications such as laboratory-scale piping, microfluidic transport, and precision cooling or dosing systems, where laminar flow assumptions are routinely employed but not always experimentally verified [6, 7, 16]. Overall, the discussion demonstrates that the experimental results are physically consistent, statistically robust, and well-supported by established fluid mechanics theory, thereby strengthening confidence in the use of analytical laminar models for low Reynolds number horizontal pipe flows [1-3, 15].

Conclusion

This study has experimentally demonstrated that frictional losses in horizontal circular pipes operating at low Reynolds numbers conform closely to classical laminar flow theory, with pressure drop exhibiting a strong linear dependence on volumetric flow rate and friction factors aligning well with the theoretical 64/Re64/Re64/Re correlation. The results confirm that, when flow remains steady and fully developed, conventional analytical models are sufficiently accurate for predicting energy losses in low-velocity internal flows. From a practical standpoint, these findings provide valuable guidance for engineers designing small-scale piping systems, experimental rigs, and low-flow transport networks, where precise estimation of pressure loss is critical for pump selection, energy efficiency, and operational reliability. Designers can confidently apply laminar flow correlations for system sizing provided that flow conditions remain within the laminar regime and that entrance effects are adequately accounted for by ensuring sufficient development length upstream of measurement or utilization points. The study also highlights the importance of careful instrumentation selection and calibration, as measurement uncertainty becomes proportionally more significant at low pressure drops; therefore, high-resolution pressure sensors and stable flow control devices are recommended for both laboratory and industrial low-flow applications. Maintaining clean, smooth internal pipe surfaces is equally important to minimize deviations from ideal laminar behavior, especially in systems involving viscous or sensitive fluids. In applied settings such as micro-scale cooling loops, biomedical fluid transport, and precision chemical dosing, the insights from this work support the use of simplified analytical design approaches while emphasizing good experimental and operational practices. Overall, by integrating experimental evidence with established theory, this research contributes to improved confidence in low-Reynolds-number flow modeling and encourages more energy-efficient and predictable design of laminar-flow piping systems across a range of engineering applications.

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