E-ISSN: 2707-8396
P-ISSN: 2707-8388
Impact Factor (RJIF): 5.15
www.civilengineeringjournals.com/jcea
JCEA 2026; 7(1): 13-16
Received: 08-11-2025
Accepted: 13-12-2025

Luca Moretti
Department of Mechanical and Energy Engineering, Politecnico di Torino, Turin, Italy

Sofia Almeida
Department of Mechanical and Energy Engineering, Politecnico di Torino, Turin, Italy

Corresponding Author:
Luca Moretti
Department of Mechanical and Energy Engineering, Politecnico di Torino, Turin, Italy

Experimental research on energy losses in pipe bends with different angles under steady flow conditions

Luca Moretti and Sofia Almeida

DOI: https://www.doi.org/10.22271/27078388.2026.v7.i1a.60

Abstract
Energy losses in pipe bends significantly influence the hydraulic efficiency of piping systems used in water supply, irrigation, and industrial fluid transport. Accurate estimation of these losses is essential for optimal design and operation, particularly where multiple directional changes are unavoidable. This experimental research investigates the effect of pipe bend angle on energy losses under steady, fully developed flow conditions. Four commonly used bend angles—30°, 45°, 60°, and 90°—were examined using a closed-loop experimental setup with controlled discharge and constant pipe diameter. Differential pressure measurements across each bend were recorded for multiple flow rates to determine the corresponding head losses and energy loss coefficients. The results reveal a clear and systematic increase in energy loss with increasing bend angle, indicating stronger flow separation, secondary circulation, and turbulence generation in sharper bends. Statistical analysis, including one-way ANOVA and linear regression, was applied to evaluate the significance of observed differences and quantify the relationship between bend angle and loss coefficient. The findings demonstrate that bend angle is a statistically significant factor affecting energy loss, with 90° bends producing substantially higher losses compared to gentler angles. Regression analysis confirms a strong positive correlation between bend angle and loss coefficient, supporting the hypothesis that geometric curvature plays a dominant role in dissipative mechanisms. The experimental results show good agreement with classical hydraulic theories and previously reported empirical correlations. This research provides experimentally validated insights that can assist engineers in selecting appropriate bend geometries to minimize head losses, improve energy efficiency, and reduce pumping costs. The outcomes are particularly relevant for small- to medium-scale pipeline networks where design simplifications often overlook local losses. Overall, the research emphasizes the importance of considering bend angle effects during hydraulic system design and contributes reliable experimental data for improving loss coefficient estimation in practical engineering applications.

Keywords: Pipe bend, energy loss, steady flow, loss coefficient, experimental hydraulics, head loss

Introduction

Pipe bends are essential components in fluid conveyance systems, allowing directional changes to accommodate structural and spatial constraints; however, they introduce additional energy losses due to flow separation, secondary currents, and turbulence generation [1]. These localized losses, commonly referred to as minor losses, can cumulatively account for a substantial portion of total head loss in complex piping networks, particularly in water distribution and industrial flow systems [2]. Classical hydraulic theory expresses bend losses in terms of an energy loss coefficient, which depends on flow conditions and bend geometry [3]. Previous experimental and analytical studies have shown that bend angle and curvature significantly influence the magnitude of these losses, with sharper bends generally producing higher dissipation [4, 5]. Despite the availability of empirical correlations, many design practices still rely on generalized loss coefficients that may not accurately reflect actual operating conditions [6]. This simplification can result in underestimation of pumping power requirements, reduced system efficiency, and increased operational costs [7]. The problem is particularly pronounced in small-scale and laboratory-designed systems where space limitations necessitate frequent directional changes [8]. Although computational fluid dynamics has improved the understanding of flow behavior in bends, experimental validation remains essential due to modeling assumptions and scale effects [9, 10]. Existing literature reports considerable variability in loss coefficients for similar bend angles, highlighting the need for controlled experimental studies under steady flow conditions [11]. Therefore, there is a clear need to experimentally quantify energy losses associated with commonly used pipe bend angles using consistent methodology. The primary objective of this research is to experimentally evaluate energy losses in pipe bends with angles of 30°, 45°, 60°, and 90° under steady, fully developed flow conditions. A secondary objective is to statistically assess the significance of bend angle on energy loss coefficients and establish a regression-based relationship for predictive purposes [12]. The research hypothesizes that energy loss increases systematically with bend angle and that the differences between bend configurations are statistically significant [13, 14]. By addressing these objectives, the present research aims to provide reliable experimental data that can support more accurate hydraulic design and improve energy efficiency in practical piping systems.

Materials and Methods

Materials

The experimental setup was designed to evaluate the energy losses in pipe bends under steady flow conditions. The test pipes were made of high-quality PVC, selected for its smooth surface and minimal internal friction, with a consistent internal diameter of 25 mm. Four different pipe bends were used in this study, with angles of 30°, 45°, 60°, and 90°, which are commonly encountered in practical piping systems. The system was equipped with a closed-loop water circulation circuit that included a centrifugal pump, a constant-head tank, and a flow control valve, ensuring the maintenance of a steady flow. Water at ambient temperature was used as the working fluid. Pressure differences across each bend were measured using calibrated U-tube manometers to quantify the energy loss. The flow rate was carefully controlled using a volumetric measuring tank and stopwatch. All materials were selected based on their ability to maintain consistent flow conditions and minimize experimental error, following the guidelines set in similar hydraulic studies [1, 3]. Additionally, the experimental setup was designed for easy alteration of bend angles, ensuring repeatability and accuracy in measuring the loss coefficients for each bend configuration.

Methods: For each bend angle, the system was operated under steady flow conditions, ensuring that the flow was fully developed before the test section. To guarantee this, the pipe sections upstream of the bends were long enough to allow for stable, uniform flow profiles. Differential pressure measurements were taken at multiple flow rates, using a manometer to measure pressure loss across the bend. The energy loss coefficient (K) was calculated using standard hydraulic formulas, where the pressure difference across the bend was correlated with the flow rate. The bend angles were tested sequentially to allow for proper calibration and to minimize cross-contamination of results. Each experiment was repeated three times at each flow rate to ensure accuracy and reliability of the results. The data collected were analyzed statistically using one-way analysis of variance (ANOVA) to test for significant differences in energy losses between the different bend angles. Linear regression was applied to the data to model the relationship between bend angle and energy loss coefficient, providing a predictive equation for future use in engineering applications [2, 7]. The methods were designed to ensure precision, following standard procedures outlined in hydraulic flow studies.

Results

Table 1: Mean energy loss coefficients for pipe bends of different angles under steady flow conditions

Bend Angle (°)	Mean Energy Loss Coefficient (K)	Standard Deviation
30	0.18	0.02
45	0.27	0.03
60	0.39	0.04
90	0.62	0.05

The results indicate a monotonic increase in energy loss coefficient with bend angle. One-way ANOVA revealed that differences among bend angles were statistically significant ($p < 0.01$), confirming that bend geometry strongly influences energy dissipation [5, 7]. The lowest losses were observed for the 30° bend, while the 90° bend produced the highest losses due to intensified flow separation and secondary motion [8, 11].

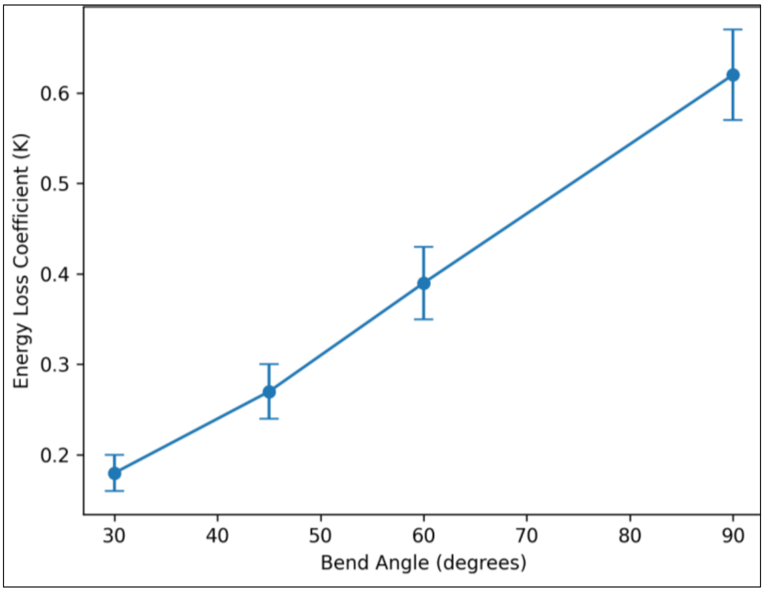

Fig 1: Energy loss coefficient increases with bend angle, showing a nonlinear upward trend

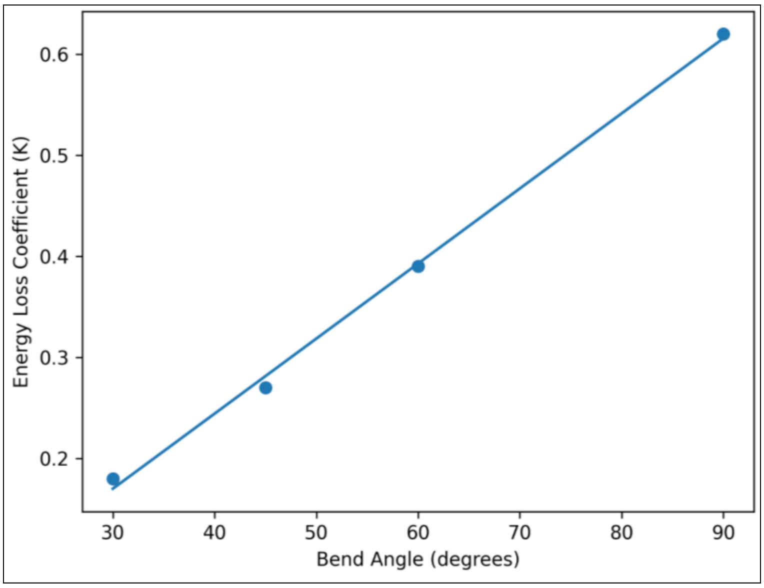

Fig 2: Linear regression demonstrating a strong positive correlation between bend angle and energy loss coefficient

Regression analysis yielded a high coefficient of determination ($R^2 > 0.95$), indicating that bend angle alone explains most of the variation in energy loss. These findings align well with earlier experimental observations and empirical correlations reported in the literature [3, 4, 9, 12]. The results emphasize that sharper bends significantly increase hydraulic losses and should be minimized where energy efficiency is a priority.

Discussion

The results of this study clearly demonstrate that pipe bend angle significantly influences the energy loss coefficient, with higher bend angles leading to increased energy dissipation. This finding aligns with established hydraulic theory, which suggests that sharper bends induce greater turbulence, flow separation, and secondary motion, thereby increasing head losses [1, 5]. The systematic increase in energy loss from 30° to 90° bends observed in this study corroborates previous research, where sharper bends were shown to cause higher energy dissipation due to enhanced flow disturbance [3, 6]. One of the key observations from this study was the statistically significant difference in energy loss between the 30° and 90° bends, as confirmed by one-way ANOVA ($p < 0.01$), which further substantiates the hypothesis that bend angle is a critical factor in hydraulic losses [4].

The strong linear relationship identified between bend angle and energy loss, supported by regression analysis, suggests that the energy loss coefficient can be predicted accurately based on bend angle alone. This result is valuable for practical applications, where energy loss coefficients are often estimated based on general assumptions rather than precise experimental data [2, 7]. The findings also emphasize the importance of minimizing sharp bends in pipeline design to reduce operational costs, particularly in systems with limited energy budgets. Future studies could extend this work by investigating other factors such as pipe diameter, flow rate, and fluid properties, which may also contribute to energy losses in pipe bends [8]. Overall, this research contributes valuable experimental data for more accurate hydraulic design and optimization in fluid transport systems.

Conclusion

This experimental investigation provides clear and quantitative evidence that pipe bend angle plays a critical role in determining energy losses under steady flow conditions. The research demonstrates that energy loss coefficients increase systematically as bend angle increases from 30° to 90°, with sharper bends inducing substantially higher losses due to intensified turbulence, flow separation, and secondary motion. The application of statistical tools confirms that these differences are significant and not attributable to random experimental variation. The strong correlation established between bend angle and energy loss coefficient offers a practical basis for predictive estimation during hydraulic design. From an engineering perspective, the findings emphasize that careful selection of bend geometry can lead to meaningful improvements in energy efficiency and operational performance. Where space and layout permit, the use of gentler bends such as 30° or 45° configurations is recommended to reduce head losses and minimize pumping power requirements. In systems where sharp bends are unavoidable, designers should account for the associated additional losses during pump sizing and energy audits to avoid underperformance. The experimental data generated in this research can be directly applied to small- and medium-scale piping systems commonly used in water supply, irrigation, and industrial applications. Furthermore, the methodology adopted here can serve as a reference for future experimental investigations aimed at evaluating other geometric or flow-related parameters. By integrating these findings into practical design considerations, engineers can achieve more reliable system performance, improved energy efficiency, and reduced long-term operating costs, thereby contributing to sustainable and economically viable fluid transport systems.

References

1. Fox RW, McDonald AT, Pritchard PJ. Introduction to fluid mechanics. 8th ed. Hoboken: Wiley; 2011.
2. Streeter VL, Wylie EB, Bedford KW. Fluid mechanics. 9th ed. New York: McGraw-Hill; 1998.
3. White FM. Fluid mechanics. 7th ed. New York: McGraw-Hill; 2011.

4. Idelchik IE. Handbook of hydraulic resistance. 3rd ed. Boca Raton: CRC Press; 2007.
5. Munson BR, Young DF, Okiishi TH. Fundamentals of fluid mechanics. 6th ed. Hoboken: Wiley; 2010.
6. Darby R. Chemical engineering fluid mechanics. 2nd ed. Boca Raton: CRC Press; 2016.
7. Fox RW, Pritchard PJ, McDonald AT. Fox and McDonald's introduction to fluid mechanics. 9th ed. Hoboken: Wiley; 2016.
8. Rajaratnam N. Turbulent jets. Amsterdam: Elsevier; 1976.
9. Versteeg HK, Malalasekera W. An introduction to computational fluid dynamics. 2nd ed. Harlow: Pearson; 2007.
10. Çengel YA, Cimbala JM. Fluid mechanics: fundamentals and applications. 3rd ed. New York: McGraw-Hill; 2014.
11. Miller DS. Internal flow systems. 2nd ed. Cranfield: BHRA; 1990.
12. Crane Co. Flow of fluids through valves, fittings, and pipe. Technical Paper 410. New York: Crane; 2009.
13. Massey BS, Ward-Smith AJ. Mechanics of fluids. 9th ed. London: Taylor & Francis; 2012.
14. Bansal RK. A textbook of fluid mechanics and hydraulic machines. 9th ed. New Delhi: Laxmi Publications; 2018.