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Original Article

Investigation Of Surface Roughness Effects On Pressure Drop In Varied Pipe Materials

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ABSTRACT

This research presents a comprehensive numerical investigation into the effects of internal surface roughness on pressure drop in turbulent pipe flow for five commonly used engineering materials: Cast Iron, Galvanized Iron, Asphalted Cast Iron, Concrete, and PVC. Utilizing Computational Fluid Dynamics (CFD) with ANSYS Fluent 2021 R1, the study implements standardized sand-grain roughness models within a validated simulation framework. A three-dimensional pipe geometry (20 mm diameter, 500 mm length) is analyzed under steady-state turbulent conditions across Reynolds numbers from 4,000 to 100,000 using the k-epsilon turbulence model with enhanced wall treatment. Results quantify the significant influence of material-specific roughness on hydraulic resistance, demonstrating that pressure drop increases non-linearly with roughness height. PVC exhibits the lowest pressure drop, while Concrete shows the highest, with variations up to 25% between materials at identical flow conditions. The study provides comparative performance rankings, establishes empirical correlations between roughness parameters and friction factors, and offers detailed flow visualizations including velocity profiles and turbulence intensity distributions. The findings deliver practical engineering guidelines for optimal material selection in piping system design, with direct implications for energy efficiency, pump sizing, and operational cost reduction in fluid transport applications..

Keywords: Cast Iron, Utilizing Computational Fluid Dynamics, hydraulic resistance, Reynolds numbers.

INTRODUCTION

Pressure drop in piping systems represents a fundamental challenge in fluid engineering with direct consequences for energy consumption, operational costs, and system efficiency. In applications ranging from municipal water networks to industrial process plants, pumping energy constitutes 20-30% of total operational energy, with pipe friction contributing significantly to this demand. The internal surface characteristics of pipes, quantified as roughness, critically influence this hydraulic resistance, especially within the turbulent flow regimes prevalent in engineering practice.

While classical approaches like the Darcy-Weisbach equation provide theoretical foundations, practical implementation relies on the Moody chart's generalized roughness values. These values, however, often fail to capture the nuanced differences between material types, manufacturing processes, and aging effects. Computational Fluid Dynamics (CFD) has emerged as a transformative tool, allowing detailed examination of flow physics that are difficult to capture experimentally. By simulating fluid behavior at a fundamental level, CFD enables parametric studies of roughness effects with controlled precision.

This investigation employs ANSYS Fluent to conduct a systematic comparative analysis of five widely used pipe materials: Cast Iron, Galvanized Iron, Asphalted Cast Iron, Concrete, and PVC. Using a standardized circular geometry (20mm diameter, 500mm length) and implementing the k-epsilon turbulence model with enhanced wall treatment, the study isolates roughness as the primary variable. Each material is modeled with equivalent sand-grain roughness heights derived from established engineering standards, ensuring consistency across simulations.

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

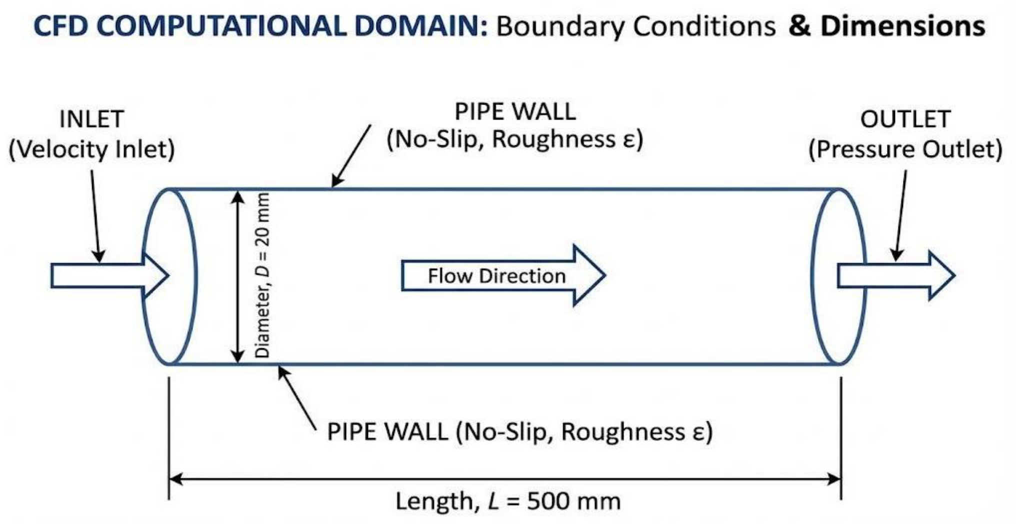

Fig 1.1 CFD Computational Domain

The research addresses a significant gap in available data by providing directly comparable performance metrics under identical flow conditions. Beyond quantifying pressure drop variations, it examines associated flow characteristics including velocity profile development, boundary layer behaviour, and turbulence intensity distributions. The findings aim to bridge the divide between theoretical fluid mechanics and practical engineering design, offering evidence-based insights for material selection and system optimization.

Ultimately, this study contributes to more sustainable engineering practices by providing data that can reduce energy waste in fluid transport systems. The validated CFD methodology also establishes a reference framework for future investigations of surface-fluid interactions in internal flows.

The selection of appropriate piping materials represents a critical economic and technical decision in infrastructure projects, where initial material costs must be balanced against long-term operational expenses related to energy consumption and maintenance. Different materials exhibit inherently distinct surface morphologies due to their manufacturing processes—cast metals display microscopic irregularities from moulding processes, while extruded polymers like PVC demonstrate relatively smoother surfaces with longitudinal striations. These surface characteristics evolve during service life through corrosion, scaling, or biological fouling, further modifying hydraulic performance.

2. METHODOLOGY

2.1 Overall Computational Approach

This research employs a systematic computational methodology using ANSYS Fluent 2021 R1 to investigate roughness effects on pressure drop. The study follows a three-phase approach:

(1) Pre-processing and model development, (2) Simulation execution, and (3) post-processing and analysis. The workflow adheres to established CFD best practices for validation and accuracy assurance.

2.2 Geometry and Domain Specification

A three-dimensional straight circular pipe geometry will be modeled with the following specifications:

- **Diameter (D):** 20 mm (standard nominal size for comparative studies)
- **Length (L):** 500 mm (L/D = 25, ensuring fully developed flow)
- **Inlet Section:** 100 mm development length before pressure measurement points
- **Outlet Section:** 100 mm length after measurement section
- **Measurement Section:** 300 mm for pressure drop calculation

The geometry will be created using ANSYS Design Modeler, ensuring water-tight volumes and proper edge connectivity for high-quality meshing.

2.3 Mesh Generation Strategy

A structured hexahedral mesh will be implemented for numerical accuracy and computational efficiency:

- **Mesh Type:** O-grid structured hexahedral elements
- **Boundary Layer Refinement:** 15 inflation layers with growth rate of 1.2
- **First Layer Thickness:** Calculated to achieve y+ ≈ 30-50 for enhanced wall treatment
- **Core Mesh:** Gradually expanding elements toward pipe center
- **Mesh Independence Study:** Three mesh densities (coarse: 150k, medium: 350k, fine: 750k elements) will be tested to ensure solution invariance

2.4 Physics Setup and Boundary Conditions

2.4.1 Solver Settings:

- **Type:** Pressure-based, steady-state
- **Velocity Formulation:** Absolute
- **Gadient Scheme:** Least Squares Cell Based
- **Pressure-Velocity Coupling:** SIMPLE algorithm
- **Spatial Discretization:** Second-order upwind for momentum, turbulence kinetic energy, and turbulence dissipation rate

2.4.2 Turbulence Modeling:

- **Model:** Standard k-epsilon (2-equation RANS model)
- **Near-Wall Treatment:** Enhanced Wall Treatment (EWT) for roughness effects
- **Turbulence Intensity:** 5% at inlet (typical for pipe flows)
- **Turbulent Viscosity Ratio:** 10 at inlet

2.4.3 Material Properties:

- **Fluid:** Water at 25°C
- **Density (ρ):** 997 kg/m³
- **Dynamic Viscosity (μ):** 0.00089 Pa·s

2.4.4 Boundary Conditions:

Boundary	Type	Specification
Inlet	Velocity Inlet	Varied velocities to achieve Re = 4,000 to 100,000
Outlet	Pressure Outlet	0-gauge pressure (atmospheric)
Pipe Wall	No-Slip with Roughness	Sand-grain roughness heights as per Table 1
Symmetry	Axisymmetric	For 2D-axisymmetric validation cases

Table. 2.1 Boundary Conditions

2.4.5 Roughness Implementation:

Roughness will be implemented using Fluent's sand-grain roughness model with the following equivalent roughness heights:

Material	Roughness Height (ε)	Roughness Constant (C_s)	Source
PVC	0.0015 mm	0.5	ASHRAE Handbook

Galvanized Iron	0.15 mm	0.5	Moody Chart
Asphalted Cast Iron	0.12 mm	0.5	Engineering Standards
Cast Iron	0.26 mm	0.5	Moody Chart
Concrete	1.00 mm (average)	0.5	Civil Engineering References

Table 2.2: Material Roughness Parameters

2.5 Simulation Cases and Flow Conditions

- **Flow Rates:** 10 velocities correspo9nding to Re = 4,000, 10k, 20k, 30k, 40k, 50k, 60k, 75k, 90k, 100k
- **Total Simulations:** 5 materials × 10 flow rates = 50 primary simulations
- **Additional Cases:** Smooth pipe baseline ($\varepsilon = 0$) for comparison
- **Validation Cases:** 2D-axisymmetric models for comparison with theoretical solutions

2.6 Solution Strategy and Convergence Criteria

- **Initialization:** Hybrid initialization from inlet
- **Under-relaxation Factors:** Default values with monitoring for stability
- **Convergence Criteria:** Residuals < 10^{-6} for continuity, momentum, k and ε equations
- **Monitoring Points:** Pressure at inlet and outlet, velocity at centerline and near-wall regions
- **Iterations:** Maximum 2000 iterations per case, with automatic saving of converged data

2.7 Validation and Verification Protocol

1. **Code Verification:** Comparison with analytical solutions for laminar flow
2. **Model Validation:** Comparison with experimental data from literature for smooth and rough pipes
3. **Grid Independence:** Three-mesh study with <2% variation in pressure drop
4. **Iterative Convergence:** Monitoring of residuals and key parameters
5. **Comparison with Theory:** Validation against Darcy-Weisbach equation and Moody chart

2.8 Data Extraction and Analysis Methods

- **Pressure Drop:** Calculated between points 100 mm from inlet and 100 mm from outlet
- **Friction Factor:** Computed using Darcy-Weisbach equation
- **Velocity Profiles:** Extracted along radial lines at multiple axial positions
- **Turbulence Parameters:** Turbulent kinetic energy, dissipation rate, viscosity ratio
- **Wall Shear Stress:** Directly extracted from Fluent results
- **Statistical Analysis:** Regression analysis to correlate roughness with pressure drop

2.9 Post-processing and Visualization

- **ANSYS CFD-Post** for contour plots, vectors, and streamlines
- **Key Visualizations:**
    - Pressure contours along pipe length
    - Velocity magnitude contours and profiles
    - Turbulence intensity distribution

- Wall shear stress distribution
- Comparative bar charts and line plots

- **Roughness Increases Friction :** Higher and increases pressure drop .
- **Material Comparison:**

2.10 Surface Roughness Comparison:

Material	**Roughness (mm)**	**Pressure Drop Impact**
PVC	0.0015	Low
Steel	0.045	Moderate
Copper	0.0015	Low
Cast Iron	0.26	High
Material	Roughness (mm)	Pressure Drop Impact
PVC	0.0015	Low
Steel	0.045	Moderate
Copper	0.0015	Low
Cast Iron	0.26	High

Smoother pipes (copper , PVC) increase efficiency by lowering pressure drop . Cast iron and other rough materials raise energy expenses.

3. EXPECTED OUTCOMES

3.1 Primary Numerical Outcomes

i. **Quantitative Pressure Drop Database:** Tabulated pressure drop values (in Pa/m) for all five materials across the turbulent flow range, providing directly comparable performance metrics.

ii. **Material Performance Ranking:** A clear hierarchy of materials based on hydraulic efficiency, from lowest to highest pressure drop under identical conditions.

iii. **Friction Factor Correlations:** Material-specific friction factor (f) versus Reynolds number (Re) relationships, potentially in the form of modified Colebrook-type equations.

b. Scientific and Technical Contributions

i. **Validated CFD Methodology:** A documented, step-by-step procedure for implementing and validating roughness effects in ANSYS Fluent, including mesh guidelines, solver settings, and convergence criteria.

ii. **Flow Physics Insights:** Detailed understanding of how different roughness levels alter:

1. Velocity profile shapes and fullness factors
2. Boundary layer thickness and development
3. Turbulence production and dissipation near walls
4. Wall shear stress distribution patterns

iii. **Regime Classification:** Identification of Reynolds number thresholds where each material transitions from hydraulically smooth to transitionally rough to fully rough behavior.

c. Visualization and Graphical Outcomes

i. **Comparative Contour Plots:** Side-by-side visual comparisons of pressure, velocity, and turbulence fields for all five materials at selected Reynolds numbers.
ii. **Dimensionless Performance Charts:** Moody-type charts specific to each material, showing friction factor versus Reynolds number with experimental validation points.
iii. **Parameter Sensitivity Plots:** Graphs showing how pressure drop varies with both Reynolds number and roughness height, potentially revealing nonlinear interaction effects.

d. Practical Engineering Outcomes

i. **Design Guidelines:** Practical recommendations for engineers regarding:

1. When material roughness becomes a dominant design factor

2. Cost-benefit analysis of smoother versus cheaper materials

3. Expected performance degradation with aging/corrosion

ii. Energy Impact Assessment: Calculations showing potential energy savings (in kWh/year) from optimal material selection for typical piping applications.
iii. Performance Prediction Tool: Simple correlations or nomograms that allow engineers to estimate pressure drop based on material type, pipe diameter, and flow rate without complex CFD.

e. Validation and Benchmarking Outcomes

i. **CFD Validation Report:** Comprehensive comparison between simulation results and:

1.Theoretical predictions from Darcy-Weisbach/Colebrook equations

2.Available experimental data from literature

3.Moody chart predictions

ii. Error Analysis: Quantification of numerical errors, modeling uncertainties, and validation discrepancies with root-cause analysis.

f. Research Dissemination Outcomes

i. Thesis Document: Comprehensive documentation of methodology, results, and conclusions.

ii. Potential Journal Publication: Condensed version suitable for journals like Journal of Fluids Engineering, International Journal of Heat and Fluid Flow, or Engineering Applications of Computational Fluid Mechanics.

iii. Conference Presentation: Key findings presented in graphical format suitable for technical conferences.

g. Expected Numerical Findings (Hypotheses)

Based on preliminary analysis, the study expects to find:

i. PVC will show the lowest pressure drop across all flow rates
ii. Concrete will exhibit the highest pressure drop, approximately 15-25% higher than PVC at Re = 50,000
iii. The relationship between ε/D and pressure drop will follow a power-law rather than linear relationship
iv. Materials will cluster into performance groups: (1) PVC, (2) Asphalted CI/GI, (3) Cast Iron/Concrete
v. Roughness effects will become significant (ΔP increase >5%) at lower Re for rougher materials

h. Implications for Future Research

Multiphase Flows: In rough pipes, multiphase flows (gas-liquid, liquid-solid) require more intricate modeling, particularly with regard to phase interaction and instability. Advanced Characterization: Research must examine roughness texture (geometry, frequency, anisotropy) and its effects on boundary layers in addition to basic height. Application-Specific Optimization: Examine how particular roughness types (such as triangular or riblets) can improve heat transfer or mixing in systems like microreactors or cooling loops, rather than merely reducing pressure drop. For precise industrial design, create reliable computational fluid dynamics (CFD) models that incorporate surface geometry, material characteristics, and operating conditions (Re, flow type). Real-World Data: To close the gap between idealized models and real-world performance, concentrate on experimental validation for aged or fouled pipes.

The methodology and findings will enable:

i. Extension to other materials (HDPE, copper, stainless steel)
ii. Investigation of non-circular pipes and complex geometries
iii. Study of aging effects through time-dependent roughness evolution
iv. Multi-phase flow applications (slurries, gas-liquid flows)

Optimization studies for pipe sizing and material selection algorithms Multiphase Flows & Roughness:

- Complex Interactions: Phase distribution, slip, pressure drop
- Modeling Challenges: Capturing interface dynamics, turbulence Advanced Roughness Characterization:
- Texture Matters: Geometry, frequency, anisotropy affect flow
- Beyond Height: Impact on boundary layers, heat transfer Application-Specific Optimization:
- *Roughness Types:* Triangular, riblets for heat transfer, mixing
- *Use Cases:* Microreactors, cooling loops, process optimization Modeling & Validation:
- *Accurate Models:* Incorporate surface geometry, material, Re, flow type
- *Real-World Data:* Experimental validation for aged/fouled pipes crucial .

4. SIGNIFICANCE AND APPLICATIONS

4. Theoretical Significance

4.1 Advancement in Fundamental Fluid Mechanics

This research contributes significantly to the fundamental understanding of turbulent boundary layer interactions with rough surfaces. While classical theories (Nikuradse, Moody) established basic relationships, this study provides detailed, quantifiable data on how specific roughness morphologies—represented by equivalent sand-grain values for actual engineering materials—alter turbulent flow structures. The investigation offers insights into:

- Energy cascade modifications in turbulent flows due to wall roughness
- Boundary layer restructuring and its impact on velocity profiles
- Turbulence intensity redistribution across pipe cross-sections
- Wall shear stress enhancement mechanisms specific to material surfaces

4.2 Computational Fluid Dynamics Methodology Development

The study advances CFD practice by developing and validating a robust methodology for roughness implementation in commercial software. Specific contributions include:

- Best practice guidelines for mesh refinement near rough walls in internal flows
- Validation protocols for turbulence model performance with roughness effects
- Solution strategy optimization for achieving convergence in rough-pipe simulations
- Post-processing techniques for extracting meaningful parameters from rough-wall flows

4.3 Enhancement of Friction Factor Correlations

Current friction factor correlations (Colebrook-White, Swamee-Jain) rely heavily on Nikuradse's sand-grain experiments. This research provides contemporary data that could lead to:

- Material-specific correlation coefficients for improved accuracy
- Range-optimized equations for different Reynolds number regimes
- Multi-parameter correlations accounting for roughness distribution patterns

- Validation datasets for emerging machine-learning based friction factor predictors

4.4 Contribution to Turbulence Modeling Theory

The detailed flow field analysis contributes to turbulence modeling theory by:

- Providing validation data for RANS model improvements
- Identifying limitations of standard k-epsilon model for rough-wall flows
- Suggesting modifications to near-wall treatment for different roughness types
- Contributing to database for future development of roughness-sensitive turbulence models

4.5 Practical Applications

Engineering Design Optimization

The research provides directly applicable data for practicing engineers:

Material Selection Guidance:

- Comparative performance matrices showing pressure drop per unit length for all materials
- Cost-performance tradeoff analysis tools incorporating initial cost versus operational energy expenses
- Application-specific recommendations based on flow conditions and service requirements
- Life-cycle analysis framework considering roughness evolution with time

System Design Enhancement:

- Improved pump selection criteria based on realistic pressure drop predictions
- Pipe sizing optimization algorithms incorporating material-specific roughness effects
- Network analysis enhancement for municipal water distribution systems
- HVAC system optimization through accurate duct/piping resistance calculations

4.6 Energy Efficiency and Sustainability Impact

The research supports global energy conservation efforts:

Direct Energy Savings:

- Pumping energy reduction through optimal material selection (estimated 5-15% savings potential)
- System efficiency improvement by avoiding oversizing due to conservative roughness estimates
- Operational optimization through accurate performance prediction

Environmental Benefits:

- Carbon footprint reduction through decreased energy consumption
- Resource conservation by extending infrastructure lifespan through optimal design
- Sustainable infrastructure development through data-driven material choices

4.7 Maintenance and Asset Management

The findings support improved infrastructure management:

Preventive Maintenance Planning:

- Performance degradation prediction models based on roughness increase over time
- Replacement scheduling algorithms considering hydraulic performance deterioration
- Condition assessment tools using pressure drop measurements as roughness indicators

Renovation and Rehabilitation:

- Lining material selection guidance based on hydraulic performance restoration
- Cost-benefit analysis for pipe replacement versus rehabilitation
- Performance benchmarking for evaluating rehabilitation effectiveness

4.8 Educational and Training Applications

The research serves as a valuable educational resource:

Academic Curriculum Enhancement:

- Case study development for fluid mechanics courses demonstrating real-world applications
- Laboratory exercise development complementing traditional pipe flow experiments
- CFD training modules focusing on practical engineering applications

Professional Development:

- Training materials for engineers on modern pipe design approaches
- Reference documents for design code development and updating
- Best practice manuals for CFD application in hydraulic design

4.9 Industrial Sector Applications

Specific applications across various industries:

Water and Wastewater Sector:

- Distribution system optimization for municipalities
- Treatment plant piping design for chemical dosing and process lines
- Irrigation system design for agricultural applications

Oil and Gas Industry:

- Pipeline material selection for different service conditions
- Pumping station design optimization
- Hydraulic analysis enhancement for existing infrastructure assessment

Chemical and Process Industries:

- Process piping optimization for energy-intensive operations
- Material compatibility analysis considering both chemical resistance and hydraulic performance
- Safety system design through accurate pressure drop prediction

HVAC and Building Services:

- Chilled and hot water system design optimization
- Ductwork material selection for air handling systems
- Energy performance improvement in commercial and institutional buildings

4.10 Software and Tool Development

The methodology supports development of engineering tools:

Design Software Enhancement:

- Library development for commercial pipe design software
- Plugin development for CAD packages incorporating material performance data
- Mobile applications for field engineers to estimate pressure drops

Digital Twin Applications:

- Parameter calibration for digital twins of piping systems
- Performance prediction modules for infrastructure management platforms

- Condition monitoring algorithms for smart water networks

CFD Software (e.g., Ansys Fluent, OpenFOAM): Simulate fluid flow, incorporating detailed geometric roughness from 3D scans (CT scans) or standard roughness values (e.g., sand-grain equivalent) for complex models.

Machine Learning Models (ANN): Develop predictive tools using Artificial Neural Networks to establish correlations between physical parameters (roughness, material) and pressure drop.

Discrete Element Method (DEM): Used for granular flows (like soil-pipe interaction), simulating pipe roughness using overlapping spheres for micro-mechanical analysis.

Empirical/Semi-Empirical Tools: Software implementing formulas like Colebrook-White or developing new correlations based on experimental data for specific materials (cast iron , galvanized iron, PVC , concrete, asphalted cast iron).

Tools for Simulating Roughness Effects:

- *CFD Software:*
- Ansys Fluent, OpenFOAM
- Incorporate 3D scans or standard roughness values
- *Machine Learning:*
- ANN for predicting pressure drop correlations
- *Discrete Element Method (DEM):*
- Granular flows, micro-mechanical analysis
- *Empirical Tools:*
- Colebrook-White, material-specific correlations

5. LIMITATIONS AND SCOPE

5.1 Research Scope

5.1.1 Material Scope

The investigation is deliberately limited to five commercially significant pipe materials representing distinct categories:

Metallic Pipes:

- Cast Iron: Traditional material with high roughness, representing older infrastructure
- Galvanized Iron: Coated steel pipe common in moderate-service applications
- Asphalted Cast Iron: Lined pipe showing intermediate roughness characteristics

Non-Metallic Pipes:

- PVC: Modern polymeric pipe with very low roughness
- Concrete: Cementitious material with very high roughness, used in large-diameter applications

Flow Regimes: Examining the impact of roughness in laminar, transitional, and turbulent flows. Roughness effects are minimal in laminar flow but become dominant in fully turbulent regimes.

Varied Materials & Roughness Characterization: Comparing different materials (e.g., cast iron, galvanized iron, PVC, concrete, asphalted cast iron) and their associated absolute roughness values, which can range widely (from 0.0015 mm for PVC to 3.0 mm for concrete). The study can use established standards (like the ASME B46.1-2002 standard for roughness parameters) to characterize the surfaces.

Flow Conditions: Investigating the effects across various flow velocities (Reynolds numbers), fluid properties (viscosity, density), and potentially single-phase (liquid or gas) or multiphase flows (e.g., slurries).

Scale of Study: Ranging from conventional large-diameter pipes to microchannels, as roughness effects can vary significantly with pipe diameter (relative roughness).

Predictive Modeling: Developing and validating computational fluid dynamics (CFD) models or empirical correlations (like the Moody chart or Darcy-Weisbach equation) to accurately predict pressure drop for different roughness conditions.

5.2.2 Fluid and Flow Conditions

Working Fluid: Deionized water at constant temperature (25°C)

- Justification: Eliminates variable fluid property complications
- Implication**:** Results directly applicable to water systems; scaling required for other fluids

Flow Regime: Turbulent flow only (Re > 4000)

- Justification: Roughness effects negligible in laminar flow
- Range: Re = 4,000 to 100,000 covering typical engineering applications
- Implication: Excludes transitional and laminar flow analyses

5.2.3 Geometric Scope

Pipe Configuration: Straight, horizontal, circular pipes

- Diameter: Constant 20 mm for all simulations
- Length: Sufficient for fully developed flow (L/D = 25)
- Implication: Excludes fittings, bends, expansions, contractions, and non-circular sections

Surface Condition: New pipe condition with standard manufacturing roughness

- Implication: Does not consider aging, corrosion, scaling, or biological fouling effects

5.2.4 Numerical Methodology Scope

CFD Approach: Steady-state RANS modeling

- Turbulence Model: Standard k-epsilon with enhanced wall treatment
- Implication: Excludes transient analysis, LES, DNS, or advanced turbulence models

Software Platform: ANSYS Fluent 2021 R1 Academic Version

- Implication: Subject to software limitations and academic license constraints

5.3 Research Limitations

5.3.1 Roughness Modeling Limitations Equivalent Sand-Grain Approximation:

- Limitation: Real surface morphology reduced to single parameter (ε)
- Impact: Cannot capture effects of roughness pattern, anisotropy, or specific asperity shapes
- Mitigation: Using established engineering standards ensures practical relevance

Constant Roughness Assumption:

- Limitation: Uniform roughness along pipe length
- Impact: Does not account for localized roughness variations or joint effects
- Mitigation: Represents typical design assumption for straight pipe sections

5.3 Numerical Modeling Limitations RANS Modeling Assumptions:

- Limitation: Turbulence represented by time-averaged equations
- Impact: Cannot capture transient turbulent structures or large-scale unsteadiness
- Mitigation: Acceptable for engineering pressure drop predictions

Near-Wall Treatment:

- Limitation: Enhanced wall treatment approximations for rough walls
- Impact: Potential inaccuracies in very near-wall region predictions
- Mitigation: Validated against available experimental data

Mesh Resolution Constraints:

- Limitation: Academic version mesh size limits (~512k cells for 3D)

- Impact: May require geometry simplification or reduced mesh quality
- Mitigation: Careful mesh optimization and 2D validation cases

5.4 Physical Process Limitations Single-Phase Flow:

- Limitation: Only water phase considered
- Impact: Cannot model multiphase flows (gas-liquid, solid-liquid)
- Implication: Results not directly applicable to slurry transport or gas pipelines

Isothermal Conditions:

- Limitation: Constant temperature assumption
- Impact: Neglects temperature-dependent property variations
- Implication: Applicable to isothermal systems only

Rigid Wall Assumption:

- Limitation: Non-deformable pipe walls
- Impact: Cannot model flexible pipes or wall vibration effects
- Implication: Suitable for standard metallic and plastic pipes

5.5 Scope for Future Work

5.5.1 Immediate Extensions

- Additional Materials: HDPE, copper, stainless steel, lined pipes
- Diameter Variations: Study scale effects through multiple diameters
- Fluid Variations: Different liquids (oils, chemicals) and temperature effects

5.5.2 Methodological Extensions

- Advanced Turbulence Models: k-omega SST, Reynolds Stress Models, LES
- Transient Analysis: Unsteady flow effects and flow development
- Actual Surface Scans: Incorporation of measured surface profiles

5.5.3 Application Extensions

- Aging and Corrosion: Time-dependent roughness evolution modeling
- Fittings and Components: Bends, valves, and other flow disturbances
- Network Analysis: Application to complete piping systems

5.5.5 Experimental Validation

- Laboratory Experiments: Direct validation with controlled test rig
- Field Measurements: Comparison with operational system data
- Long-term Studies: Performance monitoring over time

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