

Article

Assessment of Hydrodynamic Losses and Pumping Energy Penalty in Corrugated Pipes

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Abstract

Corrugated pipes are widely used due to their mechanical flexibility; however, their corrugated internal geometry is associated with increased hydraulic losses. Previous studies have reported a non-classical increase in friction factors with pipe diameter at identical Reynolds numbers, although the underlying mechanisms and related energy implications have not been fully clarified. In this study, turbulent flow behavior and pumping power requirements in stainless-steel corrugated pipes are investigated using a validated three-dimensional Computational Fluid Dynamics (CFD) framework based on the SST $k-\omega$ turbulence model. The numerical predictions show good agreement with available experimental data, with maximum deviations remaining below approximately 12% across the validated range. The results indicate that both friction factor and pumping power increase systematically with pipe diameter under dynamically similar flow conditions, demonstrating that Reynolds-number similarity alone does not ensure flow similarity in corrugated geometries. From an energy perspective, an Energy Penalty Factor (EPF) is introduced to quantify corrugation-induced pumping requirements, and a surrogate correlation is developed to relate EPF to Reynolds number and selected dimensionless geometric parameters. The proposed formulation exhibits strong predictive performance within the investigated parameter space ($R^2 = 0.972$) and enables rapid, CFD-free estimation of energy penalties for preliminary design and comparative evaluation of corrugated piping systems.

Keywords: corrugated pipes; friction factor; pumping power; CFD; diameter effect; energy penalty factor

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1. Introduction

Corrugated pipes are widely employed in HVAC (heating, ventilation, and air conditioning) installations, industrial fluid transport lines, renewable energy systems, and building services due to their flexibility, structural robustness under external loads, and ease of installation [1–3]. Corrugated stainless steel components, such as flexible line (FL) compensators and T-junctions, offer practical advantages over rigid metallic pipes by accommodating misalignment, absorbing thermal expansion without additional compensators, and reducing vibration-induced stresses at connection points [1,2]. In practical installations, corrugated stainless steel tubes (CSSTs) are commonly connected to rigid piping systems through standard fittings and expansion elements, as illustrated in Figure 1.



Figure 1. Stainless steel flexible metal pipe and an example of its application [1].

These mechanical advantages, however, are accompanied by a notable hydraulic penalty. The periodically corrugated internal surface induces flow separation, generates recirculation zones within the grooves, and intensifies turbulence production, resulting in pressure losses significantly higher than those observed in smooth pipes under identical flow conditions [4–6]. Consequently, the associated increase in pumping power demand may adversely affect overall system energy efficiency, particularly in energy-sensitive engineering applications such as HVAC circulation systems and renewable-energy-driven thermal loops [7].

Pressure losses in internal flows arise from complex interactions among Reynolds number, surface roughness, boundary-layer development, and geometric irregularities. For smooth pipes, these interactions are well described by classical friction-factor correlations, and at a fixed Reynolds number the influence of pipe diameter becomes negligible, in accordance with dynamic similarity theory [8–11]. In corrugated pipes, however, the groove geometry acts as a large-scale roughness element, amplifying the sensitivity of flow behaviour to geometric parameters. Groove pitch, depth, and profile shape directly influence separation length, vortex persistence, and frictional dissipation mechanisms [12–14].

Although corrugations may enhance fluid mixing and improve heat transfer under certain conditions, this enhancement is commonly accompanied by a pronounced increase in pressure drop. Experimental and numerical studies consistently report that corrugated pipes exhibit friction factors approximately 1.8–2.5 times higher than those of smooth pipes under turbulent flow conditions, while achieving heat-transfer enhancements typically in the range of 50–300%, depending on corrugation geometry and Reynolds number [15–17]. Recent bibliometric analyses of heat transfer enhancement research indicate a prevailing emphasis on thermal performance metrics, with pressure-drop penalties and energy-based indicators often receiving comparatively limited attention. These findings highlight the necessity of evaluating corrugated pipe performance from an energy-based perspective, rather than relying solely on hydrodynamic indicators such as friction factor.

Among the available literature, the most comprehensive experimental datasets on pressure losses in corrugated pipes were reported by Ahn and Popiel [18,19]. These studies provided friction-factor data over wide Reynolds number ranges for pipes with different diameters and corrugation profiles. A non-classical behaviour was experimentally observed, whereby the friction factor increases systematically with increasing pipe diameter at a constant Reynolds number [18–20]. This diameter-dependent trend contradicts classical smooth-pipe theory and cannot be explained solely by relative roughness arguments [8–11]. While experimental uncertainty and scaling effects may partially contribute to this observation, the underlying physical mechanisms governing groove-induced separation, vortex development, and momentum dissipation across different diameters remain insufficiently clarified. Notably, most existing studies report results for fixed pipe diameters or

within specific corrugation families, thereby limiting the generalization of diameter-scaling effects under dynamically similar flow conditions.

Computational Fluid Dynamics (CFD) offers a powerful framework for investigating the complex flow structures inherent to corrugated geometries. High-resolution numerical simulations enable detailed examination of near-wall separation, reattachment processes, and vortex dynamics that directly govern frictional losses in corrugated pipes [21–23]. While numerous numerical studies have investigated corrugated channels and pipes, a significant portion of this literature relies on two-dimensional channel models, simplified corrugation representations, or equivalent roughness approaches, primarily aimed at identifying parametric trends in friction or heat-transfer enhancement [24]. As a result, the experimentally observed diameter-dependent friction behavior in realistic corrugated pipes cannot be fully explained or generalized within these modelling frameworks.

In the present study, turbulent flow in corrugated pipes is investigated numerically using a two-stage CFD strategy. First, a two-dimensional axisymmetric numerical framework is employed as a baseline approach to quantify pressure losses in a commercially available corrugated stainless-steel pipe. The numerical procedure is verified by comparison with classical smooth-pipe correlations and with established empirical pressure-drop relations reported in the literature for corrugated pipes [21–23], ensuring consistency within accepted uncertainty bounds. While the two-dimensional framework provides a computationally efficient and numerically robust basis for pressure-loss prediction, it inherently suppresses circumferential vortical structures, azimuthal momentum transfer, and secondary flow motions, which are expected to intensify with increasing pipe diameter and to play a decisive role in the observed non-classical friction scaling. Capturing these mechanisms therefore necessitates a fully three-dimensional representation of the corrugated geometry.

Accordingly, building upon the verified two-dimensional baseline, fully three-dimensional CFD simulations are subsequently performed to investigate how groove-induced flow structures evolve with pipe diameter under otherwise identical flow conditions. Although various correlations and performance criteria have been proposed to balance heat-transfer enhancement and pressure-drop penalties [15–17], most available results have been obtained for fixed pipe diameters or specific corrugation families. Consequently, the manner in which frictional and energetic penalties scale with pipe diameter, and how this scaling translates into pumping power requirements at the system level, has not yet been systematically clarified.

Moreover, while energy-based performance metrics such as constant pumping power comparisons, Performance Evaluation Criteria (PEC), Performance Enhancement Factors (PEFs), and exergy efficiency analyses are widely employed [15–17], many numerical investigations continue to rely on idealized channel models or simplified surface representations [25]. Although such approaches are useful for parametric investigations, they remain limited in their ability to capture diameter-scaling effects observed in realistic corrugated pipes.

The primary objective of the present study is therefore to elucidate the physical origin of diameter-dependent friction behavior in corrugated pipes and to assess its implications from an engineering energy perspective. By explicitly relating pressure losses to pumping power requirements, the analysis extends conventional hydrodynamic evaluation toward system-level relevance, highlighting how moderate variations in friction factor may result in appreciable energy penalties in practical applications. Within this framework, a generalized Energy Penalty Factor (EPF) is introduced as an engineering-oriented performance metric that directly links hydrodynamic losses to pumping power demand while accounting for Reynolds number and key geometric parameters. In addition, a surrogate correlation is developed to enable CFD-free estimation of pumping power requirements,

providing a practical tool for preliminary design and energy-efficient selection of corrugated piping systems.

Accordingly, the present investigation is structured to bridge engineering-oriented pressure-loss assessment with physics-based flow interpretation in a progressive manner. First, a verified two-dimensional numerical framework is employed to quantify pressure losses in a commercially available corrugated stainless-steel pipe under practical operating conditions. Building upon this baseline, three-dimensional numerical analyses are then conducted for experimentally documented corrugated pipe geometries in order to examine the flow mechanisms associated with the observed diameter-dependent friction behavior. This combined strategy allows practical engineering relevance and fundamental physical insight to be addressed within a unified and consistent framework.

2. Materials and Methods

2.1. Numerical Model and Governing Equations

The flow inside corrugated pipes is characterized by strong geometric confinement, periodic cross-sectional variations, and intense near-wall interactions, which promote flow separation, reattachment, and groove-induced vortex formation. These mechanisms govern frictional losses and cannot be adequately described using simplified roughness-based models. Accordingly, the internal flow is modeled as steady, incompressible, and turbulent, consistent with previous numerical and experimental investigations on corrugated pipes [14,18,20].

The governing equations consist of the Reynolds-Averaged Navier–Stokes (RANS) equations, expressing conservation of mass and momentum as

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \rho \overline{u_i' u_j'} \right] \quad (2)$$

where u_i denotes the velocity components, p is the pressure, ρ is the fluid density, and μ is the dynamic viscosity. The Reynolds stress tensor $\overline{u_i' u_j'}$ accounts for turbulent velocity fluctuations and requires appropriate closure through turbulence modeling [21,22].

The flow regime was characterized using the Reynolds number,

$$Re = \frac{\rho V D}{\mu} \quad (3)$$

where V denotes the bulk mean velocity and D represents the characteristic internal diameter of the pipe. For corrugated pipes, the hydraulic diameter is defined based on the minimum internal diameter measured at the corrugation crests, consistent with the experimental definitions adopted by Ahn and Uslu [18] and Popiel et al. [19]. This crest-to-crest diameter corresponds to the flow-controlling cross-section governing pressure losses and is therefore used in the Reynolds number definition and subsequent friction factor evaluations.

Accurate prediction of wall shear stress, adverse pressure gradients, and separation–reattachment behavior is essential for corrugated pipe flows. Among two-equation eddy-viscosity models, the Shear Stress Transport (SST) $k-\omega$ turbulence model is selected due to its proven capability in resolving near-wall turbulence while maintaining robustness in the core flow region [21]. The SST $k-\omega$ model blends the $k-\omega$ formulation near solid boundaries with the $k-\varepsilon$ behavior in the free-stream region, making it particularly suitable for flows involving strong curvature effects, periodic acceleration–deceleration, and flow separation inherent to corrugated pipe geometries [14,20]. The detailed transport

equations are not repeated here for brevity and can be found in the original formulation by Menter [21].

Wall functions are intentionally avoided. Instead, the near-wall region is fully resolved using the low-Reynolds-number formulation of the SST $k-\omega$ model, with the first grid point placed at $y^+ \approx 1$. This approach enables direct resolution of wall shear stresses and avoids the limitations associated with wall-function-based treatments, which are known to be inadequate for accurately capturing strong flow separation and reattachment phenomena commonly observed in corrugated pipe geometries [26].

Moreover, while energy-based performance metrics such as constant pumping power comparisons, Performance Evaluation Criteria (PEC), Performance Enhancement Factors (PEFs), and exergy-based indicators are widely employed in recent corrugated-pipe studies [15–17], many numerical investigations continue to rely on idealized channel representations or equivalent roughness-based surface models. In the present work, this limitation is explicitly addressed by resolving the full corrugation geometry within the computational domain, thereby enabling direct capture of groove-scale separation, reattachment, and vortex dynamics that govern diameter-dependent hydraulic losses.

2.2. Pipe Geometries and Computational Domain

The numerical investigation is conducted on eight corrugated pipe geometries reported in the experimental studies of Ahn and Uslu [18] and Popiel et al. [19], which constitute some of the most comprehensive and systematically documented datasets available for friction factor measurements in corrugated pipes. These geometries span a wide range of inner diameters, corrugation pitches, and groove widths, thereby enabling a systematic assessment of diameter-dependent friction behavior under turbulent flow conditions.

The geometric parameters of the investigated pipes—including the inner diameter d_i , outer diameter d_o , corrugation pitch P , and groove width W —are summarized in Table 1, together with their corresponding reference sources. The availability of detailed geometric definitions in combination with experimentally measured pressure-drop data allows direct and quantitative validation of numerical predictions.

Table 1. Geometric characteristics of the simulated corrugated pipes.

Reference Source	d_i (mm)	d_o (mm)	Pitch P (mm)	Groove Width W (mm)
Ahn [18]	20.4	26.1	4.8	2.5
	25.4	31.3	5.3	3.1
	34.5	40.5	4.8	3.1
	40.5	49	6.6	3.8
Popiel [19]	9.1	12.3	4.2	2.3
	13	16.8	5.12	2.8
	19.7	25	6.46	3.6
	26.7	32.8	7.2	4

In addition to these reference geometries, a commercially available corrugated stainless steel flexible pipe (CSST) commonly used in building-service and industrial piping systems is included in the analysis. This commercial pipe is investigated exclusively using a two-dimensional axisymmetric model, with the objective of quantifying realistic pressure-loss penalties relative to an equivalent smooth pipe under practical operating conditions. No three-dimensional simulations are performed for the CSST geometry, as corresponding experimental reference data are unavailable, which precludes physically

meaningful validation and generalization of three-dimensional flow features for this configuration.

In contrast, the eight corrugated geometries documented in the literature are further analyzed using fully three-dimensional CFD simulations. This three-dimensional framework is essential for identifying and generalizing the flow mechanisms responsible for the experimentally observed diameter-dependent friction behavior, including circumferential vortex structures and secondary flows that cannot be represented within a two-dimensional formulation. This deliberate distinction between the CSST case and the literature geometries enables both practical engineering relevance and fundamental physical insight to be addressed within a single unified study.

All corrugated pipes are modeled by explicitly resolving the full corrugation profile within the computational domain. Simplified wall treatments or equivalent roughness approximations are deliberately avoided, because such approaches are unable to capture the localized flow separation, reattachment, and groove-scale vortex dynamics that dominate pressure-loss mechanisms in corrugated geometries. Previous studies have shown that representing corrugations solely through equivalent roughness parameters leads to significant loss of physical fidelity, particularly when separation-driven losses are dominant [14,20].

2.3. Mesh Strategy, Boundary Conditions, and Numerical Solution Procedure

The computational domains are discretized using high-resolution polyhedral meshes to accurately represent the complex corrugated pipe geometries. Local mesh refinement is applied in the corrugation regions to resolve sharp velocity gradients, flow separation, and recirculation occurring near groove crests and valleys. This strategy ensures that groove-scale flow structures governing pressure losses are sufficiently captured.

Particular attention is devoted to the near-wall region, where viscous effects dominate pressure loss mechanisms. Inflation layers are applied along all solid boundaries, and the first cell height is determined based on the dimensionless wall distance y^+ , defined as

$$y^+ = \frac{\rho u_\tau y}{\mu} \quad (4)$$

where u_τ is the friction velocity and y is the wall-normal distance [8,27]. For compatibility with the low-Reynolds-number formulation of the SST $k-\omega$ model, a target value of $y^+ \approx 1$ is adopted, such that the near-wall region is fully resolved without the use of wall functions [21,27].

The friction velocity is evaluated as

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} \quad (5)$$

For all simulations, the near-wall mesh was designed to satisfy a target non-dimensional wall distance of $y^+ \approx 1$, consistent with the requirements of the SST $k-\omega$ turbulence model. The wall shear stress used for estimating the first-layer thickness was initially approximated using classical empirical correlations for turbulent flow in smooth circular pipes solely for pre-processing; during the CFD computations, the wall shear stress distribution was fully resolved by the turbulence model. The resulting first-layer thickness values and near-wall resolution parameters are summarized in Appendix A1 (Table A1).

At the pipe inlet, a velocity inlet boundary condition is imposed, with inlet velocities prescribed to cover the Reynolds number range

$$10^4 \leq \text{Re} \leq 1.5 \times 10^5 \quad (6)$$

which corresponds to fully developed turbulent flow conditions commonly encountered in industrial piping and building-service applications [3,18]. For each simulation case, the inlet velocity is calculated using the Reynolds number definition given in Equation (3). Turbulence quantities at the inlet are specified using the empirical turbulence intensity relation

$$I = 0.16 Re^{-1/8} \quad (7)$$

which is valid for fully developed turbulent internal flows and is used here solely for inlet specification. At the outlet, a pressure outlet boundary condition with zero-gauge pressure is applied, allowing the flow to develop naturally while minimizing artificial numerical constraints. All pipe walls are modeled as stationary no-slip boundaries,

$$u = v = w = 0 \quad (8)$$

The working fluid is defined as water with constant thermophysical properties, consistent with the experimental studies used for validation [19,20], as the present investigation focuses exclusively on hydrodynamic pressure losses under isothermal conditions.

The numerical simulations are performed using the finite volume method implemented in ANSYS (Ansys 2024 R1) Fluent under steady-state conditions [23]. Pressure-velocity coupling is handled using the SIMPLE algorithm, and second-order discretization schemes are employed for the momentum, turbulence transport, and pressure equations to minimize numerical diffusion. Convergence is assumed when all scaled residuals fall below 10^{-6} and when monitored integral quantities, including pressure drop and friction factor, reach steady asymptotic values.

To ensure numerical reliability, the computational meshes were designed with sufficiently fine resolution to accurately capture near-wall gradients and groove-induced flow structures in corrugated pipe geometries. High-resolution polyhedral meshes were employed, with particular emphasis on near-wall refinement to satisfy a target non-dimensional wall distance of $y^+ \approx 1$ along the entire corrugated surface, in accordance with the requirements of the low-Reynolds-number formulation of the SST $k-\omega$ turbulence model.

The adequacy of the adopted mesh resolution is supported by the stability of the predicted pressure losses and friction factors across the investigated Reynolds number range, as well as by the close agreement obtained with classical smooth-pipe correlations and independent experimental data. In particular, the numerical framework reproduces experimental friction-factor trends reported by Ahn and Uslu and Popiel et al. within acceptable deviation limits, as demonstrated in Sections 2.4 and 3.1. This level of agreement indicates that the adopted mesh resolution is appropriate for capturing the primary hydrodynamic quantities considered herein.

Periodic boundary conditions are intentionally not employed, since the primary objective is the direct evaluation of pressure losses and pumping power requirements in corrugated pipes. Instead, sufficiently long inlet-outlet computational domains are adopted to ensure hydrodynamically fully developed flow conditions. The influence of domain length on the numerical results is assessed through a sub-domain analysis, in which the pressure drop per unit length ($\Delta P/L$) is evaluated over multiple axial sub-sections of increasing length within the same computational solution, while excluding the inlet development region and the outlet-affected zone. The resulting $\Delta P/L$ values exhibit negligible variation with increasing evaluation length, confirming that the reported results are independent of the computational domain length and representative of fully developed turbulent flow. Representative polyhedral mesh structures and detailed near-wall refinement characteristics are presented in Appendix A2 (Figures A1 and A2) for completeness.

2.4. Validation of the Numerical Model

The validation strategy was designed to decouple numerical accuracy from geometric complexity by first establishing consistency with canonical smooth-pipe benchmarks before extending the same computational framework to fully resolved corrugated geometries. Turbulent flow in a smooth circular pipe provides a well-established reference case, as its friction-factor behavior is reliably described by classical empirical correlations over a wide range of Reynolds numbers [8,11].

The validation configuration consists of a smooth pipe with an inner diameter of $D = 30$ mm and a length sufficient to ensure hydrodynamically fully developed turbulent flow. The same governing equations, SST $k-\omega$ turbulence model, near-wall resolution strategy, mesh topology, boundary conditions, and solver settings employed for the corrugated-pipe simulations are retained to ensure methodological consistency.

The pressure drop ΔP obtained from the numerical simulations is used to calculate the Darcy friction factor according to

$$f = \frac{2\Delta PD}{\rho LV^2} \quad (9)$$

where L is the pipe length and V is the bulk mean velocity [8,11]. The validation is performed over the Reynolds-number range

$$10^4 \leq Re \leq 1.5 \times 10^5 \quad (10)$$

which corresponds to fully turbulent flow conditions for smooth circular pipes.

For comparison, the CFD-predicted friction factors are evaluated against widely accepted smooth-pipe correlations. The Blasius correlation, $f = 0.3164Re^{-0.25}$, is applicable to hydraulically smooth pipes in the range $4 \times 10^3 < Re < 10^5$. The Colebrook equation provides an implicit formulation incorporating relative roughness effects, while the Haaland equation offers an explicit approximation suitable for engineering calculations [8,11]. The reference friction-factor values used in the present comparison are provided in Appendix A3 (Table A2). The resolved velocity field and groove-scale vortex structures for the Ahn and Uslu configuration at $Re = 50,000$ are further illustrated in Appendix A4 (Figure A3), confirming the capability of the numerical framework to capture the dominant flow features induced by the corrugation geometry.

A quantitative comparison between the CFD-predicted friction factors and the Blasius, Colebrook, and Haaland correlations is presented in Figure 2.

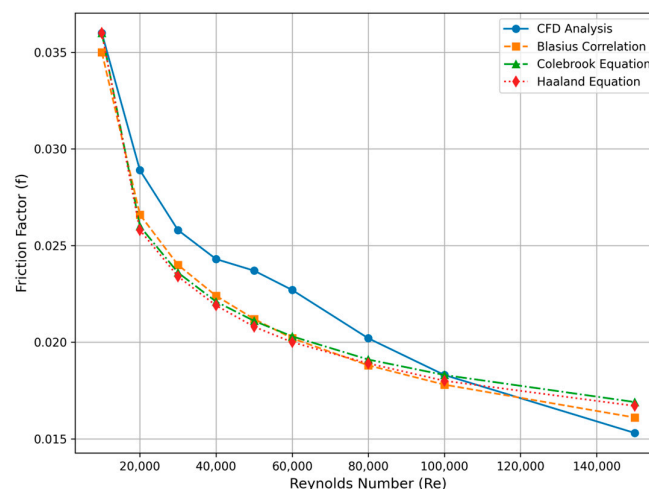


Figure 2. Validation of the numerical model: comparison of simulated friction factors with the Blasius, Colebrook, and Haaland correlations for turbulent flow in a smooth pipe.

Figure 2 presents the quantitative comparison between the CFD predictions and the classical correlations. Across the investigated Reynolds-number range, the numerical results show good agreement with the reference formulations. The maximum deviation remains within approximately $\pm 5\%$, with the closest correspondence observed at higher Reynolds numbers where turbulence is more fully developed. Minor deviations at intermediate Reynolds numbers are attributed to numerical discretization effects, finite computational domain length, and the simplifying assumptions inherent in empirical correlations, rather than to numerical instability.

The close correspondence between the CFD-predicted friction factors and the classical smooth-pipe correlations suggests that:

1. the governing equations and turbulence model are consistently implemented,
2. the near-wall mesh resolution ($y^+ \approx 1$) is sufficient to resolve wall shear stresses without the use of wall functions, and
3. the discretization schemes and solver settings provide stable and grid-consistent solutions for smooth-pipe turbulent flow.

Within the framework of Reynolds-averaged turbulence modeling, these results provide confidence that the dominant physical characteristics of fully turbulent smooth-pipe flow are adequately captured. The maximum deviation between the CFD predictions and the empirical correlations remains within approximately $\pm 5\%$ across the investigated Reynolds-number range, with the closest agreement observed at higher Reynolds numbers where turbulence is more fully developed. Minor discrepancies at intermediate Reynolds numbers are attributed to numerical discretization effects, finite computational domain length, and the simplifying assumptions embedded in empirical correlations, rather than to numerical instability or insufficient near-wall resolution.

This smooth-pipe validation establishes a reliable numerical baseline before introducing the additional geometric complexity associated with corrugated pipe configurations. In corrugated geometries, analytical solutions are unavailable and experimental results reveal significantly more complex flow behavior governed by groove-induced separation, reattachment dynamics, vortex generation, and geometry-dependent turbulence production [14,18,19]. While the discrepancies observed in corrugated-pipe simulations are therefore primarily driven by these physical mechanisms, it is acknowledged that Reynolds-averaged turbulence modeling inherently represents time-averaged flow behavior and may not fully resolve small-scale unsteady structures within individual corrugation cavities.

3. Results

3.1. Validation Against Experimental Data

The numerical framework was assessed against independent experimental friction-factor datasets to establish its predictive reliability prior to the diameter-dependent analysis presented in the following sections. Validation was conducted using two widely cited experimental studies: Ahn and Uslu [18] and Popiel et al. [19]. Together, these datasets cover a broad range of pipe diameters, corrugation geometries, and Reynolds numbers representative of turbulent internal flow in corrugated pipes.

The primary validation was performed using the comprehensive dataset of Ahn and Uslu [18], which reports friction-factor measurements for corrugated pipes with inner diameters of 20.4, 25.4, 34.5, and 40.5 mm over a Reynolds-number range of 10,000–150,000. In numerical simulations, the original geometric parameters documented in the experiments—including corrugation pitch and groove width—were preserved to ensure geometric consistency. Boundary conditions and flow properties were matched to the experimental conditions.

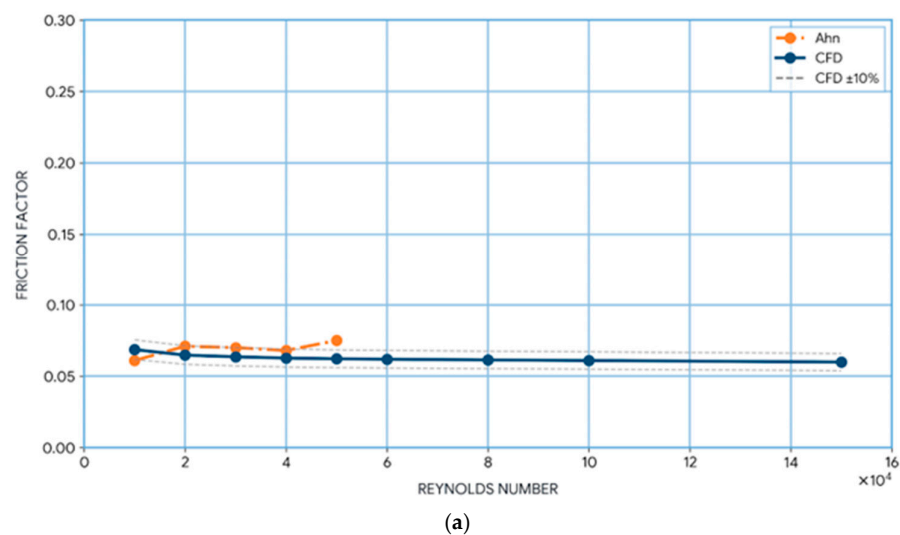
To quantify the agreement between numerical and experimental results, the relative deviation of the Darcy friction factor was defined as the absolute difference between CFD predictions and experimental values normalized by the corresponding experimental reference value. For each pipe diameter, the mean relative deviation was computed over the investigated Reynolds-number range, while the maximum deviation corresponds to the largest discrepancy observed within that range.

The resulting mean and maximum deviations are summarized in Table 2. As shown, the mean relative deviation remains within approximately 6–7% for all investigated diameters, while the maximum deviation does not exceed about 12% across the examined Reynolds-number range. Deviations are generally more pronounced at lower Reynolds numbers and decrease as the flow approaches fully developed turbulent conditions. Over most operating conditions, the numerical predictions remain within a $\pm 10\%$ deviation band relative to the experimental data. Given the complex separation and reattachment phenomena inherent to corrugated geometries, deviations of this magnitude are consistent with values commonly reported for Reynolds-averaged turbulence simulations of similar configurations.

Table 2. Mean and maximum relative deviations between CFD-predicted and experimentally measured friction factors for corrugated pipes reported by Ahn [18].

Inner Diameter, d (mm)	Reynolds Number Range	Mean Deviation (%)	Maximum Deviation (%)
20.4	10,000–150,000	6.3	11.8
25.4	10,000–150,000	5.7	10.6
34.5	10,000–150,000	6.9	12.0
40.5	10,000–150,000	7.4	11.5

Representative comparisons for the smallest and largest Ahn geometries (20.4 mm and 40.5 mm) are presented in Figures 3a and 3b, respectively. The remaining validation plots and corresponding flow-field visualizations for the intermediate geometries are provided in Appendix A4 (Figures A3 and A4).



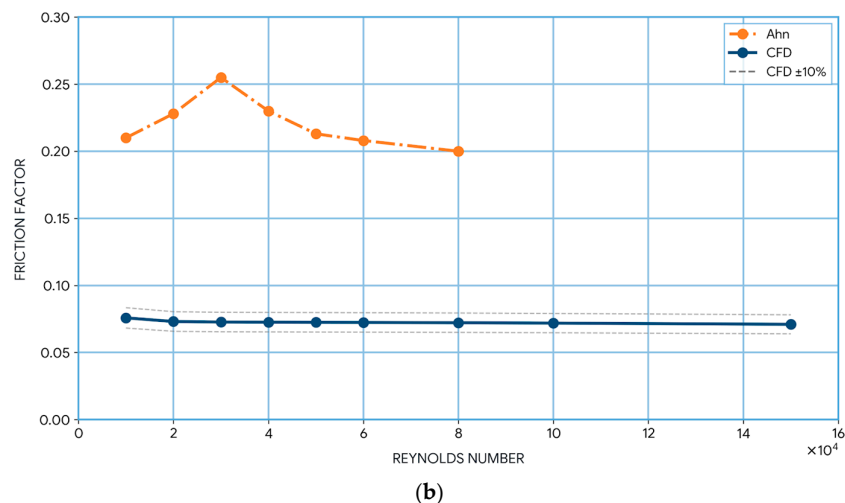


Figure 3. (a) Comparison of CFD-predicted and experimentally measured friction factors as a function of Reynolds number for a corrugated pipe with an inner diameter of $d = 20.4$ mm (Ahn [18]). (b) Comparison of CFD-predicted and experimentally measured friction factors as a function of Reynolds number for a corrugated pipe with an inner diameter of $d = 40.5$ mm (Ahn [18]).

To further assess the robustness and generality of the numerical framework, additional validation was performed using the dataset reported by Popiel et al. [19], which covers smaller nominal diameters (DN10–DN25) and lower Reynolds numbers (approximately 3000–30,000). These cases extend the validation toward different geometric scales and partially transitional flow conditions. A representative comparison for the DN20 geometry is presented in Figure 4, whereas the corresponding flow-field visualization for completeness is provided in Appendix A5 (Figure A5).

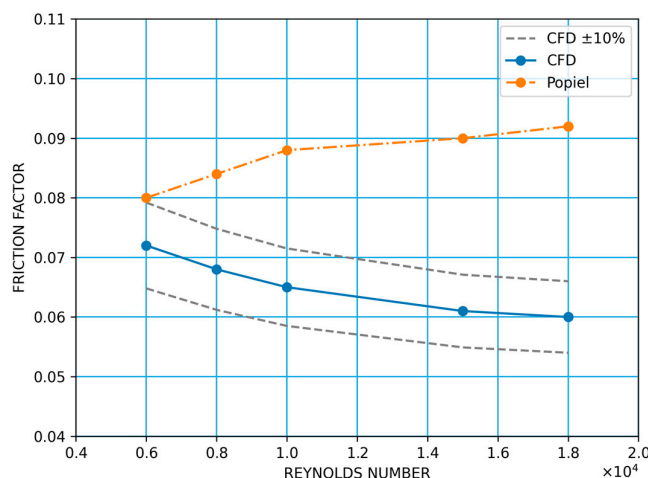


Figure 4. Comparison of CFD-predicted and experimentally measured friction factors as a function of Reynolds number for the DN20 corrugated pipe reported by Popiel et al. [19].

Although the absolute deviation levels for the Popiel dataset are somewhat larger than those obtained for the Ahn and Uslu data, particularly at the lower end of the Reynolds-number range, the numerical model preserves the overall order of magnitude and captures the dominant trend of friction-factor variation within the investigated interval.

Taken together, the validation results based on the datasets of Ahn and Uslu [18] and Popiel et al. [19] indicate that the adopted numerical framework provides a consistent and

quantitatively reliable representation of frictional behavior in corrugated pipes over a broad range of diameters and Reynolds numbers. This validated basis supports the systematic investigation of diameter-dependent friction trends presented in the following section.

3.2. Diameter-Dependent Friction Behavior

Building upon the validated numerical framework established in Section 3.1, the variation of the Darcy friction factor with pipe diameter is examined under dynamically similar turbulent flow conditions. The objective is to isolate the influence of diameter scaling on frictional behavior while maintaining Reynolds-number similarity.

For all investigated corrugated geometries, the friction factor decreases with increasing Reynolds number, consistent with classical turbulent pipe-flow behavior. However, a clear and systematic diameter-dependent trend emerges at identical Reynolds numbers, larger-diameter corrugated pipes consistently exhibit higher friction factors than smaller-diameter pipes. This separation persists across the entire Reynolds number range considered and is observed for all simulated geometries.

To interpret this trend within the framework of geometric scaling, the principal geometric parameters and the associated relative corrugation depth ratios (e/D) for the Popiel and Ahn configurations are summarized in Appendices B1 and B2 (Tables A3 and A4), respectively. As documented therein, the relative corrugation depth decreases with increasing pipe diameter. Under classical roughness-based scaling arguments, a reduction in relative roughness would be expected to reduce friction factors at larger diameters. The opposite trend observed in both experiments and simulations therefore indicates that equivalent roughness concepts alone are insufficient to explain the diameter-dependent friction behavior in corrugated pipes.

The persistence of this trend under Reynolds-number similarity conditions suggests that diameter scaling modifies the interaction between groove geometry and the bulk flow field. In corrugated pipes, flow separation, reattachment length, and vortex development are governed not only by local roughness amplitude but also by the spatial relationship between groove geometry and the overall pipe cross-section. As diameter increases, the relative spatial development of separated shear layers within the core region changes, altering turbulence production and momentum exchange mechanisms. Consequently, frictional similarity is not ensured solely by matching Reynolds numbers.

These observations demonstrate that pipe diameter acts as an additional governing parameter in corrugated turbulent flow. Reynolds-number similarity alone is therefore insufficient to guarantee frictional similarity, highlighting the importance of geometry–flow coupling effects beyond classical smooth-pipe scaling concepts.

3.3. Pumping Power Requirements and Energy Implications of Diameter-Dependent Friction

The diameter-dependent friction behavior identified in Section 3.2 directly influences the pumping power requirements of corrugated piping systems. For incompressible internal flows, the pumping power required to overcome frictional losses is expressed as

$$P_{\text{pump}} = \Delta P \dot{V} \quad (11)$$

where ΔP denotes the pressure drop along the pipe and $\dot{V}$ is the volumetric flow rate.

Using the pressure losses obtained from the CFD simulations, the pumping power was evaluated for corrugated pipes of different inner diameters operating under dynamically similar Reynolds-number conditions. The variation of pumping power with Reynolds number is presented in Figure 5 for representative diameters of 20.4 mm and 40.5 mm, including smooth-pipe baselines.

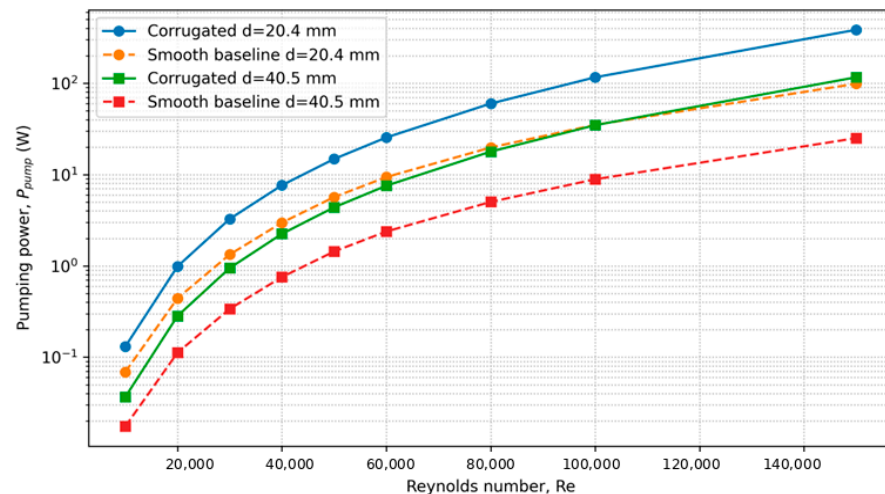


Figure 5. Pumping power requirement as a function of Reynolds number for corrugated pipes with inner diameters of 20.4 mm and 40.5 mm.

For all investigated cases, pumping power increases monotonically with Reynolds number. More importantly, at fixed Reynolds numbers, larger-diameter corrugated pipes consistently require higher pumping power than smaller-diameter pipes. This systematic separation mirrors the diameter-dependent friction behavior discussed in Section 3.2 and confirms that diameter scaling has direct energetic consequences.

Across the investigated parameter range, corrugated pipes exhibit significantly higher pumping power requirements than smooth pipes operating under identical Reynolds-number and diameter conditions. The separation between smooth and corrugated configurations becomes increasingly pronounced at higher Reynolds numbers, indicating that corrugation-induced dissipation intensifies with increasing flow inertia.

These results demonstrate that Reynolds-number similarity does not ensure energetic similarity in corrugated pipes. When the frictional amplification associated with diameter scaling is combined with the volumetric flow rate required to maintain dynamic similarity, the resulting pumping power demand grows disproportionately. This energy-based interpretation reinforces the conclusion that pipe diameter acts as an independent governing parameter in corrugated turbulent flow systems.

Building upon this physically grounded interpretation, a compact predictive formulation is introduced in the following section to represent the diameter-dependent energy penalty within the validated parameter space. While the CFD analysis provides detailed insight into the flow–geometry interaction mechanisms, a surrogate correlation enables practical estimation of pumping penalties without the need for repeated high-resolution simulations.

3.4. Surrogate Correlation for the Energy Penalty Factor

The results of the energy-based analysis provide the foundation for constructing a surrogate correlation for the Energy Penalty Factor (EPF), enabling rapid, CFD-free performance estimation. Consistent with prior CFD-based correlation development for corrugated heat exchanger geometries [28,29], a simplified yet physically grounded predictive formulation is proposed.

While detailed CFD simulations offer valuable insight into the underlying flow physics and diameter-dependent friction behavior, their routine use in engineering design and system-level optimization is often impractical due to computational cost, particularly

when extensive parametric analyses are required. Therefore, a simplified correlation suitable for preliminary design and performance assessment is introduced.

The EPF is defined as

$$EPF = \frac{\Delta P_{corrugated}}{\Delta P_{smooth}} = \frac{f_{corrugated}}{f_{smooth}} \quad (12)$$

where the smooth-pipe friction factor is evaluated under identical Reynolds-number and diameter conditions using conventional turbulent-flow correlations. By normalizing pressure losses with respect to a smooth-pipe baseline, the EPF isolates the additional energetic cost associated with corrugation geometry and pipe diameter.

The variation of EPF with Reynolds number for representative pipe diameters is shown in Figure 6. For all investigated geometries, EPF increases monotonically with Reynolds number. In addition, larger-diameter pipes consistently exhibit higher EPF values at identical Reynolds numbers. This behavior reflects the cumulative influence of diameter scaling on groove-induced separation intensity and associated energy dissipation.

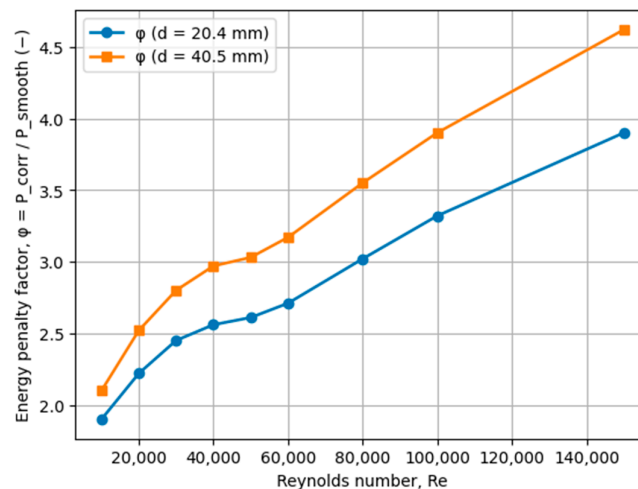


Figure 6. Energy penalty factor, $\phi = P_{corr}/P_{smooth}$, as a function of Reynolds number for corrugated pipes with inner diameters of $d = 20.4$ mm and 40.5 mm, obtained from CFD simulations using smooth-pipe CFD results as the baseline.

Based on dimensional considerations and the CFD dataset obtained in this study, EPF was correlated as a function of Reynolds number and two dimensionless geometric parameters: the relative corrugation depth e/D and the pitch-to-depth ratio p/e . Applying logarithmic least-squares regression to the numerical database, the following correlation was obtained:

$$EPF = 0.1755 Re^{0.1693} \left(\frac{e}{D}\right)^{-0.3730} \left(\frac{p}{e}\right)^{0.3846}$$

where the prefactor (0.1755) and the exponents of Re , e/D , and p/e were obtained via logarithmic least-squares fitting of the numerical dataset over the Reynolds number range $5 \times 10^3 \leq Re \leq 2 \times 10^4$. All regression coefficients were derived directly from the CFD dataset. The fitted exponents exhibit physically consistent trends. The positive Reynolds-number exponent indicates that increasing turbulence intensity enhances the energetic penalty induced by corrugations. The negative exponent of $\frac{e}{D}$ arises from the normalization inherent in the EPF definition, reflecting the relative scaling between corrugated and smooth-pipe friction behavior. The positive exponent of p/e suggests that more widely

spaced corrugations promote stronger energy penalties by allowing separated shear layers to persist over longer axial distances before reattachment.

The correlation was calibrated using 56 CFD data points corresponding to multiple corrugated pipe geometries and Reynolds numbers. Within this parameter space, the coefficient of determination is $R^2 = 0.972$. The mean absolute percentage error is approximately 3.6%, while the maximum deviation remains below 11% across the validated range.

Its validated applicability range is:

- $3000 \leq Re \leq 1.5 \times 10^5$
- $9.1 \leq D \leq 40.5 \text{ mm}$
- $0.0899 \leq e/D \leq 0.2527$
- $1.548 \leq p/e \leq 1.920$

An additional qualitative consistency check was performed using pressure-drop measurements from a commercially available corrugated stainless steel flexible pipe (CSST) configuration not included in the regression dataset. Although detailed measurement data cannot be disclosed due to industrial confidentiality constraints, the predicted EPF values remained within the experimental uncertainty band of the available measurements, supporting the robustness of the proposed formulation beyond the regression dataset.

Predictions outside the validated parameter ranges may involve increased uncertainty; therefore, caution is advised when extrapolating beyond the tested conditions. Within the investigated ranges, however, the surrogate model provides a practical and computationally efficient alternative to detailed three-dimensional CFD simulations for estimating corrugation-induced pumping penalties, particularly during preliminary design evaluations and comparative engineering assessments.

4. Discussion

The present study provides a combined numerical and energy-based assessment of turbulent flow in corrugated pipes, with particular emphasis on the experimentally reported diameter-dependent friction behavior. In smooth circular pipes, Reynolds-number similarity generally ensures dynamically similar flow structures and diameter-independent friction characteristics. Corrugated geometries, however, introduce strong flow-geometry interactions that modify this classical scaling behavior.

The CFD results are consistent with the experimental observations of Ahn and Uslu and Popiel et al., confirming that the friction factor increases systematically with pipe diameter at identical Reynolds numbers. This trend cannot be explained solely through classical relative roughness arguments, since the corrugation depth-to-diameter ratio decreases with increasing diameter for the geometries considered. Similar limitations of equivalent roughness formulations for grooved and corrugated surfaces have been reported in hydraulic resistance compilations and detailed flow analyses [14,30], indicating that roughness amplitude alone is insufficient to describe the scaling behavior of periodically corrugated walls.

From a physical perspective, the present simulations indicate that diameter scaling modifies the development and persistence of groove-induced separation and reattachment processes. In larger-diameter pipes, separated shear layers extend further into the core region and reattach over longer axial distances, promoting sustained turbulence production and enhanced momentum exchange between the near-wall region and the bulk flow. Comparable separation-dominated loss mechanisms have been identified in experimental and numerical studies on corrugated and grooved channels, where deviations from smooth-pipe scaling were observed despite similar Reynolds numbers [14,31,32].

The observation that Reynolds-number similarity alone does not ensure frictional similarity in corrugated pipes is further supported by recent geometry-resolved numerical investigations. Studies by Stel et al. and Alhamid et al. demonstrated that variations in corrugation geometry and channel scale significantly influence turbulence structure and pressure losses even under nominally similar Reynolds-number conditions [14,32]. The present results extend these findings by systematically isolating pipe diameter as an independent governing parameter through simulations conducted at fixed Reynolds numbers.

When these hydrodynamic results are interpreted from an energy perspective, the practical implications become more pronounced. Because pumping power is proportional to the product of pressure drop and volumetric flow rate, moderate increases in friction factor can translate into substantially higher energy requirements. At fixed Reynolds numbers, larger-diameter corrugated pipes require higher bulk velocities to maintain dynamic similarity, and when combined with diameter-dependent friction amplification, this results in a compounded increase in pumping power demand. Similar geometry-scaling effects on pressure loss and energy consumption have been reported in experimental studies on corrugated channels and ducts [33].

The introduction of the Energy Penalty Factor (EPF) provides a normalized and physically interpretable metric to quantify this behavior relative to a smooth-pipe baseline. By normalizing pressure losses under dynamically similar conditions, the EPF isolates the energetic contribution of corrugation geometry and pipe diameter. Recent numerical comparisons of turbulence modeling strategies for corrugated pipes have emphasized the importance of geometry-resolved simulations in predicting such performance metrics [29]. The present findings are consistent with these observations and suggest that design approaches relying solely on smooth-pipe correlations may underestimate pumping power requirements in corrugated piping systems.

From an engineering design standpoint, the results highlight important limitations of intuition derived from smooth-pipe theory. In corrugated systems, increasing pipe diameter does not necessarily reduce energy consumption, and assumptions based purely on Reynolds-number similarity may lead to non-conservative estimates of operating costs. Instead, geometry-sensitive analysis and energy-based performance metrics are advisable when corrugated pipes are employed in HVAC, building services, and industrial fluid transport applications.

Several limitations should be acknowledged. The simulations are based on Reynolds-averaged turbulence modeling, which captures mean-flow behavior but does not resolve unsteady vortex dynamics within individual grooves. In addition, the investigated geometries are limited to axisymmetric transverse corrugation profiles reported in the literature. Supplementary simulations performed for a commercially available corrugated stainless steel flexible pipe (CSST), summarized in Appendix B3, indicate that the identified diameter-dependent friction and energy-penalty trends persist for industrially relevant geometries, although publicly available experimental datasets for these configurations remain limited.

Overall, the present study demonstrates that pipe diameter acts as an independent parameter influencing hydraulic losses and pumping power requirements in corrugated pipes. The integration of CFD-based flow analysis with energy-oriented performance metrics provides a consistent and practically applicable framework for interpreting and evaluating corrugated piping systems within the investigated parameter range.

5. Conclusions

This study presented a CFD-based investigation of turbulent flow and pressure losses in corrugated stainless-steel pipes, with emphasis on the experimentally observed diameter-dependent friction behavior induced by periodic wall corrugations.

The numerical results confirm that Reynolds-number similarity alone does not ensure diameter-independent friction characteristics in corrugated geometries. Within the investigated parameter range, the friction factor increases systematically with pipe diameter at identical Reynolds numbers. This behavior is associated with diameter-dependent modifications in groove-induced separation, reattachment length, and turbulence production mechanisms, which alter the classical smooth-pipe scaling framework.

From an energy perspective, the identified friction trends translate directly into increased pumping power requirements. Because pumping power depends on both pressure drop and volumetric flow rate, the combination of diameter-dependent friction amplification and dynamic similarity constraints leads to a compounded increase in energy demand. Within the examined Reynolds-number and diameter ranges, corrugated pipes require substantially higher pumping power than smooth pipes operating under dynamically similar conditions, and the magnitude of this energy penalty increases consistently with both Reynolds number and pipe diameter.

To support practical engineering applications, an Energy Penalty Factor (EPF) was introduced as a normalized metric to quantify corrugation-induced energetic effects relative to a smooth-pipe baseline. A surrogate correlation derived from the CFD dataset relates EPF to Reynolds number and key dimensionless geometric parameters, providing a statistically consistent representation of the dominant scaling trends within the validated parameter space. Supplementary qualitative consistency checks using industrial CSST configurations indicate that the identified diameter-dependent behavior persists for commercially relevant geometries.

Overall, the findings demonstrate that pipe diameter acts as an independent governing parameter influencing hydraulic losses and pumping power requirements in corrugated turbulent flow systems. The combined CFD-based analysis and surrogate modeling framework provide a coherent and computationally efficient basis for preliminary design evaluation and comparative energy assessment of corrugated piping systems within the investigated ranges.

Future research may extend the analysis to broader corrugation geometries, incorporate targeted experimental validation, and examine coupled heat-transfer or transient operating conditions to further assess the generality of the proposed energy-based framework.

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Appendix A

Appendix A1. Mesh Resolution and Near-Wall Treatment

For all simulations, the near-wall mesh was designed to achieve a target non-dimensional wall distance of $y^+ \approx 1$, which is consistent with the requirements of the SST $k-\omega$ turbulence model. The wall shear stress required for estimating the first-layer thickness was initially approximated using classical empirical correlations for turbulent flow in smooth circular pipes. This approximation was employed solely for mesh generation prior to the simulations; during the CFD computations, the wall shear stress distribution was fully resolved by the turbulence model. The resulting first-layer thickness and corresponding near-wall resolution parameters are summarized in Table A1 [34]. During the simulations, the resulting y^+ values were monitored and confirmed to remain below unity along the entire corrugated wall surface for all investigated cases.

Table A1. Parameters used for estimating the first-layer thickness based on a target y^+ value.

y^+	μ (kg/ms)	ρ (kg/m ³)	V (m/s)	d (mm)	y^+ (mm)
1	1.7894×10^{-5}	1.225	50	15.8	5.78×10^{-2}

Appendix A2. Mesh Structure and Flow Visualization

Representative polyhedral mesh structures employed for the corrugated pipe geometries reported by Ahn and Uslu [18] and Popiel et al. [19] are presented in Figures A1 and A2. The meshes illustrate near-wall refinement and accurate resolution of the corrugation profile, ensuring adequate capture of groove-scale flow features. The applied mesh topology and near-wall resolution are consistent with the $y^+ \approx 1$ criterion adopted for the SST $k-\omega$ turbulence model, thereby supporting reliable resolution of wall-bounded turbulent structures.

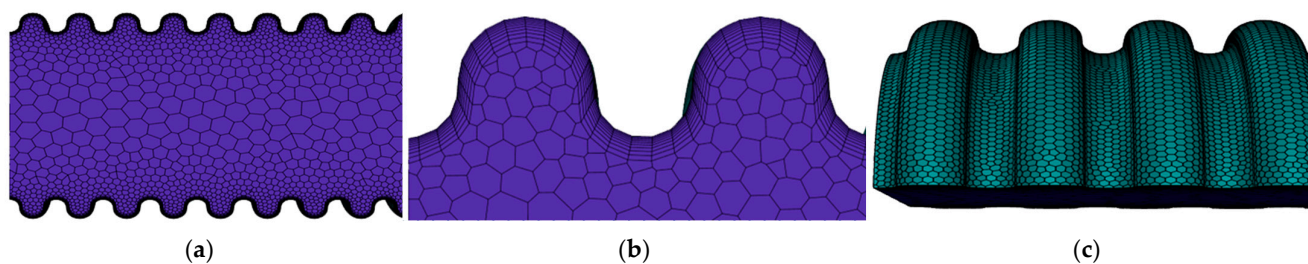


Figure A1. Polyhedral mesh structure generated for the Ahn geometry [18]: (a) Global view of the corrugated pipe computational domain; (b) Detailed view of the corrugation region illustrating near-wall mesh refinement consistent with the $y^+ \approx 1$ criterion; (c) Three-dimensional representation of the polyhedral mesh topology.

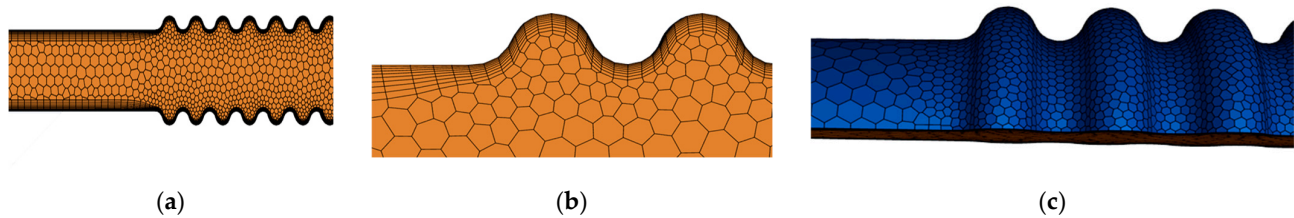


Figure A2. Polyhedral mesh structure generated for the Popiel geometry [19]: (a) Overall computational domain of the corrugated pipe; (b) Close-up view of the groove region highlighting boundary-layer mesh resolution; (c) Three-dimensional visualization of the polyhedral mesh distribution along the corrugated section.

Appendix A3. Reference Friction Factor Values for Numerical Validation

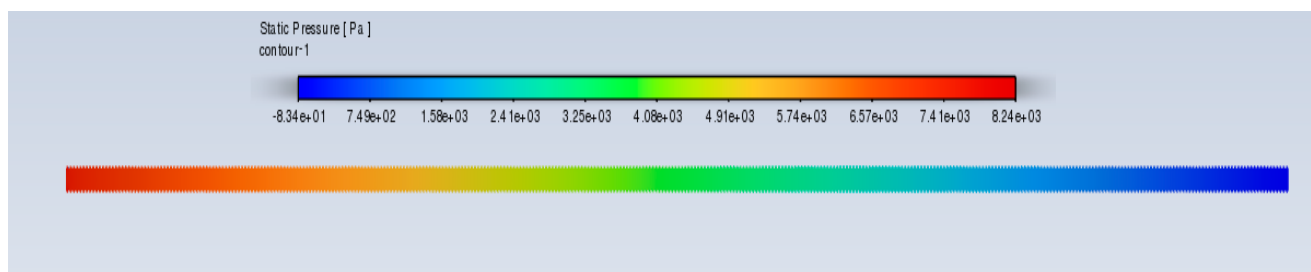
To support validation of the numerical framework, friction factor values obtained from CFD simulations for a smooth straight pipe are compared with classical correlations over a range of Reynolds numbers. The corresponding values calculated using the Darcy–Weisbach formulation, together with the Blasius, Colebrook, and Haaland correlations, are summarized in Table A2.

Table A2. Friction factors calculated using Darcy–Weisbach formulation and classical correlations (Blasius, Colebrook, and Haaland) as a function of Reynolds number.

Reynolds	Friction Factor (CFD, Darcy–Weisbach)	Blasius	Colebrook	Haaland
10,000	0.036	0.035	0.036	0.036
20,000	0.0289	0.0266	0.026	0.0258
30,000	0.0258	0.024	0.0236	0.0234
40,000	0.0243	0.0224	0.0221	0.0219
50,000	0.0237	0.0212	0.0211	0.0208
60,000	0.0227	0.0202	0.0203	0.02
80,000	0.0202	0.0188	0.0191	0.0189
100,000	0.0183	0.0178	0.0183	0.018
150,000	0.0153	0.0161	0.0169	0.0167

Appendix A4. Representative Validation Results for Ahn and Uslu Corrugated Pipe Geometries

To avoid repetition, representative validation results are shown for selected geometries. Figure A3 presents the comparison between CFD-predicted and experimentally measured friction factors for an intermediate Ahn geometry, while Figure A4 shows the corresponding flow-field visualization at $Re = 50\,000$ [35].



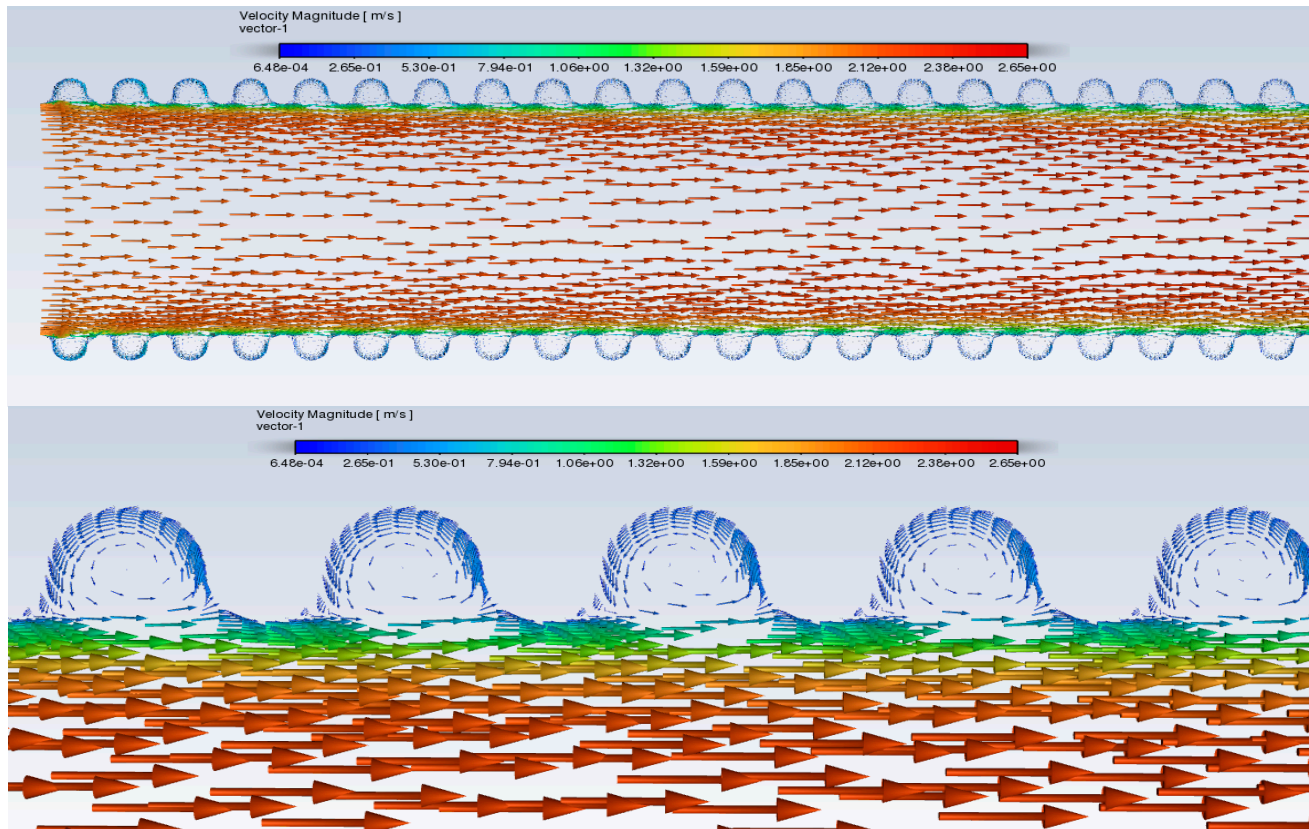


Figure A3. Numerical visualization of the velocity field and groove-scale vortex structures for the $d = 25.4$ mm corrugated pipe geometry reported by Ahn and Uslu [18] at $Re = 50,000$.

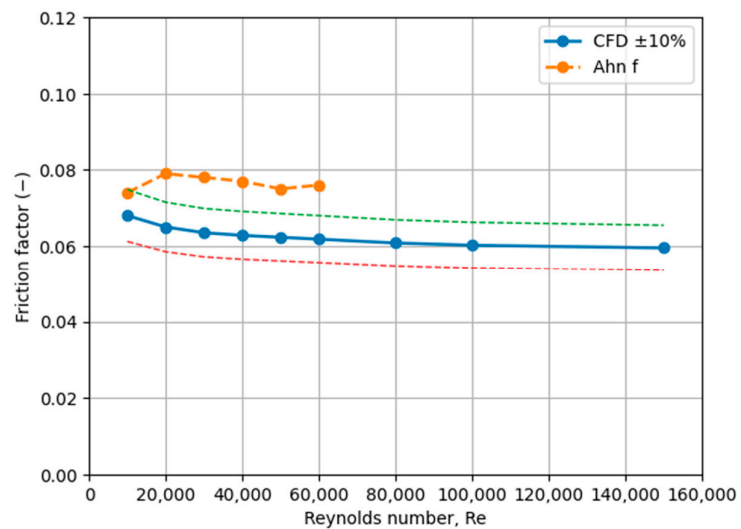


Figure A4. Comparison of CFD-predicted and experimentally measured friction factors for the $d = 25.4$ mm corrugated pipe geometry reported by Ahn and Uslu [18].

Appendix A5. Representative Popiel Validation

For the Popiel dataset, the main-text validation results are presented in Figure 4. In this appendix, only the associated flow-field visualization for the DN20 geometry is provided for completeness.

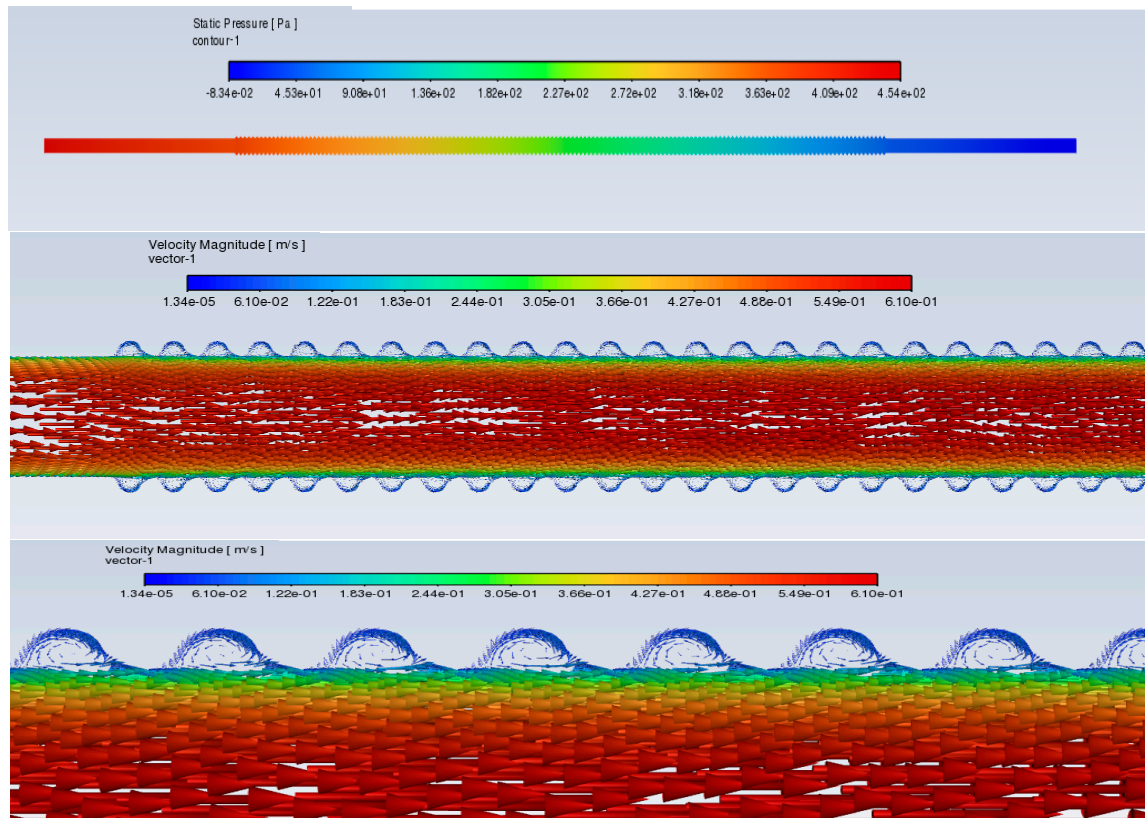


Figure A5. Numerical visualization of the velocity field and groove-induced flow structures for the DN20 corrugated pipe geometry reported by Popiel et al. [19] at $Re = 10,000$.

These supplementary results confirm that the numerical framework consistently captures the dominant flow mechanisms induced by corrugated geometries across different diameters and Reynolds numbers.

Appendix B

Appendix B1. Geometric Parameters and Corrugation Depth-to-Diameter Ratios for the Corrugated Pipe Geometries Reported by Popiel et al. [19]

Table A3 summarizes the geometric parameters of the corrugated pipe geometries reported by Popiel et al. [19]. Similarly to the Ahn dataset, the corrugation depth-to-diameter ratio (e/d_i) exhibits a non-monotonic variation while showing an overall decreasing trend with increasing pipe diameter. This behavior further supports the generality of the diameter-scaling effects discussed in Section 3.2, indicating that the observed trends are not restricted to a single experimental dataset

Table A3. Geometric parameters of the corrugated pipe geometries reported by Popiel et al. [19]

Pipe ID	Inner Diameter, d_i (mm)	Outer Diameter, d_o (mm)	Corrugation Pitch, P (mm)	Groove Width, W (mm)	Groove Depth, e (mm)	e/d_i (–)
P1 (DN10)	9.1	12.3	4.2	2.3	1.35	0.148
P2 (DN12)	13.0	16.8	5.12	2.8	1.60	0.123
P3 (DN20)	19.7	25.0	6.46	3.6	2.35	0.119
P4 (DN25)	26.7	32.8	7.2	4.0	2.75	0.103

Appendix B2. Geometric Parameters and Corrugation Depth-to-Diameter Ratios for the Corrugated Pipe Geometries Reported by Ahn and Uslu [18].

Although the corrugation depth-to-diameter ratio (e/d_i) shows an overall decreasing trend with increasing pipe diameter, the friction factor is found to increase systematically with diameter at identical Reynolds numbers, indicating that relative roughness alone cannot explain the observed behavior.

Table A4. Geometric parameters and corrugation depth-to-diameter ratios for the corrugated pipe geometries reported by Ahn and Uslu [18].

Pipe ID	Inner Diameter, d_i (mm)	Outer Diameter, d_o (mm)	Corrugation Pitch, P (mm)	Groove Width, W (mm)	Groove Depth, e (mm)	e/d_i (–)
A1	20.4	26.1	4.8	2.5	2.85	0.140
A2	25.4	31.3	5.3	3.1	2.95	0.116
A3	34.5	40.5	4.8	3.1	3.00	0.087
A4	40.5	49.0	6.6	3.8	4.25	0.105

Appendix B3. Supplementary CSST Pipe Results

Supplementary numerical simulations were performed for a commercially available corrugated stainless steel flexible pipe (CSST), representative of typical building-service and industrial piping applications. The CSST geometry was modeled using the same numerical framework, turbulence model, mesh resolution strategy, and solver settings adopted in the main study, thereby ensuring full methodological consistency.

The CSST simulations exhibited friction factors and Energy Penalty Factor (EPF) trends that are consistent with those observed for the experimentally validated geometries reported by Ahn and Popiel. In particular, the predicted EPF values remained within a comparable range and increased systematically with Reynolds number, reflecting similar groove-induced flow separation and persistent vortical structures. These supplementary results indicate that the diameter-dependent hydraulic behavior identified in the present study is not restricted to idealized laboratory-scale geometries but appears to remain relevant for commercially used corrugated piping systems.

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