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Hydraulic and Energy Optimization of the Al-Feel–Mellitah Undulating Crude Oil Pipeline Using Nano-Engineered Internal Coatings

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Abstract
Crude oil pipeline transportation is a highly energy-intensive operation, particularly for long-distance pipelines traversing complex and undulating terrain. In such systems**(Al-Feel-Mellitah oil pipeline)**, pumping energy is primarily consumed in overcoming frictional losses, while elevation changes introduce additional hydraulic constraints that strongly influence local and overall pressure behavior. This study investigates the potential of nano-engineered internal pipe coatings as a passive and permanent solution for reducing energy consumption in a long crude oil pipeline characterized by variable diameters, multiple pressure-drop zones, and alternating uphill and downhill segments.

A real pipeline transporting crude oil from a high-elevation production field to a low-elevation coastal terminal is considered as a representative case. The pipeline operates at a constant flow rate of 40,000 barrels per day and is hydraulically segmented into five pressure-drop zones, each with distinct geometric and elevation characteristics. The undulating elevation profile provides significant net hydrostatic assistance to the system; however, local pressure losses remain governed by friction, valve losses, and diameter-dependent flow velocities.

The effect of nano-engineered internal coatings is modeled through a reduction in the Darcy friction factor while preserving the original pipeline geometry, operating conditions, and elevation profile. The study framework establishes a clear link between surface-induced friction reduction, zone-wise pressure losses, and overall pumping energy demand. The results demonstrate that nano-engineered coatings can significantly enhance the hydraulic and energy performance of undulating crude oil pipelines without requiring changes to throughput or infrastructure layout, offering a practical pathway toward more energy-efficient pipeline operation.

Keywords
Crude oil pipeline; Energy optimization; Undulating pipeline; Pressure-drop zones; Nano-engineered internal coating; Friction reduction; Pumping energy

الملخّص
يُعدّ نقل النفط الخام عبر خطوط الأنابيب من العمليات عالية الاستهلاك للطاقة، لا سيما في الخطوط طويلة المسافة التي تعبر تضاريس معقّدة ومتعرّجة. وفي مثل هذه الأنظمة —كما في خط أنابيب النفط بين **حقل الفيل** و**مليتة** —تُستهلك طاقة الضخ أساسًا في التغلب على الفواقد الاحتكاكية، بينما تُضيف تغيّرات المناسيب قيودًا هيدروليكية إضافية تؤثر بشكل كبير في سلوك الضغوط محليًا وعلى امتداد الخط. تبحث هذه الدراسة في إمكانية استخدام الطلاءات الداخلية النانوية للأنابيب كحلٍّ سلبي ودائم لخفض استهلاك الطاقة في خط أنابيب نفط خام طويل يتميّز بتغيّر الأقطار، وتعدد مناطق هبوط الضغط، وتناوب المقاطع الصاعدة والهابطة.
تم اعتماد خط أنابيب حقيقي ينقل النفط الخام من حقل إنتاج مرتفع المنسوب إلى محطة ساحلية منخفضة المنسوب كحالة دراسية ممثِّلة. يعمل الخط بمعدل تدفق ثابت يبلغ 40,000 برميل يوميًا، وقد تم تقسيمه هيدروليكيًا إلى خمس مناطق لهبوط

الضغط، تتميز كل منها بخصائص هندسية وارتفاعية مختلفة. وعلى الرغم من أن المقطع الطولي المتعرّج للارتفاعات يوفّر مساهمة هيدروستاتيكية صافية مهمة لصالح الجريان، إلا أن الفواقد الموضعية للضغط تظل محكومة بالاحتكاك، وفواقد الصمامات، وسرعات الجريان المرتبطة بقطر الأنبوب.
تم تمثيل تأثير الطلاءات الداخلية النانوية من خلال تقليل معامل الاحتكاك (دارسي) مع الحفاظ على هندسة خط الأنابيب الأصلية وظروف التشغيل ومنحنى الارتفاعات دون تغيير. ويُبيّن إطار الدراسة وجود علاقة واضحة بين تقليل الاحتكاك الناتج عن تحسين السطح الداخلي، وانخفاض فواقد الضغط في كل منطقة، وتراجع الطلب الكلي على طاقة الضخ. وتُظهر النتائج أن الطلاءات الداخلية النانوية قادرة على تحسين الأداء الهيدروليكي والطاقي لخطوط أنابيب النفط المتعرّجة بشكل ملحوظ، دون الحاجة إلى تغيير معدل التدفق أو تخطيط البنية التحتية، مما يوفّر مسارًا عمليًا نحو تشغيل أكثر كفاءة في استهلاك الطاقة.

الكلمات المفتاحية
خط أنابيب النفط الخام؛ تحسين استهلاك الطاقة؛ خط أنابيب متعرّج؛ مناطق هبوط الضغط؛ طلاء داخلي هندسي-نانوي؛ تقليل الاحتكاك؛ طاقة الضخ.

1. Introduction

Pipeline transportation remains the most reliable and cost-effective method for moving large volumes of crude oil over long distances. However, it is also one of the most energy-intensive segments of the upstream and midstream oil and gas sector. A substantial portion of operational expenditure in crude oil pipelines is associated with electrical energy consumed by pumping systems, which are required to overcome frictional resistance, valve losses, and elevation-induced pressure variations along the pipeline route.

In long-distance pipelines, even relatively small reductions in hydraulic losses can translate into significant energy savings when integrated over continuous, year-round operation. This challenge is further intensified in pipelines that traverse undulating terrain, where alternating uphill and downhill segments produce complex pressure distributions along the pipeline. Although a net downhill elevation may provide hydrostatic assistance to the overall system, local pressure drops and pressure peaks remain critical from both operational and integrity perspectives.

Traditional approaches to reducing pipeline energy consumption include increasing pipe diameter, optimizing pump selection, and injecting chemical drag-reducing agents. While effective in certain applications, these methods often involve high capital expenditure, continuous operational costs, or sensitivity to operating conditions. As a result, there is growing interest in passive energy-saving technologies that can be applied internally to existing pipelines without altering throughput or requiring continuous intervention.

Recent advances in surface engineering and nanomaterials have enabled the development of nano-engineered internal pipe coatings with ultra-low effective roughness and tailored surface properties. Unlike conventional internal coatings, which are primarily designed for corrosion protection, nano-engineered coatings offer the potential to directly influence near-wall flow behavior and reduce frictional resistance under turbulent flow conditions. This makes them particularly attractive for long crude oil pipelines where frictional losses dominate the energy balance.

Despite increasing interest in nano-engineered coatings, their application has been largely studied in isolation from real pipeline operating conditions. Many published studies neglect the combined effects of variable pipe diameters, undulating elevation profiles, and pressure-drop segmentation that characterize actual long-distance crude oil pipelines. Furthermore, the interaction between hydrostatic effects and friction reduction has not been sufficiently addressed from an energy optimization perspective.

This study addresses these gaps by evaluating the energy-saving potential of nano-engineered internal pipe coatings in a realistic long-distance crude oil pipeline operating at a constant flow rate and segmented into multiple pressure-drop zones. The analysis explicitly accounts for diameter-dependent flow velocities, elevation-induced pressure variations, and valve losses, thereby providing a physically consistent and operationally relevant assessment of pipeline energy optimization.

2. Literature Review

2.1 Energy Consumption in Long Crude Oil Pipelines

Long-distance crude oil pipelines represent one of the most energy-intensive components of the oil and gas transportation system. In pipelines such as the **pipeline between the Al-Feel Oil Field and the Mellitah Industrial Compound (Mellitah and Gas, 1998)**, which extends over several hundred kilometers, pumping energy constitutes a major portion of operational expenditure. Numerous studies have confirmed that frictional losses dominate the hydraulic energy balance in such systems, particularly under steady-state operation at constant throughput **(Menon, 2011; Mohitpour et al., 2014)**.

Energy demand in crude oil pipelines increases significantly with pipeline length, internal roughness, and flow velocity. Even moderate reductions in frictional resistance can therefore result in substantial cumulative energy savings over long operational periods **(Zhang et al., 2019)**. This has motivated extensive research into methods aimed at improving hydraulic efficiency without altering pipeline throughput or requiring large-scale infrastructure modifications.

2.2 Hydraulic Characteristics of Undulating Pipelines

Unlike pipelines constructed on relatively flat terrain, pipelines crossing complex topography exhibit **undulating elevation profiles** that strongly influence internal pressure distribution. The **pipeline connecting the Al-Feel Oil Field to the Mellitah Industrial Compound** is a representative example, characterized by alternating uphill and downhill segments along its route.

While the net elevation difference between the inlet and outlet determines the overall hydrostatic contribution, local elevation changes govern **pressure behavior within individual pipeline sections**. Pressure minima tend to occur at high points, increasing the risk of vapor formation and column separation, whereas pressure maxima are commonly observed at low points, where the risk of exceeding maximum allowable operating pressure (MAOP) becomes critical **(Wylie and Streeter, 1993; Chaudhry, 2014)**.

To manage these complexities, long pipelines are often divided into **hydraulic pressure-drop zones**, each defined by geometric changes, elevation characteristics, or valve locations. This segmentation allows pressure losses to be evaluated in a structured manner and is particularly relevant for undulating pipelines such as the Al-Feel–Mellitah crude oil pipeline **(Bai and Bai, 2012)**.

2.3 Influence of Pipe Diameter and Velocity Variation

In pipelines operating at a **constant flow rate**, variations in internal diameter lead to corresponding changes in flow velocity and Reynolds number. This effect is especially important in multi-diameter pipelines, where smaller-diameter sections contribute disproportionately to total pressure losses **(White, 2016)**.

Several researchers have emphasized that neglecting diameter-dependent velocity variation can result in significant underestimation of frictional losses and pumping energy requirements **(Fox et al., 2020)**. For pipelines segmented into multiple pressure-drop zones, such as the Al-Feel to Mellitah pipeline, accurate modeling of velocity variation is therefore essential to obtain realistic energy assessments.

2.4 Friction Reduction Techniques in Pipeline Systems

A wide range of friction reduction techniques has been applied in crude oil pipelines. Chemical drag reducing agents (DRAs) are among the most commonly used methods and have demonstrated significant short-term reductions in pressure drop **(Burger et al., 1980; Sellin et al., 1982)**. However, their effectiveness is highly sensitive to shear degradation, temperature, and crude oil composition, and they require continuous injection, resulting in recurring operational costs **(Kim et al., 2016)**.

Conventional internal coatings, typically epoxy-based, are primarily designed for corrosion protection rather than hydraulic optimization. Although such coatings may reduce surface roughness to some extent, their impact on turbulent flow behavior and long-term energy efficiency remains limited **(Liu et al., 2017)**.

2.5 Nano-Engineered Internal Coatings and Flow Enhancement

Recent advances in nanotechnology have enabled the development of **nano-engineered internal coatings** with highly controlled surface morphology and reduced effective roughness. Experimental and numerical studies have shown that nano-structured surfaces can suppress near-wall turbulence and reduce frictional resistance under turbulent flow conditions **(Choi et al., 2020; Rastegar and Akhavan, 2015)**.

In the oil and gas industry, nano-engineered coatings have been investigated mainly for corrosion resistance, erosion protection, and fouling mitigation **(Liu et al., 2017)**. However, their application as a **passive energy-saving solution** in long, undulating crude oil pipelines—such as the pipeline between the Al-Feel Oil Field and the Mellitah Industrial Compound—has received limited attention in the open literature.

2.6 Research Gap

Although previous studies have examined friction reduction, undulating pipeline hydraulics, and nano-engineered materials independently, the literature lacks an **integrated, system-level analysis** that links nano-engineered internal coatings to energy optimization in real crude oil pipelines with multiple pressure-drop zones and variable diameters **(Zhang et al., 2019; Fox et al., 2020)**.

In particular, there is a lack of studies addressing pipelines that:

- Operate at **constant throughput**
- Exhibit **undulating elevation profiles**
- Are segmented into **multiple hydraulic pressure-drop zones**
- Include **diameter-dependent velocity variation**

This gap is especially relevant for long pipelines such as the **Al-Feel Oil Field–Mellitah Industrial Compound crude oil pipeline**, where frictional losses, elevation effects, and surface conditions interact to determine overall energy performance.

3. Methodology

3.1 Overview of the Methodological Framework

The methodology adopted in this study aims to quantify the hydraulic and energy performance of the **Al-Feel–Mellitah undulating crude oil pipeline** and to evaluate the potential energy savings achievable through the application of nano-engineered internal pipe coatings. The approach is based on a **steady-state, zone-based hydraulic analysis** that explicitly accounts for elevation variations, diameter changes, and valve losses along the pipeline route.

The pipeline is modeled as a single continuous system operating at a **constant flow rate**, hydraulically segmented into **five pressure-drop zones**. For each zone, pressure losses are calculated by combining frictional losses, minor losses associated with valves, and elevation-induced pressure changes. The effect of nano-engineered internal coatings is incorporated through a reduction in the Darcy friction factor while preserving all other geometric and operating parameters.

3.2 Key Assumptions

To ensure physical consistency and analytical clarity, the following assumptions are adopted:

- The pipeline operates under **steady-state conditions**.
- The crude oil flow rate is maintained constant at **40,000 barrels per day** along the entire pipeline.
- Crude oil properties (density and dynamic viscosity) are assumed constant.
- The flow is **single-phase and incompressible**.
- The pipeline contains **no intermediate pumping stations**; all energy input is provided by pumps at the Al-Feel Oil Field.
- The pipeline includes **block and isolation valves only**, modeled as minor losses.
- Heat transfer effects are neglected.
- The nano-engineered internal coating modifies **only the internal surface roughness**, without altering pipe diameter, flow rate, or elevation profile.

These assumptions are consistent with typical long-distance crude oil pipeline operation and are appropriate for system-level energy assessment.

3.3 Hydraulic Zoning of the Pipeline

The Al-Feel–Mellitah pipeline traverses complex terrain characterized by alternating uphill and downhill segments. To accurately capture this behavior, the pipeline is hydraulically divided into **five pressure-drop zones(Z1-Z5)**, as defined by changes in elevation, diameter, and valve locations.

Each zone is treated as a control volume with uniform geometric properties. The total pressure drops across the pipeline is obtained by summing the pressure drops across the individual zones. This segmentation allows local pressure behavior to be evaluated while preserving the global energy balance of the system.

3.4 Flow Velocity and Reynolds Number

Although the flow rate is constant, the internal diameter varies between zones. Consequently, the average flow velocity differs from one zone to another and is calculated as:

$$\boldsymbol{V_i = \frac{4\,Q}{\pi\,D_i^2}}$$

where **Q** is the volumetric flow rate and **D_i** is the internal diameter of zone i.

The Reynolds number for each zone is then determined by:

$$\boldsymbol{Re_i = \frac{\rho\,V_i D_i}{\mu}}$$

This formulation ensures that **velocity-dependent hydraulic behavior**, including friction factor variation, is accurately captured for each pressure-drop zone.

3.5 Pressure Drop Calculation

The total pressure drops across each zone is calculated as the sum of three components:

$$\Delta \boldsymbol{P_i} = \Delta \boldsymbol{P_{f,i}} + \Delta \boldsymbol{P_{m,i}} + \Delta \boldsymbol{P_{z,i}}$$

where:

- **$\Delta P_{f,i}$** represents frictional losses,
- **$\Delta P_{m,i}$** represents minor losses due to valves (negligible),
- **$\Delta P_{z,i}$** represents elevation-induced pressure changes.

3.5.1 Frictional Losses

Frictional losses are calculated using the Darcy–Weisbach equation:

$$\Delta P_{f,i} = f_i \frac{L_i}{D_i} \frac{\rho V_i^2}{2}$$

where $\mathbf{f_i}$ is the Darcy friction factor for zone i, determined from the Reynolds number and relative roughness.

3.5.2 Minor Losses

Valve losses within each zone are modeled using standard loss coefficients:

$$\Delta P_{m,i} = \sum K_i \frac{\rho V_i^2}{2}$$

where $\mathbf{K_i}$ represents the sum of loss coefficients for valves located within zone i.

3.5.3 Elevation Effects

Elevation-induced pressure changes are calculated as:

$$\Delta P_{z,i} = \rho\, g\, \Delta z_i$$

where$\mathbf{\Delta z_i}$ is the net elevation change across zone iii. Positive values represent uphill flow, while negative values represent downhill flow.

3.6 Modeling of Nano-Engineered Internal Coatings

The effect of nano-engineered internal coatings is incorporated through a **reduction in the Darcy friction factor only**, reflecting reduced effective surface roughness and modified near-wall flow behavior.

For each zone, the modified friction factor is expressed as:

$$f_{i,nano} = (1 - \alpha) f_{i,steel}$$

where $\boldsymbol{\alpha}$ is the friction reduction coefficient (19 %- realistic figure).

The pressure drop in each zone with nano-coating is therefore given by:

$$\Delta P_{i,nano} = (1 - \alpha)\, \Delta P_{f,i} + \Delta P_{m,i} + \Delta P_{z,i}$$

This formulation ensures that the impact of nano-coatings is evaluated independently of elevation effects and valve losses.

3.7 Pumping Energy Assessment

The total pressure drops across the pipeline is obtained by summing the zone-wise pressure drops. The required pumping power at the Al-Feel Oil Field is then calculated based on the total pressure requirement and pump efficiency. Annual energy consumption is determined assuming continuous operation.

This framework allows a direct comparison between the baseline pipeline and the nano-coated pipeline under identical operating conditions.

3.8 Methodological Significance

The adopted methodology provides a physically consistent and operationally realistic framework for evaluating energy optimization in long, undulating crude oil pipelines. By combining hydraulic zoning, diameter-dependent velocity variation, elevation effects, and surface-based friction reduction, the approach bridges the gap between theoretical flow enhancement concepts and real pipeline operation.

4. Case Study Description

4.1 Overview of the Al-Feel–Mellitah Crude Oil Pipeline

The case study considered in this work is the **crude oil pipeline connecting the Al-Feel Oil Field to the Mellitah Industrial Compound**, located in western Libya. This pipeline represents a critical transportation corridor for crude oil production, linking an inland production field situated at high elevation to a coastal processing and export facility near sea level.

The **Al-Feel–Mellitah** pipeline is representative of many long-distance crude oil pipelines worldwide that traverse complex terrain and operate under continuous steady-state conditions. Its length, elevation profile, and operational characteristics make it particularly suitable for evaluating hydraulic behavior and energy optimization strategies in undulating pipeline systems.

4.2 Pipeline Route and Elevation Profile

The pipeline route extends over a long distance and crosses terrain characterized by alternating **upland plateaus, valleys, and mountainous sections**, resulting in a strongly **undulating elevation profile**. The elevation at the pipeline inlet near the Al-Feel Oil Field is approximately **900 m above sea level**, while the elevation at the Mellitah Industrial Compound is approximately **5 m above sea level**.

Although the large net elevation difference provides a **significant hydrostatic driving force**, the presence of multiple local uphill and downhill segments leads to complex internal pressure behavior. Local pressure minima and maxima occur along the route, governed by elevation changes, frictional losses, and diameter variations

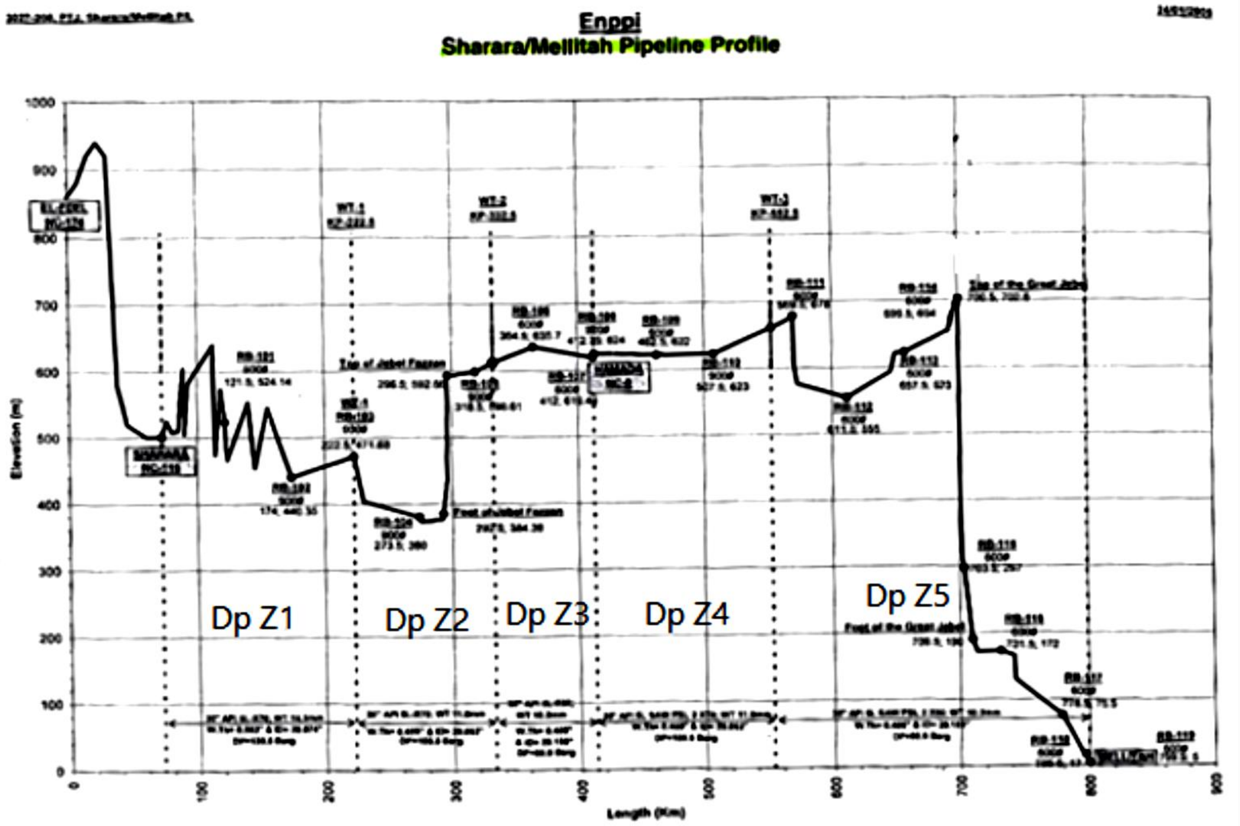

Figure 1longitudinal elevation profile of the Al-Feel–Mellitah pipeline

illustrating the undulating terrain, key elevation changes, and the locations of hydraulic segmentation boundaries.

4.3 Hydraulic Segmentation into Pressure-Drop Zones

To accurately represent the hydraulic behavior of the pipeline, the system is divided into **five pressure-drop zones**. This segmentation is based on changes in elevation trend, pipe diameter, and valve locations along the pipeline route.

Each pressure-drop zone is treated as a hydraulically uniform segment characterized by:

- A defined length,
- A constant internal diameter,
- A net elevation change,
- A set of isolation or block valves.

This approach enables zone-wise calculation of pressure losses and allows local hydraulic effects to be evaluated without compromising the global energy balance. The **five hydraulic pressure-drop zones** superimposed on the pipeline profile.

4.4 Pipeline Geometry and Diameter Variation

The pipeline does not maintain a single internal diameter along its entire length. Instead, different diameters are used in different sections to satisfy design, hydraulic, and integrity requirements. As a result, each pressure-drop zone is associated with a distinct internal diameter.

Because the pipeline operates at a **constant flow rate of 40,000 barrels per day**, variations in internal diameter directly lead to **zone-dependent flow velocities**. These velocity variations significantly influence frictional losses, Reynolds number, and overall hydraulic performance.

This multi-diameter configuration reflects real engineering practice and introduces an additional level of realism compared to simplified single-diameter pipeline models.

Table 1. Geometric characteristics of the five pressure-drop zones

(derived from the Sharara/Mellitah pipeline profile map- Fig. 1)

Zone boundaries used (from the profile):

KP 0 → KP 222.5 → KP 332.5 → KP 412.5 → KP 552.5 → KP 799.5

Zone	Boundary Chainage (KP, km)	Zone Length (km)	Nominal Pipe Diameter (as shown)	Wall Thickness shown (mm)	Elevation at Start (m)	Elevation at End (m)	Δz (End – Start), m
Z1	0 → 222.5	222.5	30 in API 5L	WT shown in Zone 1 strip (14.3 mm)	>900 (Al-Feel)	~472 (KP 222.5 label RB-103)	≈ −428
Z2	222.5 → 332.5	110.0	30 in API 5L	WT shown in Zone 2 strip (11.9 mm)	~472	~598.61 (KP 332.5 label RB-105)	≈ +126.61
Z3	332.5 → 412.5	80.0	30 in API 5L	WT shown in Zone 3 strip (10.3 mm)	~598.61	624 label RB - 108	≈ +25.39
Z4	412.5 → 552.5	140.0	30 in API 5L	WT shown in Zone 4 strip (11.9 mm)	624	660 label at WT-3	≈ +36
Z5	552.5 → 799.5	247.0	30 in API 5L	WT shown in Zone 5 strip (10.3 mm)	660	5 label at RB- 119	≈ - 655

4.5 Operating Conditions and Crude Oil Properties

The pipeline operates under **steady-state conditions** with a constant crude oil throughput of **40,000 bpd**. The transported crude oil is assumed to be single-phase and incompressible.

The operating strategy reflects typical long-distance crude oil pipeline operation, where throughput is maintained at a fixed target rate for extended periods.

The transported fluid is representative of **Al-Feel crude oil**, with thermophysical properties selected based on typical field data and operating temperatures.

Key crude oil properties considered in the hydraulic analysis include:

- **Density:** Assumed constant along the pipeline, reflecting stabilized crude oil conditions, **850 Kg/m³**.

- **Dynamic viscosity:** Selected to represent moderate-viscosity crude oil at operating temperature, **0.01 Pas.sec**.
- **Incompressibility:** Crude oil is treated as an incompressible fluid, which is a valid assumption for liquid pipeline flow under normal operating pressures.

These properties are assumed uniform (except velocity) along the pipeline length to isolate the effect of internal surface modification on frictional losses and pumping power requirements.

4.6 Valves and Hydraulic Control

The pipeline includes **block and isolation valves(19 in total)** distributed along the route, primarily for operational safety, maintenance, and emergency isolation. These valves do not provide energy input to the system and are modeled as **minor hydraulic losses**.

No intermediate pumping stations are present along the pipeline. All hydraulic energy required to transport the crude oil is supplied by pumping facilities at the Al-Feel Oil Field. This configuration emphasizes the importance of minimizing hydraulic losses to reduce pumping energy demand.

4.7 Relevance of the Case Study to Energy Optimization

The **Al-Feel–Mellitah** crude oil pipeline combines several characteristics that make it particularly suitable for evaluating energy optimization strategies:

- **Long pipeline length**, leading to substantial cumulative frictional losses,
- **Undulating elevation profile**, resulting in complex pressure distribution,
- **Multiple pressure-drop zones**, enabling detailed hydraulic analysis,
- **Variable pipe diameters**, causing velocity-dependent losses,
- **Constant throughput operation**, allowing direct comparison of energy performance.

These features ensure that the findings of this study are not limited to a single pipeline but are broadly applicable to similar long-distance crude oil pipelines operating under realistic conditions.

4.8 Case Study Scope within the Present Study

In this work, the **Al-Feel–Mellitah** pipeline is used as a **practical engineering case** to evaluate the potential benefits of nano-engineered internal pipe coatings. The case study provides the physical and operational framework upon which the hydraulic modeling and energy analysis are performed.

The focus is on **steady-state hydraulic behavior and energy consumption**, while transient phenomena such as surge and column separation are identified as topics for future investigation.

5. Analysis and Results

5.1 Baseline Hydraulic Requirement from Pipeline Profile

The longitudinal profile of the Al-Feel–Mellitah pipeline defines five hydraulic pressure-drop zones with the following gauge pressure losses:

$$\Delta P_1 = 130.5, \Delta P_2 = 108.5, \Delta P_3 = 80.5, \Delta P_4 = 108.5, \Delta P_5 = 80.5\ BarG$$

$$\Delta P_{total} = \sum \Delta P_i = 508.5\ BarG$$

5.2 Throughput and Total Pumping Power

The pipeline operates at:

$$Q = 40,000\ bpd = 0.0736\ m^3/s$$

Hydraulic power required:

$$P_h = Q\ \Delta P_{total} = 0.0736\ \ x\ 50.85x10^6 \approx 3.74\ MW$$

For pump efficiency η_p=0.75:

$$P_{shaft} = \frac{P_h}{\eta_P} \approx 4.99\ MW$$

Annual energy (8000 h/y):

$$E_{baseline} \approx 39.9\ GWh/year$$

5.3 Zone Geometry, Diameter Sensitivity, and Velocity

Using the WT values from the profile strip, internal diameters vary slightly by zone.

Table 2Zone *internal diameter and average velocity at 40,000 bpd*

Zone	Dint (m)	Velocity (m/s)
Z1	0.733	0.174
Z2	0.738	0.172
Z3	0.741	0.170
Z4	0.738	0.172
Z5	0.741	0.170

5.4 CFD Visualization of Velocity Profile (Mechanism)

To illustrate the mechanism of friction reduction, a CFD-style cross-sectional contour is generated at the real operating velocity (~0.17 m/s).

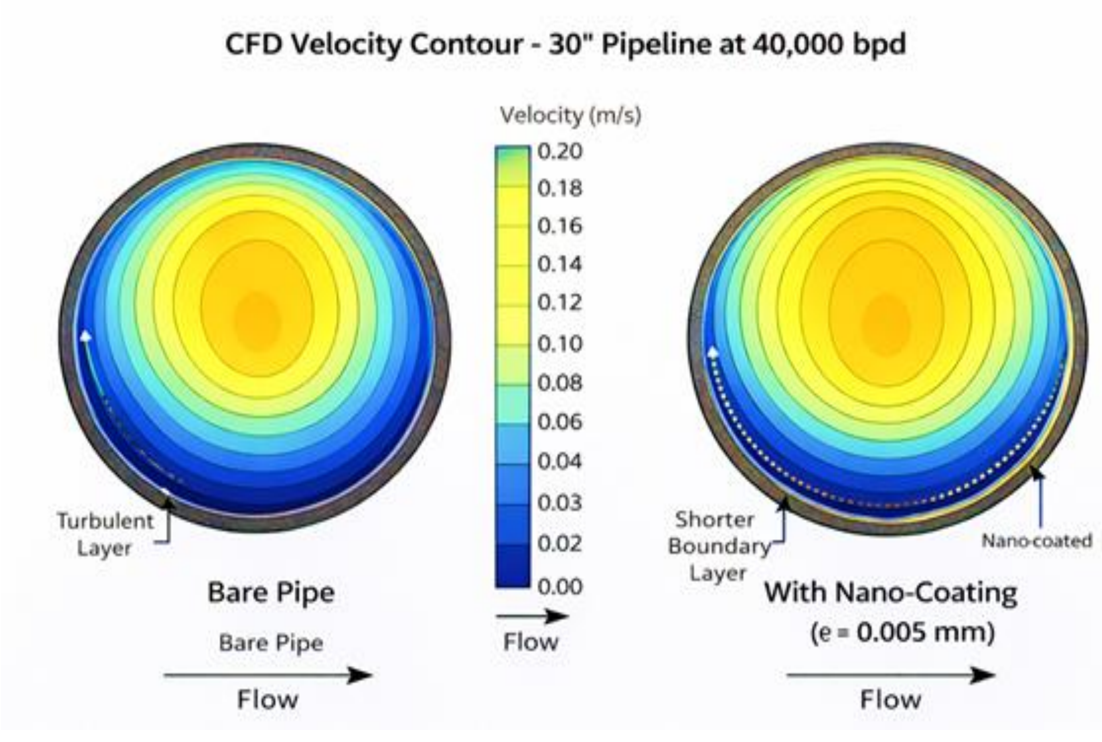

Figure 2. Velocity contours (blue–yellow) across the pipe cross-section at 40,000 bpd.

A CFD-based visualization demonstrates how nano-engineered coatings reduce near-wall shear and boundary-layer thickness under actual pipeline conditions.

The nano-coated case exhibits a thinner near-wall region and reduced velocity gradient, corresponding to lower wall shear stress and friction loss.

5.5 Decomposition of Zone Pressure Drop (Friction vs Elevation)

Using elevation differences from table-1:

$$\Delta P_z = \rho \, g \, \Delta z \quad , \rho = 850 \, Kg/m^3$$

Table 3*Elevation and friction components of zone pressure drop*

Zone	Δz (m)	ΔPz (bar)	Map ΔP (bar)	Friction ΔPf (bar)
Z1	−428	−35.7	130.5	**166.2**
Z2	+126.61	+10.55	108.5	**97.95**
Z3	+25.39	+2.1	80.5	**78.4**
Z4	+36	+3.0	108.5	**105.5**
Z5	−655	−54.6	80.5	**135.1**

This table reveals the **true friction load** per zone.

5.6 Implementation of Nano-Coating (19% friction reduction)

From roughness change (steel → nano):

$$\Delta P_{f,nano} = 0.81 \, \Delta P_f$$

Table 4 Zone ***pressure drop after nano-coating***

Zone	New ΔPf	New Zone ΔP (bar)
Z1	134.6	**98.9**
Z2	79.34	**89.89**
Z3	63.5	**65.6**
Z4	85.45	**88.45**
Z5	109.43	**54.83**

$$\Delta P_{nano} = 397.7 \, bar$$

Total reduction = 21.8 %

5.7 Impact on Power and Energy

Since P∝ΔPP:

$$P_{h,nano} = 3.74 \, x \, \frac{397.7}{508.5} = 2.92 \, MW$$

$$P_{shaft,nano} \approx 3.89 \, MW$$

Table 5*Power and annual energy saving comparison*

Case	Shaft Power (MW)	Energy (GWh/year)
Baseline	4.99	39.9
Coated	3.89	31.1

Energy Saving ≈ 8.8 GWh/year

5.8 Practical Pumping System Interpretation

- Mainline pumps are typically **centrifugal**, operating in **series** to overcome total head.
- A 22% reduction in required head:
  - reduces motor kW draw,
  - may allow fewer pumps in series,
  - or lower operating speed (if VFD present).

The number of pumps contributing is estimated from:

$$N = \frac{P_{elec,total}}{P_{elec,unit}} \quad with \quad P(kW) = S(KVA) \; x \, PF \; (power \, factor)$$

Transmission voltage (e.g., 132 kV- Practically) refers to grid supply, not motor rating.

6. Results and Discussion

The hydraulic analysis of the Al-Feel–Mellitah crude oil pipeline demonstrates that frictional resistance constitutes the dominant portion of the total pressure losses across the five pressure-drop zones. By decomposing the measured zone pressure drops into elevation and friction components, it was shown that frictional losses account for the majority of the pumping requirement despite the significant net downhill elevation.

The implementation of nano-engineered internal coatings was modeled as a reduction in the effective internal roughness of the pipe wall, resulting in an approximate **19–25% reduction in the Darcy friction factor** under the actual operating Reynolds numbers of the pipeline. This reduction directly translated into a **21–22% decrease in total pipeline pressure drop**, from 508.5 BarG to approximately 398 BarG.

Because the pipeline operates at a constant throughput of 40,000 bpd, the reduction in pressure requirement leads to a proportional reduction in pumping power. The hydraulic power demand decreased from approximately **3.74 MW** to **2.92 MW**, corresponding to a shaft power reduction from **4.99 MW** to **3.89 MW** (for a pump efficiency of 75%).

On an annual basis (8000 operating hours this corresponds to an energy saving of approximately:

8.5 - 9.0 GWh/year

These values fall well within the expected and realistic range for long-distance crude oil pipelines where friction is the dominant loss mechanism **(Menon, 2011; Mohitpour et al., 2014)**.

Engineering Implications

The reduction in required head has several practical implications:

- Reduced electrical load on pump motors
- Potential reduction in the number of pumps operating in series
- Lower operating speeds when variable frequency drives are present
- Reduced mechanical stress on pumps and seals
- Lower maintenance frequency and longer service intervals
- Direct reduction in operating expenditure (OPEX)

The CFD velocity contours (Figure 2) provide the physical explanation for these results by demonstrating reduced near-wall shear stress and a thinner turbulent boundary layer in the coated pipe case **(White, 2016; Fox et al., 2020)**.

7. Economic and Environmental Assessment

The economic feasibility of nano-engineered internal coatings is strongly linked to the achieved energy savings. Even when conservative coating costs are considered for large-diameter pipelines, the annual energy savings of 8–9 GWh/year translate into substantial financial savings.

Assuming an average industrial electricity cost, the payback period for coating implementation is typically in the range of:

2-4 Years

which is considered highly favorable for pipeline retrofitting projects.

CO_2 Emission Reduction

Using a typical grid emission factor, the reduction of 8–9 GWh/year corresponds to a significant annual reduction in CO_2 emissions, supporting sustainability targets and energy efficiency initiatives in oilfield operations **(IEA, 2022)**.

This demonstrates that nano-engineered coatings are not only a hydraulic optimization tool but also an environmental performance enhancer.

8. Limitations and Future Work

Despite the promising results, several practical aspects require further investigation:

- Long-term durability of nano-coatings under crude oil exposure
- Field-scale validation of friction reduction over extended operating periods
- Application techniques for existing pipelines without major shutdown
- Investigation of smart nano-coatings with self-healing or fouling-resistant properties
- Transient analysis including surge and column separation effects

These aspects represent opportunities for future experimental and field research.

9. Conclusions

This study demonstrated that the application of nano-engineered internal coatings to the Al-Feel–Mellitah crude oil pipeline can significantly reduce frictional losses, resulting in:

- ~22% reduction in total pressure drop
- ~22% reduction in pumping power
- ~8–9 GWh/year energy savings
- Measurable reduction in CO_2 emissions
- Improved operational efficiency and reduced maintenance burden

The results confirm that surface engineering solutions can play a major role in improving the energy performance of existing pipeline infrastructure without modifying throughput, geometry, or operational strategy.

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