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Impact of Riser Inclination on Multiphase Flow Performance and Production Rate Stability

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Abstract: *Multiphase flow behaviour in offshore production systems is highly sensitive to riser inclination. Improper riser geometry can lead to excessive pressure drops, flow instabilities, and reduced production efficiency. Understanding the impact of riser angle on flow performance is therefore essential for optimizing offshore pipeline design and operation. This study investigates the impact of riser inclination on multiphase flow performance and production rate stability, with the aim of identifying the inclination that minimizes flow instabilities while enhancing production efficiency. A multiphase pipeline network was modelled in PIPESIM software, incorporating a flowline and riser system under four inclination angles: 15°, 30°, 60°, and 90°. Simulations were performed for the different inclination on oil and gas flow rates, pressure distribution, liquid holdup, flow patterns, density variation, and temperature profiles along a 40,000 ft pipeline. The results show that shallower risers (15°) maintained higher oil flow rates and pressure stability but promoted liquid holdup and flow regime transitions that increase slugging risks. Steeper risers (60°–90°) reduced liquid accumulation and promoted gas-dominated regimes but incurred higher pressure drops and accelerated gas expansion. Thermal analysis further indicated that shallow risers experienced greater temperature losses, while vertical risers retained higher temperatures due to reduced residence time. Riser inclination exerts a significant influence on multiphase flow dynamics, with shallow angles supporting more efficient oil transport and pressure retention, and steeper angles favouring gas expansion but at higher hydraulic cost. The optimum inclination must therefore balance hydraulic efficiency and flow stability, supported by operational strategies such as slug management and thermal control.*

Keywords— Riser inclination; Steeper angle; Flow performance; Liquid holdup; Slugging; Modelling

1. INTRODUCTION (*Heading 1*)

Multiphase flow in offshore oil and gas production involves the simultaneous movement of oil, gas, and water phases through pipelines and risers [17]. This flow behaviour directly affects the efficiency and safety of hydrocarbon extraction, especially where fluid phases interact dynamically under varying pressure and temperature. Marine risers, acting as conduits between seabed wells and surface facilities, present unique challenges in managing these flows due to their exposure to environmental forces and complex internal flow patterns. The multiphase mixture characteristics, such as phase holdup and pressure gradients, are crucial for predicting flow stability and mitigating operational risks [3].

Production rate stability is critical to continuous and efficient hydrocarbon recovery, where fluctuations caused by multiphase flow instabilities, especially slugging, lead to unsteady production and potential damage to surface facilities. Slug flows cause abrupt pressure surges and flow rate variations that challenge process control and reduce equipment lifespan [16]. The riser inclination modifies these dynamics, often worsening production fluctuations and necessitating tailored design and operational strategies to enhance system stability [6].

Riser inclination arises from several real-world factors including platform motions, ocean currents, and installation angles, which deviate the riser from a purely vertical orientation [2]. Vertical and inclined risers exhibit significantly different flow characteristics, where inclination influences phase distribution and flow regime transitions, often leading to increased operational complexity [1]. Inclined risers show altered pressure drops and phase holdup behaviours due to gravity effects acting differently on each phase, causing flow instability and challenges in multiphase flow management.

Improper riser inclination is a critical design flaw that often leads to unstable multiphase flow behaviour, particularly the onset of severe slugging a periodic fluctuation in liquid and gas phases that causes pressure surges detrimental to production equipment. Typical multiphase flow regimes include bubbly, slug, annular, and stratified flows, each characterized by distinct phase distributions and flow dynamics [18]. In catenary and inclined risers, slugging arises because gravitational and frictional forces act unevenly across the phases, disturbing the flow regime equilibrium [10]. When the riser is not optimally aligned, the gravity-induced stratification of phases can cause gas to accumulate and push slugs of liquid upward violently. This disrupts flow stability, leads to cyclic stresses on topside separators, and challenges control systems, particularly in deepwater settings [9].

Another serious issue is the exacerbation of vortex-induced vibration (VIV) in risers with suboptimal inclination. Flow instability caused by incorrect angling results in oscillatory forces from internal and external fluid movements, which, over time, can lead to fatigue failure of the riser system [10]. These vibrations are amplified at certain inclinations due to phase shift resonance, and if not properly accounted for, may cause structural collapse. Additionally, wrong inclination often leads to high wall shear stress, particularly around 45–60°, where liquid momentum and pipe curvature interact maximally [4]. This stress intensifies the potential for erosion-corrosion, pipe thinning, and costly interventions, increasing operational risk. Together, these problems underscore the importance of precise inclination in offshore riser design.

The need to select a correct riser inclination angle lies in its direct control over flow regime distribution and mechanical loadings within the riser. Inaccurate inclination may not only alter the pressure drop but also shift the flow regime from stable to unstable patterns, leading to operational inefficiencies. Studies have demonstrated that inclination directly determines the frequency and amplitude of slugging cycles, which must be avoided through careful design. For instance, at certain inclination thresholds, gas pockets tend to coalesce more frequently, leading to violent slug bursts, especially under low-pressure scenarios typical in deepwater risers.

Moreover, the selection of an appropriate inclination has been found to affect parametric resonance thresholds in hydrate- and wax-laden flows, especially in systems subjected to dynamic environmental loading (Liang and Lou, 2021). These effects are magnified in systems with flexible riser strings, where improper geometry leads to undesired coupling between flow-induced vibrations and structural natural frequencies. Additionally, researchers have emphasized that the risk of hydrate formation and blockage increases in improperly inclined risers due to stagnant regions forming along the pipe walls [4]. Selecting the right angle not only improves flow but enhances system longevity by reducing internal stress zones and flow instabilities.

To improve both flow assurance and production rate stability, selecting riser inclination requires a multi-disciplinary approach involving hydrodynamics, thermodynamics, and structural mechanics. The inclination angle must be optimized based on flow regime maps, predicted slug frequency, and pipe structural response under environmental loading. Modulating the angle between 10° to 30° from vertical often helps prevent resonance between slug frequency and riser natural vibration modes. This reduces the severity of liquid surges and smoothens production

From a structural dynamic's perspective, Lou and Liang [7] recommend employing computational fluid–structure interaction models that simulate how inclination affects fatigue life and stress propagation. These simulations also predict flow-induced vibration amplitudes, allowing engineers to exclude harmful inclination ranges. Additionally, Montoya-Hernandez et al. [10] propose using dimensional analysis and experimental model testing to determine inclination-dependent pressure drops and optimize for minimum energy losses. Hydrate-prone conditions require inclinations that prevent phase segregation and stagnation, which can be addressed using CFD models validated by He *et al.,* [4] to ensure that the angle promotes full-bore sweeping and discourages dead zones. Thus, inclination selection becomes a balance of suppressing flow instability while enhancing total recovery performance.

Correctly selecting the riser inclination offers several technical and economic benefits. From a production standpoint, optimized inclination reduces flow regime transitions, particularly from stratified to slug flow, thereby ensuring smoother and more predictable production profiles. Stable flow improves separator efficiency, reduces the risk of production interruptions, and minimizes the frequency of surge-related shutdowns.

Understanding the impact of riser inclination on multiphase flow behaviour is crucial for enhancing offshore production efficiency and reliability. This study provides valuable insights into how inclination influences flow regimes, pressure gradients, and flow instabilities, which are essential for accurate flow assurance and operational planning [17], [3], [15]. By clarifying the connection between riser inclination and production rate stability, operators can better predict and manage production fluctuations, reducing the risk of severe slugging and associated equipment fatigue or failure.

Moreover, the research findings will support the design of more resilient marine riser systems, accommodating the dynamic conditions offshore platforms face due to waves, currents, and platform movement [6], [7]. The proposed models can help improve economic outcomes by minimizing downtime and optimizing production, thereby contributing to safer and more cost-effective offshore operations.

The challenges posed by riser inclination on multiphase flow performance and production rate stability remain a critical concern in offshore petroleum engineering. Multiphase flows through inclined risers experience complex flow regimes, pressure variations, and phase holdups that differ significantly from vertical risers, complicating flow assurance and operational efficiency [2]. These flow deviations contribute to unpredictable pressure drops and severe slugging events, which disrupt stable production and increase the risk of equipment damage.

Furthermore, existing models and experimental studies often focus on vertical or slightly inclined systems, leaving a gap in understanding for a wider range of riser inclinations commonly encountered due to dynamic platform motions or installation constraints [18]. This limited scope affects the reliability of predictive tools for multiphase flow behaviour, thereby increasing operational uncertainties. Flow regime transitions in inclined risers also introduce instabilities that propagate to surface facilities, resulting in fluctuating production rates and potentially causing operational shutdowns or costly maintenance [15].

Additionally, the compounded effects of environmental forces, hydrate phase transitions, and internal flow oscillations are inadequately integrated into current riser stability assessments [6], [10]. These factors not only affect the mechanical integrity of risers but also directly influence the multiphase flow patterns and the consistency of production rates. Hence, there is a critical need to comprehensively study the impact of riser inclination on multiphase flow performance and the resulting production stability, to inform better riser design, operational strategies, and flow assurance techniques that mitigate the negative effects of inclination-induced flow problems and production instabilities. The purpose of this work is to investigate the impact of riser inclination on multiphase flow behaviour and its effects on production rate stability in offshore oil and gas systems.

2.0 MATERIAL AND METHOD

2.1 MATERIAL

2.1.1 Data Collection

The data required for this study was obtained from [13], [11], [5] and [12] as presented in table 3.1 to 3.2.

Table 2.1 Pipeline characteristics, API 5L Grade X-65 Steel material properties [13]

Parameter	**Value**
Nominal Pipe Size (NPS)	10 inch (0.254 m)
Actual Outside Diameter (OD)	10.75 inch (0.273 m)
Wall Thickness	0.562 inch (0.0143 m)
Center Line Radius (Riser Bend)	50 inch (1.27 m)
Yield Strength (YS)	448 MPa
Tensile Strength (TS)	531 MPa
Young’s Modulus (E)	207 GPa
Poisson’s Ratio (v)	0.3
Density (ρ)	7850 kg/m³
Roughness	0.000028 m
Specific heat	500 J/Kg K
Operating pressure	197.7bar
Operating temperature	62 °C

Table 2.2: Fluid Composition [13], [11], [5], [12]

Component	**Molar %**
C1	72.3926
C2	3.9559
C3	1.9255
iC4	0.4267
nC4	0.8707
iC5	0.2657
nC5	0.3694
C6	0.6521
C7	0.8089
C8	0.9728
C9	0.9472
C10	0.8035
C11	0.8183
C12	0.7203
C13	0.6129
C14	0.6856
C15	0.7077
C16	0.5276
C17	0.4486
C18	0.4802
C19	0.4234
$C20^+$	8.0818
N_2	0.1026
CO_2	2.0000

2.1.2 Software Tool: PIPESIM

Pipesim is an industry-standard multiphase flow simulation software widely used for designing, analyzing, and optimizing oil and gas pipeline systems. Developed by Schlumberger, itoffers a comprehensive suite of tools that simulate the flow of oil, gas, and water in pipelines under various conditions. It integrates mechanistic flow models and empirical correlations to predict pressure drop, flow regime, and liquid holdup in complex pipeline configurations including horizontal, vertical, and inclined sections. Pipesim is particularly effective for handling multiphase flow because it accounts for the interaction between phases and the influence of operating conditions on flow behavior. The software supports detailed input of pipeline geometry, fluid properties, and operating scenarios, making it ideal for simulating the flow performance and corrosion potential within pipelines. It also includes modules for corrosion rate estimation based on flow parameters and fluid chemistry, thus facilitating integrated flow and corrosion analysis. The intuitive graphical user interface and robust solver algorithms enable efficient scenario testing and optimization, critical for operational decision-making in pipeline management.

2.2 Model Equations

The multiphase flow within the pipeline is governed by a set of mechanistic equations that describe the conservation of mass, momentum, and energy for each phase. The fundamental model used in Pipesim is based on the steady-state flow assumption with separate continuity and momentum balance equations for the gas and liquid phases.

The key governing equations include:

- **Continuity equation for phase i:**

$$\frac{d}{dx}(\rho_i A_i v_i) = 0 \qquad 1$$

Where: ρ_i = density of phase i (kg/m³), A_i = cross-sectional area occupied by phase i (m²), v_i = velocity of phase i (m/s).

- **Momentum balance for phase i:**

$$\frac{d}{dx}(\rho_i A_i v_i^2) = -A_i \frac{dp}{dx} - F_{wall,i} - F_{int} \qquad 2$$

Where: p = pressure (Pa), $F_{wall,i}$ = wall friction force acting on phase i, F_{int} = interfacial friction force between phases.

- **pipeline inclination angle** (θ)

Pipeline inclination angle is calculated using basic trigonometry, based on the vertical rise and horizontal run of the pipeline segment.

$$\theta = \tan^{-1}\left(\frac{\text{Vertical Elevation Change (H)}}{\text{Horizontal Length (L)}}\right) \qquad 3$$

Where:

θ = inclination angle (in degrees or radians, depending on your calculator setting)

H = vertical height or elevation change (m or ft)

L = horizontal projection length of the pipeline segment (m or ft)

2.3 Method

The simulation approach shall follow steps in the flowchart in figure 1

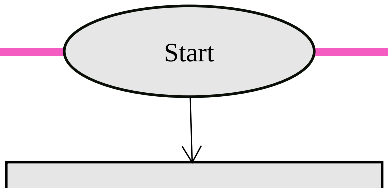

Figure 1: Simulation flowchart

3.0 RESULTS AND DISCUSSION

3.1 Oil flow rate profile along the pipeline

Figure 2 illustrates the variation in oil flow rate along a combined flowline and riser section for four different riser inclinations: 15°, 30°, 60°, and 90°, with the flowline terminating at a distance of 14,107.61 ft. Beyond this point, the riser section begins, and the impact of inclination becomes increasingly pronounced. Across all cases, oil flow rate declines progressively with distance, reflecting frictional losses and pressure depletion along the pipeline. However, the rate and extent of this decline vary significantly with riser angle. At inlet pressure of 179.7 bar for case, 90° riser inclination delivers highest volume of fluid from inlet. This is due short riser length for case. The 90° vertical riser exhibits the steepest decline, ending with the lowest oil rate among all scenarios. This behaviour underscores the detrimental effect of steep riser angles on flow performance, as vertical configurations amplify gravitational and frictional forces, leading to greater energy losses. This is followed by riser with 60° inclination. The 30° cases follow similar downward trends but with noticeably lower flow rates, indicating increased resistance and reduced hydraulic efficiency. The 15° inclination consistently maintains the high oil flow rate throughout the entire length with minimum drops in flow rate, compared to steeper angles. Generally, the figure clearly demonstrates that minimizing riser inclination enhances oil transport efficiency, with shallower angles supporting higher and more stable flow rates over long distances for the operating condition and fluid composition being studied.

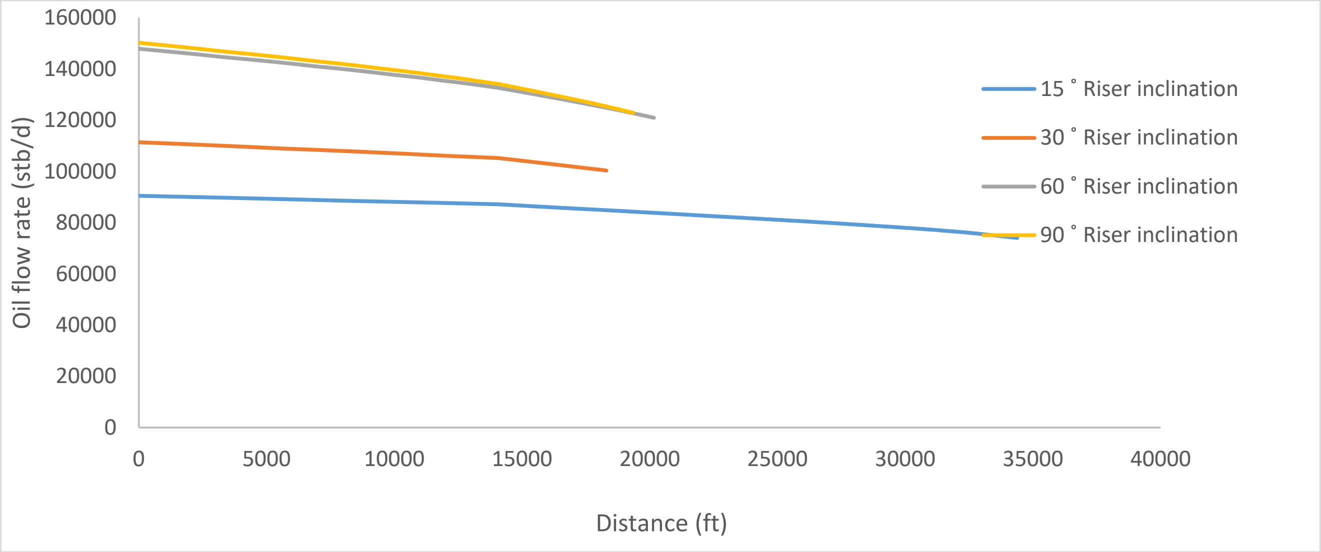

Figure 2: Oil flow rate profile along the flowline and riser

3.2 Gas flow rate profile along the pipeline

Figure 3 presents the gas flow rate profile along a combined flowline and riser section for four riser inclination angles 15°, 30°, 60°, and 90° with the flowline terminating at 14,107.61 ft. Unlike the oil rate trend, gas flow rate increases progressively with distance for all inclination cases, reflecting gas expansion and reduced density as pressure drops along the pipeline. However, the magnitude and steepness of this increase are strongly influenced by riser angle. The 90° vertical riser exhibits the most pronounced rise in gas flow rate, ending with the highest value among all scenarios. This behaviour is attributed to the dominant effect of gravitational separation and pressure relief in vertical configurations, which accelerates gas liberation and volumetric expansion. The 60° and 30° cases follow similar upward trends but with slightly lower final rates, indicating moderated expansion due to reduced vertical lift. The 15° inclination shows the least increase, ending with the lowest gas flow rate, suggesting that shallow riser angles constrain gas acceleration and expansion.

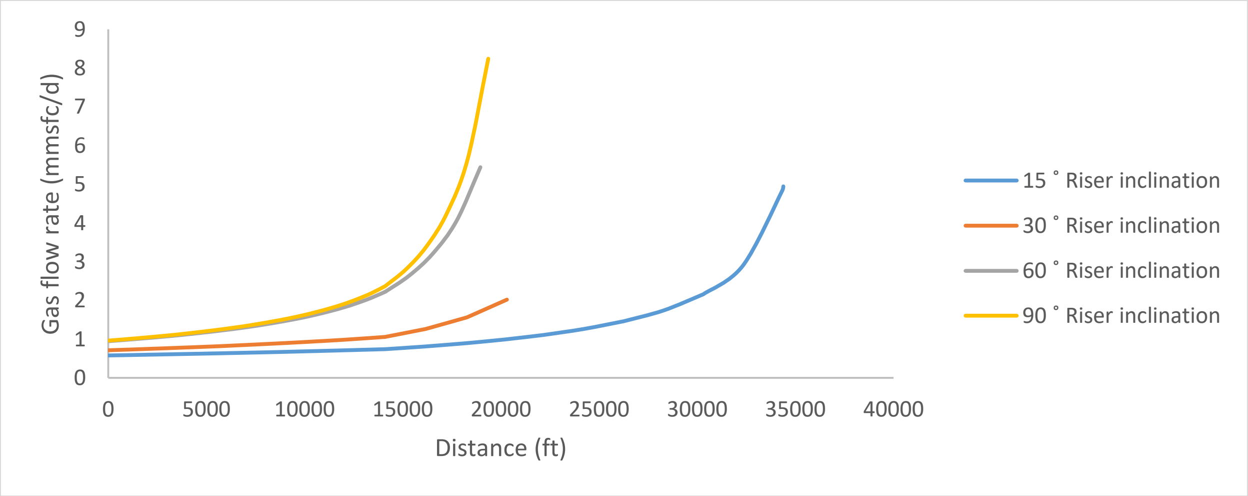

Figure 3: Gas flow rate profile along the flowline and riser

3.3 Fluid flow pattern along the pipeline

The figure illustrates the evolution of gas-liquid flow patterns along a flowline and riser system for four riser inclination angles 15°, 30°, 60°, and 90° extending to a total distance of 40,000 ft, with the flowline terminating at 14,107.61 ft. The flow pattern index, which reflects the nature of multiphase interactions, varies across the pipeline length and is strongly influenced by riser geometry. The code for the flow regime includes 7-intermitent flow, 8-distributed flow, >8-slug flow, The 15° inclination exhibits a pronounced peak around 30,000 ft, indicating a significant transition in flow regime likely a shift toward slug or churn flow due to increased liquid accumulation and intermittent gas surges. In contrast, the 30°, 60°, and 90° cases show relatively flat and subdued profiles, suggesting more stable or less dynamic flow regimes. The vertical riser (90°) maintains the lowest and most consistent flow pattern index, implying a dominance of annular or mist flow, where gas carries dispersed liquid droplets upward with minimal phase separation. This behaviour underscores the role of riser inclination in shaping flow regime transitions: shallow angles promote complex, unstable patterns due to enhanced liquid holdup and gravitational resistance, while steeper angles favour streamlined gas-dominated flow.

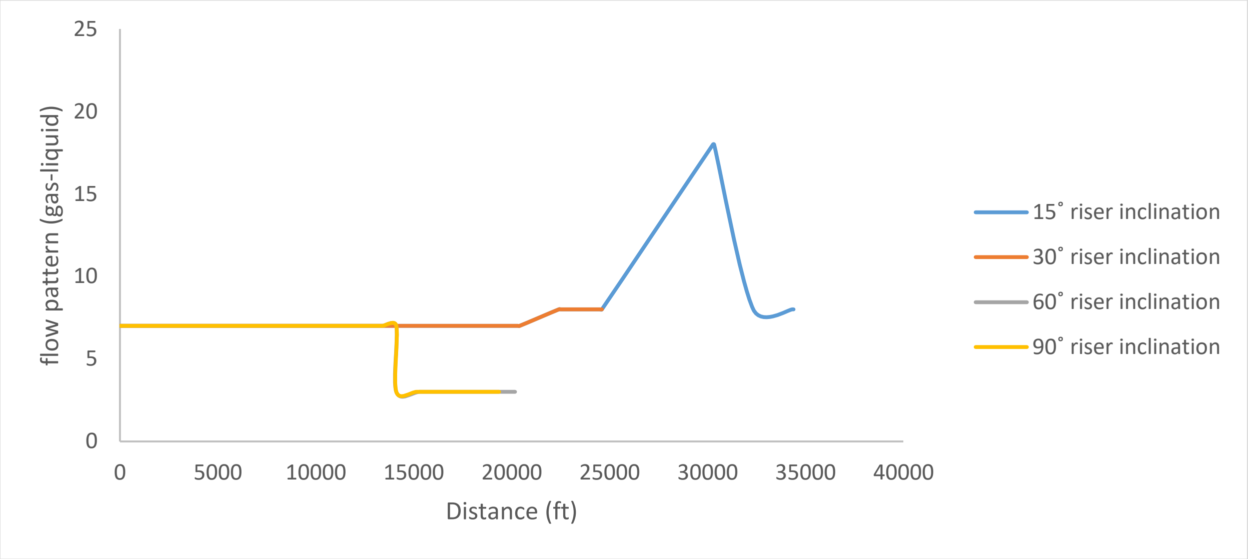

Figure 4: Flow pattern along the pipe line

3.4 pressure drop distribution along the pipeline

The figure presents the pressure distribution along a flowline and riser section for four riser inclination angles, 15°, 30°, 60°, and 90° extending to a total distance of 40,000 ft, with the flowline terminating at 14,107.61 ft. Across all cases, pressure declines steadily with distance, reflecting frictional losses, gravitational effects, and fluid expansion typical of multiphase transport. However, the rate of pressure drop varies significantly with riser angle. The 15° inclination maintains the highest-pressure profile throughout, indicating minimal gravitational resistance and efficient pressure retention. As the riser angle increases, pressure losses become more pronounced. The 30° and 60° cases show intermediate behaviour, with steeper gradients and lower terminal pressures. The 90° vertical riser exhibits the sharpest decline, ending with the lowest pressure, which highlights the compounded effect of vertical lift and hydrostatic head. This trend underscores the critical influence of riser inclination on pressure dynamics shallower angles preserve pressure and enhance flow assurance, while steeper angles intensify energy losses and may necessitate additional boosting or flow stabilization strategies. Overall, the figure reinforces the importance of optimizing riser geometry to balance pressure management and production efficiency in offshore pipeline system.

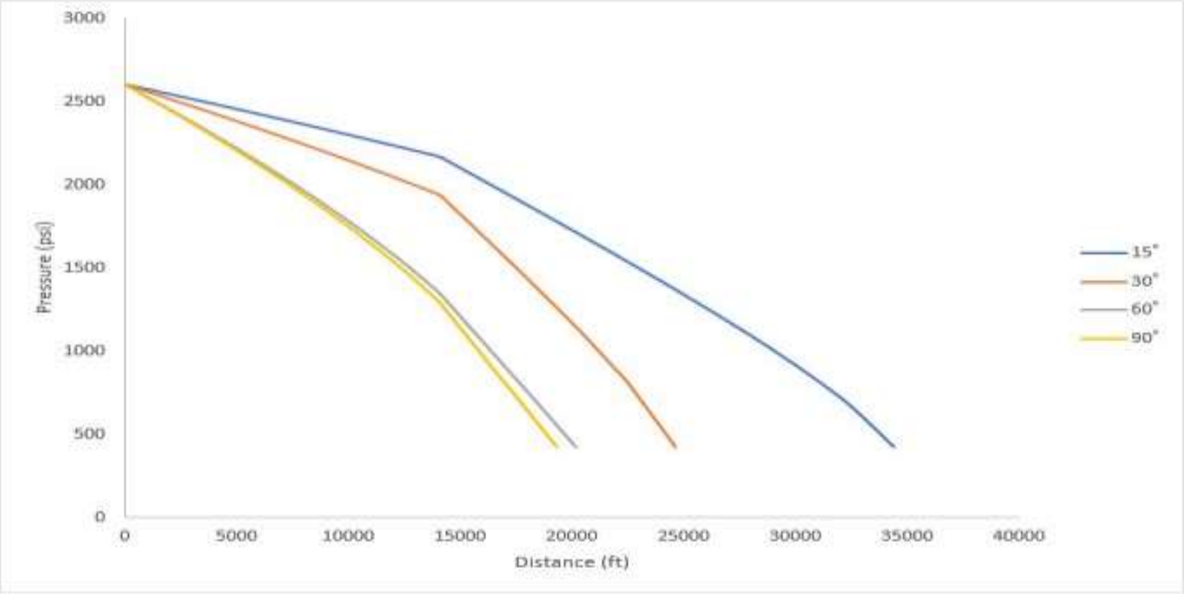

Figure 5: Pressure drops along the pipe line

3.5 Liquid holdup along the pipeline

The figure illustrates the liquid holdup fraction along a combined flowline and riser section for four riser inclination angles 15°, 30°, 60°, and 90° with the flowline terminating at 14,107.61 ft. Across all cases, the liquid holdup fraction decreases progressively with distance, reflecting the natural separation and acceleration of gas in multiphase flow. However, the rate and extent of this decline are strongly influenced by riser angle. The 15° inclination maintains the highest liquid holdup throughout the entire length, indicating that shallow angles promote liquid retention and reduce gravitational segregation. As the inclination steepens, liquid holdup diminishes more rapidly. The 30° and 60° cases show intermediate behaviour, with moderate liquid drainage and increasing gas dominance. The 90° vertical riser exhibits the lowest liquid holdup, especially beyond the flowline section, where gravitational effects intensify phase separation and gas lift. This trend highlights the critical role of riser inclination in controlling liquid distribution and flow regime stability. Shallower risers tend to preserve liquid continuity, which can be beneficial for certain production strategies, while steeper risers accelerate gas breakout and reduce liquid loading, potentially leading to flow instabilities such as slugging

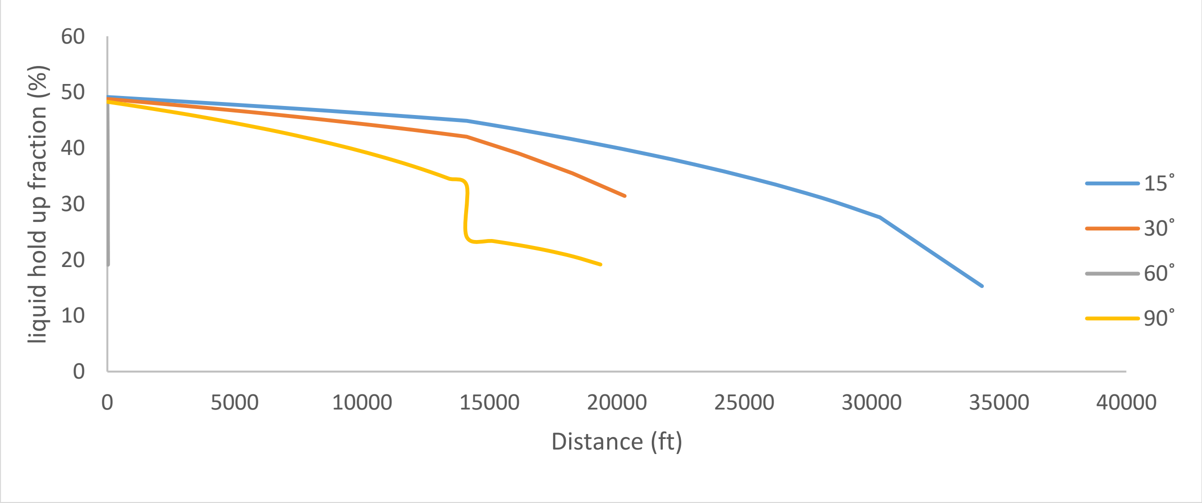

Figure 6: Liquid holdup along the pipeline

3.6. Density variation along the pipeline

Figure 7 displays the variation in oil density along a flowline and riser system for four riser inclination angles 15°, 30°, 60°, and 90° over a distance of 25,000 ft. Across all cases, oil density increases gradually with distance, reflecting the thermodynamic response of the fluid to pressure and temperature changes along the pipeline. However, the rate of increase is strongly influenced by riser angle. The 90° vertical riser shows the steepest rise in oil density, suggesting that vertical lift intensifies pressure gradients and compressive effects, thereby increasing fluid density. The 60° and 30° cases follow similar upward trends but with slightly moderated slopes, indicating intermediate compressive behaviour. The 15° inclination maintains the lowest and most stable density profile, implying minimal gravitational compression and a more uniform pressure distribution. This trend highlights the role of riser geometry in shaping fluid properties steeper angles enhance pressure buildup and fluid compaction, while shallower angles preserve lighter, less compressed flow. From a design perspective, understanding these density variations is crucial for predicting flow behaviours, sizing equipment, and ensuring accurate metering in multiphase transport systems.

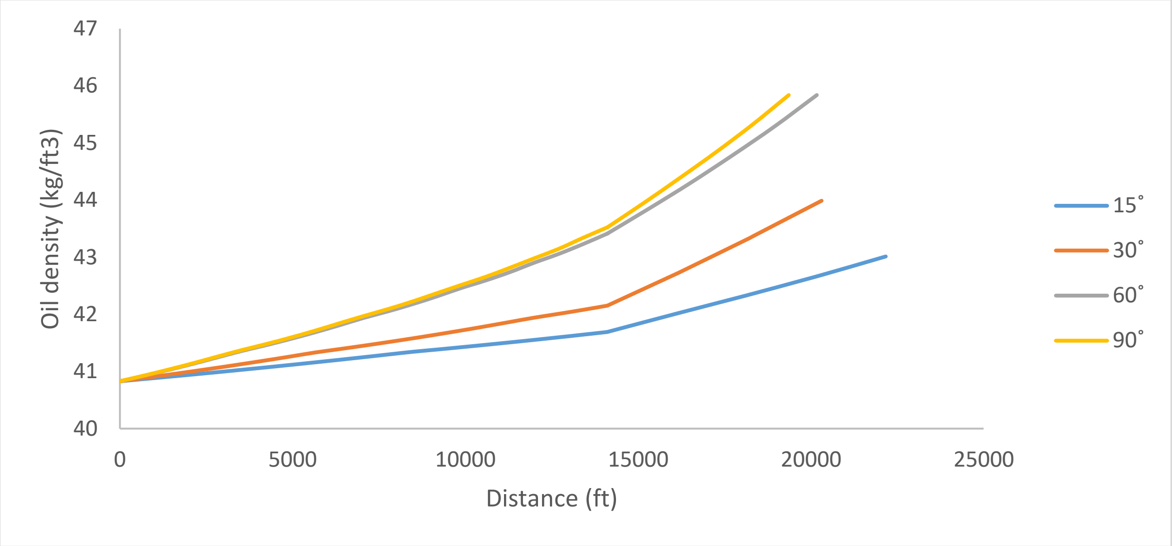

Figure 7: Density variation along the pipeline

3.7. Temperature variation along the pipeline

The figure illustrates the temperature profile along a flowline and riser system for four riser inclination angles 15°, 30°, 60°, and 90° over a total distance of 40,000 ft. Across all cases, temperature decreases steadily with distance, reflecting heat loss to the surrounding environment and the thermodynamic behaviours of fluids under pressure drop and expansion. However, the rate of temperature decline varies notably with riser angle. The 15° inclination exhibits the steepest temperature drop, indicating greater exposure to ambient cooling and extended residence time due to slower fluid velocities. As the riser angle increases, the temperature gradient becomes less pronounced. The 30° and 60° cases show intermediate cooling rates, while the 90° vertical riser maintains the highest temperature throughout, suggesting reduced heat exchange and faster fluid transit. This trend highlights the influence of riser geometry on thermal dynamics steeper risers minimize temperature loss by shortening flow path and reducing contact time with cooler surroundings, whereas shallower risers promote greater thermal dissipation. From an operational standpoint, understanding these temperature variations is essential for managing viscosity, preventing hydrate formation, and optimizing thermal insulation strategies in offshore production systems.

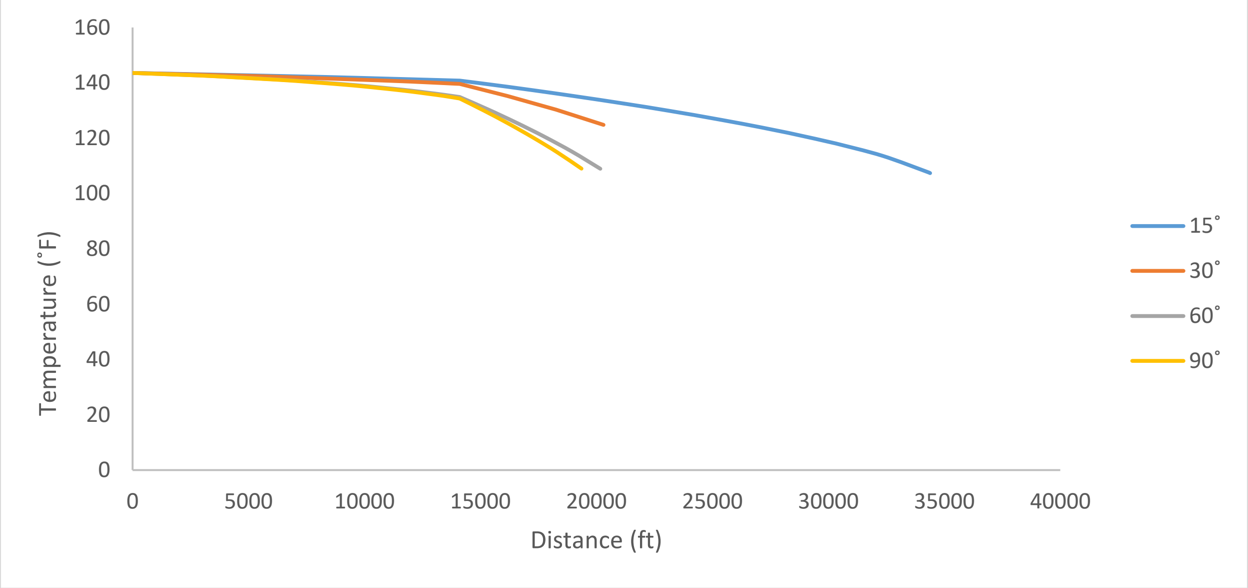

Figure 8: Temperature variation along the pipeline

4.0 CONCLUSION

The results of this study clearly illustrate the significant impact of riser inclination on multiphase flow performance and production stability. At shallower angles, specifically 15°, oil flow rates were notably higher, and pressure retention was more efficient, which contributed to more stable production at the topside. In contrast, steeper risers, particularly those at angles between 60° and 90°, resulted in increased pressure losses and reduced oil deliverability, with the vertical configuration (90°) exhibiting the most severe decline in performance.

Moreover, the analysis of flow patterns and liquid holdup indicated that shallower risers facilitate greater liquid retention and complex regime transitions, thereby increasing the likelihood of slugging events. Conversely, steeper risers tended to favor gas-dominated flow regimes characterized by lower liquid holdup, which diminished liquid loading but heightened the risks associated with gas expansion and flow instability. Variations in thermal and fluid properties further underscored the influence of riser geometry, as steeper inclinations resulted in sharper increases in density and gas expansion, while shallower angles maintained a more uniform density profile but experienced greater thermal losses. Consequently, the findings suggest that optimizing riser inclination is essential for balancing hydraulic efficiency and flow regime stability, necessitating tailored design and operational strategies to address the specific challenges presented by each configuration.

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APPENDIX

Appendix i: flowline-riser model