(RESEARCH ARTICLE)

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Time-Dependent CFD modelling of a Stalling Pig Wall Shear Stress in a Subsea Riser at 45°, 60°, and 90° Inclinations

Charles U. Orji *, Glory O. Esebene and Oghenethoja M. Umuteme

Centre of Excellence in Marine and Offshore Engineering, Rivers State University, PMB 5080 Port-Harcourt, Nigeria.

Abstract

Subsea oil and gas operations rely on extensive pipeline networks to transport crude oil efficiently, economically, and safely. Pigging a critical pipeline maintenance technique uses devices known as "pigs" to clean, inspect, and manage pipelines. However, operational challenges such as pig stalling, where pigs become lodged and disrupt flow, can lead to significant downtime and costs. This research employs transient CFD modeling to investigate the effects of a partially stalled bi-directional pig on wall shear stress and axial force in subsea pipeline risers at angles of 45°, 60°, and 90°. The study specifically aims to identify gaps in understanding flow characteristics and pig motion under stalling conditions, which can pose severe operational risks in subsea environments. Simulations conducted in ANSYS Fluent, with a single-phase flow velocity of 0.744 m/s, indicate stalling velocities of 0.45 m/s (45°), 0.3 m/s (60°), and 0.25 m/s (90°). Correspondingly, wall shear stress increased from 15 kPa at 45° to 35 kPa at 90°, highlighting the significant impact of pig orientation on flow dynamics and pipeline integrity.

Keywords: Riser Angle; Stalling Velocity; Flowing Wall Shear Stress; Subsea Pipeline Pigging; Stalling Velocity

1. Introduction

Offshore pipelines are critical marine infrastructure used for transporting hydrocarbons from seabed reservoirs to floating production systems or export pipelines, as well as for delivering crude oil to shore [1]. Pipelines play a vital role in hydrocarbon transportation, as most oil traverses pipelines for at least part of its journey. With the increasing demand for oil and gas, pipeline transportation has become one of the primary methods for moving crude oil. These pipelines often span long distances, operate in harsh marine environments, and are subjected to complex physical, chemical, and mechanical stresses. Maintaining pipeline integrity is essential to ensure safe and efficient operation, as impurities such as wax and hydrates can accumulate during long-term operation, leading to flow assurance challenges [2], [3]. To mitigate these flow assurance issues, various maintenance techniques are employed, with pigging operations being the most widely used method for subsea pipeline maintenance [4]. Effective pipeline maintenance is crucial to preserving integrity and protecting assets.

The term "PIG" is commonly thought to be an acronym for *Pipeline Inspection Gauge*. Pigging refers to the insertion and movement of a mechanical device known as a pig through a pipeline to perform cleaning, inspection, or separation tasks [4], [5]. Pigging is a routine component of pipeline integrity management and flow assurance, with applications including pre-commissioning, line-proving, cleaning, liquid removal, batching, and in-line inspection (ILI). Previous studies (e.g., [4], [5], [6], [7], [8], [9], [10]) have investigated the motion-related behavior of pipeline pigs; however, none have explicitly examined the wall shear stress acting on bi-directional pig discs across varying riser inclinations. This study addresses this gap by quantifying the time-dependent wall shear stress and associated axial forces on pig sealing

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* Corresponding author: Charles U. Orji

discs in subsea risers at 45°, 60°, and 90°, providing new insight into the mechanisms governing pig stalling under inclined flow conditions.

Operational issues may arise in pipeline risers, causing pigs to stall or become damaged due to obstacles or unintended bypasses. Among these challenges, partial pig stalling is particularly critical. In pipeline risers with a 90° inclination, fluid must overcome the full effect of gravity, leading to increased pressure drops and potential slugging. At 45° or 60° inclinations, gravity has a moderate influence; however, the multiphase nature of the fluid can result in flow regime transitions [11], [12], [13]. Against this background, this study aims to model time-dependent flowing pipewall shear stress in subsea pipeline risers during pigging operations with a partially stalled pig. A comprehensive hydraulic model is developed to evaluate the effects of different riser angles (45°, 60°, and 90°) on fluid dynamics. The study objectives are:

- To develop a 3D transient CFD model of a subsea riser-pig system at 45°, 60°, and 90° angles to simulate time-dependent, single-phase flow through the riser with a partially stalled bi-directional pig near the riser base.
- To analyze time-dependent wall shear stress, axial forces, and velocity contours around the pig disc induced by fluid pressure gradients.
- To recommend optimal riser designs and operational strategies to reduce pig stalling risks.

1.1. Relevant Field Data of the Study Area

The study focuses on a deepwater subsea pipeline system connected to a Floating Production, Storage, and Offloading (FPSO) unit. Key parameters include:

- Water depth: 500 m below sea level, indicating significant hydrostatic pressure.
- FPSO tie-in point: 10 m above mean sea level (MSL).
- Design pressure: 69 barg at the reservoir, reducing to 5 barg at the receiving facility, requiring substantial pressure management and flow control.
- Crude oil properties: Temperature of 70°C; viscosity to be specified.
- Pipeline material: API 5L X60 steel, selected for high strength and toughness suitable for deepwater applications.

These parameters form the basis for the CFD simulation and hydraulic analysis of pigging operations under stalling conditions in subsea risers.

2. Methodology

This study employed numerical simulation using Computational Fluid Dynamics (CFD) in ANSYS Fluent to model time-dependent, single-phase flow, complemented by PIPESIM to investigate the hydraulic response of a partially stalled bi-directional pig in subsea pipeline risers. The methodology involved a two-step process: first, generating hydraulic baseline data using PIPESIM, and second, performing detailed CFD analysis in ANSYS Fluent.

2.1. Hydraulic Baseline Modeling with PIPESIM

The PIPESIM simulator was used to establish the hydraulic baseline for the pipeline-riser system. Single-phase flow of black oil was modeled using the multiphase PVT package, incorporating fluid composition analysis to determine phase behavior through Multiflash. The simulation provided essential hydraulic parameters, including pressure, flow velocity, and temperature profiles along the riser, which served as input for subsequent CFD modeling.

2.2. CFD Modeling in ANSYS Fluent

Using the hydraulic data from PIPESIM, a 3D transient CFD model of the riser-pig system was developed in ANSYS Fluent. The model simulated the interaction between the pipeline fluid and a partially stalled bi-directional pig, focusing on time-dependent wall shear stress on the pig disc. The CFD analysis allowed detailed investigation of fluid-induced pressure gradients, flow recirculation, and the effects of riser inclination (45°, 60°, and 90°) on pig stalling behavior.

This combined PIPESIM-CFD approach provided a robust framework for assessing operational risks associated with pig stalling and informed strategies to optimize subsea pipeline integrity and flow assurance.

2.3. Pipeline Riser Geometrical Configurations (45°, 60°, and 90°)

The various Pipeline Riser inclination angles considered for this study are shown in Figures 1, 2 and 3.
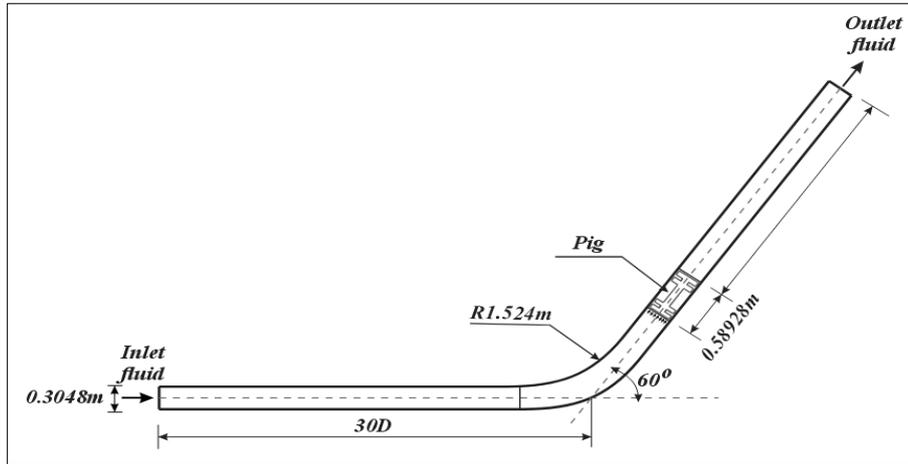
Figure 1 45^0 Pipeline Riser bend
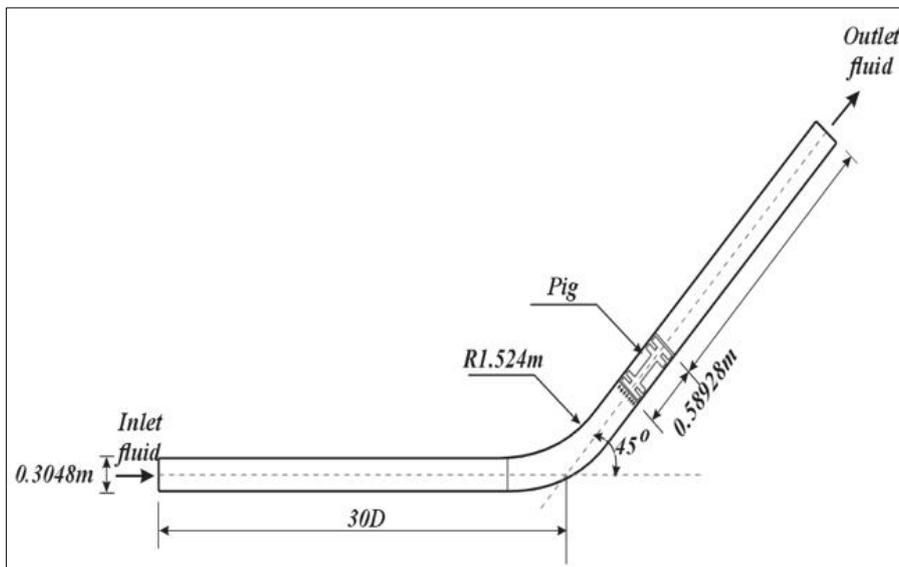
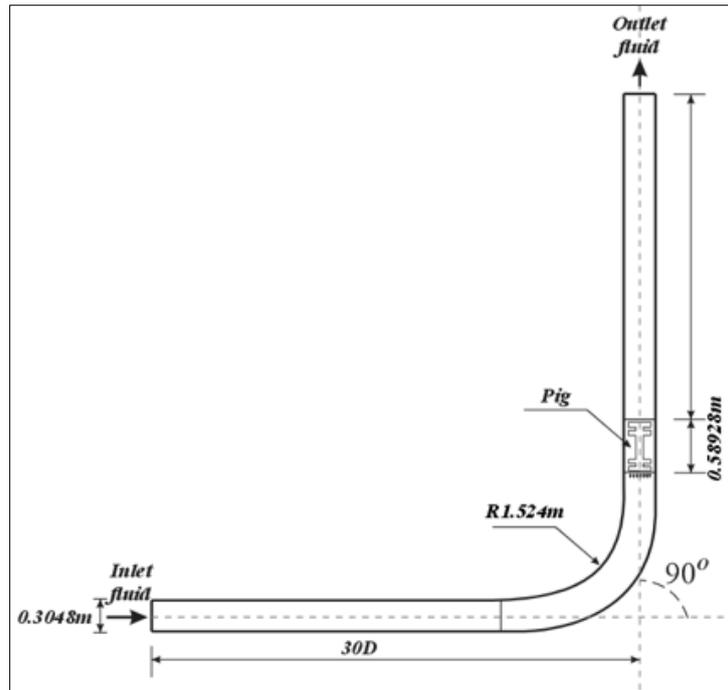**Figure 2** 60^0 Pipeline Riser Bend

Figure 3 90[0] Pipeline Riser Bend

2.4. 3D Meshing

For the 45° pipeline riser, a structured mesh was generated in ANSYS student version to accurately capture the fluid–pig interactions as shown in Figure 4. The mesh parameters were set with a maximum element size of 0.03 m and a defeaturing tolerance of 1, ensuring sufficient resolution around complex geometrical features of the pig and riser. The resulting mesh consisted of 119,034 nodes and 130,816 elements, providing a balance between computational efficiency and solution accuracy for transient CFD simulations of wall shear stress and flow behavior.
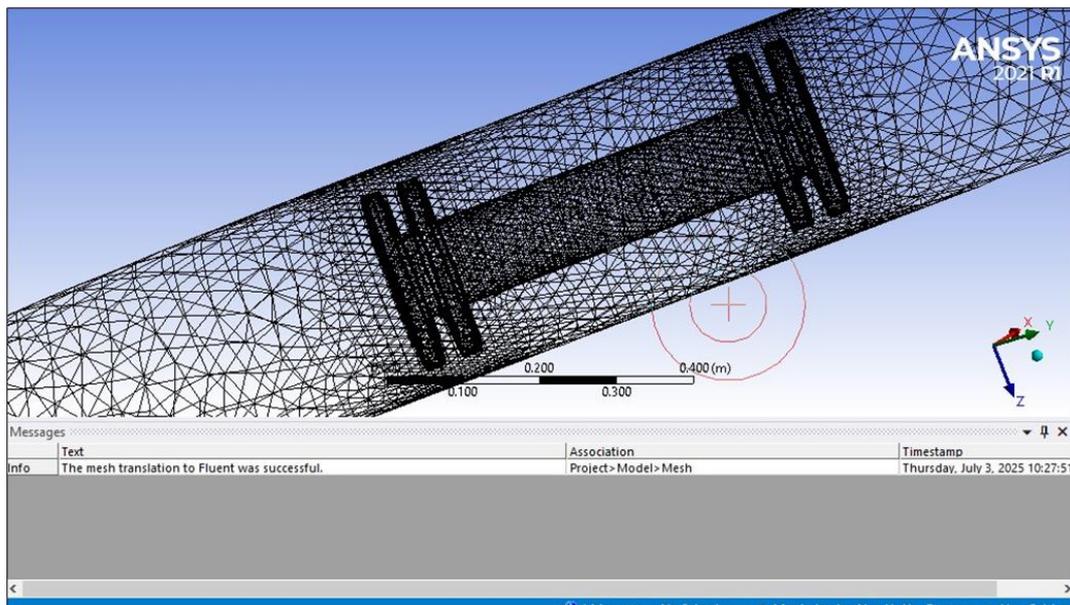

Figure 4 Typical Meshing showing Bi-directional Pig for 45[0] Pipeline Riser Bend

2.5. Solver Methods and Controls

The $k-\epsilon$ turbulence model with enhanced wall functions was adopted to model turbulent flow. All simulations were transient, solved using a pressure-based solver, with a negative gravity of –9.81 m/s^2 to account for upward flow

against gravity. An implicit body force formulation captured the density difference in separated flow conditions. A constant time step of 0.1 s and a maximum of 100 iterations per step ensured stable convergence. The solution discretization is presented in Table 1 below.

Table 1 Solution Discretization Scheme

Variable	Scheme	Rationale
Pressure-Velocity Coupling	SIMPLE	Ensures stable pressure–velocity coupling with robust convergence.
Pressure	Second Order	Accurate pressure interpolation for slugging flows.
Momentum	Second Order Upwind	Reduces numerical diffusion and improves velocity accuracy.
Turbulent Kinetic Energy	Second Order Upwind	Stabilizes turbulence transport calculations.
Turbulent Dissipation Rate	Second Order Upwind	Maintains stable dissipation field without oscillations.
Transient Formulation	Second Order Implicit	Guarantees unconditional stability for transient simulations.

Wall shear stress, critical for assessing hydraulic interaction with a stalled pig, was computed using the **realizable k–ϵ** model with enhanced wall treatment in ANSYS Fluent. This approach resolves velocity gradients near the pig (0.24384 m diameter) and pipe surfaces, accurately capturing boundary layer effects. Sensitivity analysis confirmed its reliability across 45°, 60°, and 90° risers.

Understanding entrance length is essential for predicting flow development, heat transfer, and flow assurance issues such as hydrate or slug formation. Entrance length is defined as the region where flow transitions from non-uniform to fully developed. For the studied pipeline, using an L/D ratio of 30 (D = 0.3048 m), the entrance length is calculated as 9.144 m. hence, a horizontal riser approach length of 10 m was adopted. Flow characteristics within this region influence local velocity, pressure, and temperature, directly affecting hydrate deposition and overall pipeline performance.

2.6. Bidirectional Pig Specification

The properties of the bi-directional pig used in this study are summarized in **Table 2.**

Table 2 Bidirectional Pig Specification

Parameter	Value
Pig Body Diameter (D)	0.3048 m
Pig Length (L)	0.58928 m
Pig Weight (Pw)	72 kg
Sealing Disc Diameter (SD)	0.24384 m

2.7. Governing Equations

The governing equations for this study are derived from the Navier–Stokes equations for incompressible, single-phase flow to accurately model transient hydraulic behavior in subsea pipelines.

2.7.1. Conservation of mass

The continuity equation for single-phase flow states that the mass flow rate is conserved throughout the system and assumes a steady state, incompressible flow. The general formula for the continuity equation for single-phase flow in a volume is given by:

$$\frac{\partial p}{\partial t} + \nabla.(pv) = 0 \qquad (1)$$

Where:

p = Fluid density (kg/m³) assumed constant for incompressible flow

v =Velocity vector (m/s,)

$\frac{\partial \rho}{\partial t}$ =The rate of change of density with time is zero for steady-state flow.

$\nabla.(\rho v)$ = Divergence of the mass flux, representing the net mass flow into or out of the control volume.

2.7.2. Conservation of momentum

The conservation of momentum is described by the Navier-Stokes equation, which balances the forces acting on the fluid, and is given by;

$$\rho \left(\frac{\partial \rho}{\partial t} + (V.\nabla)V \right) = -\nabla p + \mu \nabla^2 V + \rho g \qquad (2)$$

Where:

ρ = Fluid density (kg/m³).

v = Velocity vector (m/s)

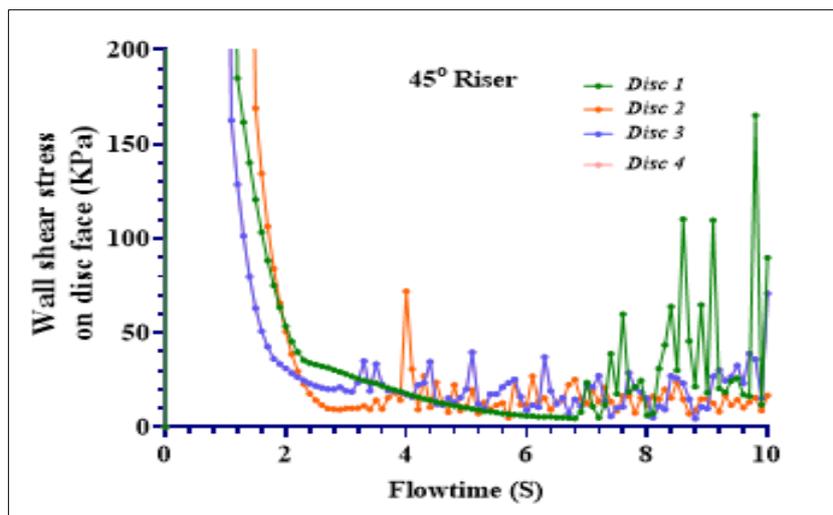$\frac{\partial v}{\partial t}$ = Time rate of change of velocity (zero for steady-state flow).

$(V.\nabla)V$ = Convective acceleration (nonlinear term).

∇p = Pressure gradient force (Pa/m),

$\mu \nabla^2 V$ = Viscous force, where μ is the dynamic viscosity

ρg = Gravitational body force (m/s²)

3. Analysis and Results

Figure 5 Pig Discs Wall Shear Stress at 45° Riser Angle

The results shows that wall shear stress significantly influences the hydraulic response and operational performance of pigs in subsea pipelines. Understanding its variation around the sealing disc is critical for assessing stalling risks, particularly under different riser inclinations. The impact of wall shear stress on the sealing disc of the bi-directional pig for riser angles of 45°, 60°, and 90° is presented in Figures 5, 6 and 7 and summarized in Table 3. The analysis indicates that wall shear stress exhibits an initial spike followed by a decline in all configurations. Maximum shear stress

is highest for the 90° riser, followed by 60°, and lowest for 45°, correlating with the likelihood of pig stalling: the higher the shear stress gradient induced by riser inclination, the greater the risk of stalling due to localized pressure differentials [4]. In Table 2, Disc 1 was selected for analysis of stalling severity because it is the first disc on the fluid-approach inlet and therefore experiences the highest fluid impact. Its interaction with the flow makes it the most critical indicator of wall shear stress, axial forces, and overall stalling behavior of the pig. Consequently, maximum shear stress on Disc 1 provides a reliable measure of the pig's likelihood to stall under varying riser inclinations.
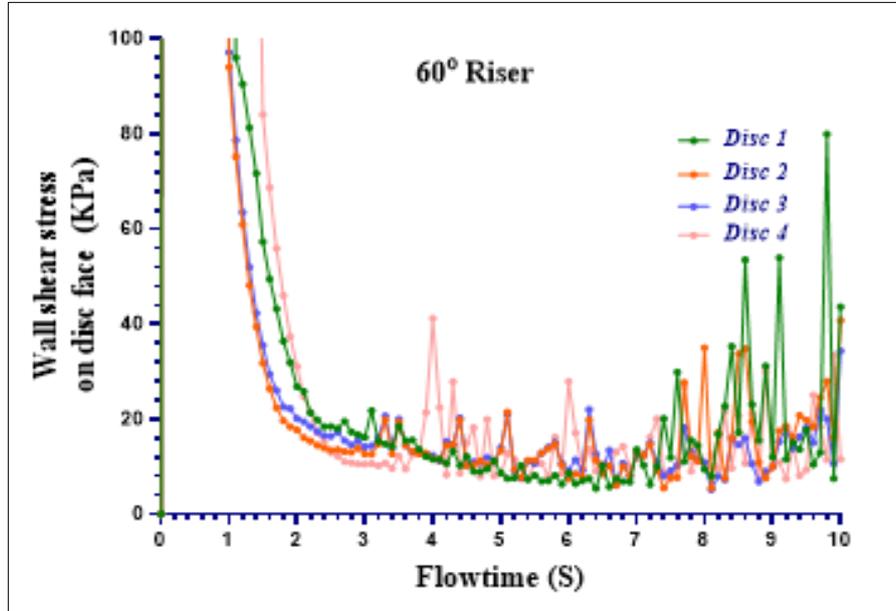

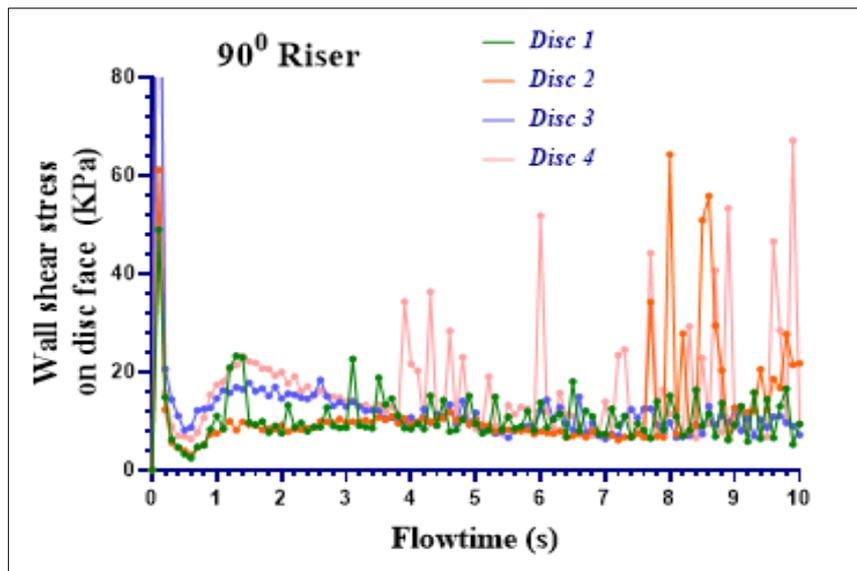**Figure 6** Pig Discs Wall Shear Stress at 60° Riser Angle

Figure 7 Pig Discs Wall Shear Stress at 90° Riser Angle

Table 3 Shear Stress Result for Disc 1

Riser Angle	Maximum Shear Stress on Disc 1 (kPa)	Likelihood of Pig Stalling
45°	15	Very Low
60°	80	Low
90°	160	High

As shown in Figures 5, 6 and 7 and Table 3, stalling risk is minimized at a 45° riser angle due to lower wall shear stress. In contrast, the 90° riser exhibits the highest shear stress on the propelling disc, indicating a greater tendency for the pig to stall. Intermediate angles, such as 60°, present moderate stalling risk. These results demonstrate that pig stalling is strongly dependent on riser inclination: as the riser angle increases toward vertical, wall shear stress and localized pressure differentials rise, increasing the likelihood of operational issues. Maintaining lower riser inclinations where feasible can therefore reduce stalling risk and improve pigging efficiency. Higher shar stress values suggest possible deformation of discs [7], [14].

4. Discussion

The analysis of time-dependent wall shear stress around the bi-directional pig's sealing disc reveals a strong relationship between riser inclination and stalling risk. The unsteady signal across Figures 5, 6 and 7 is consistent with experimental observations in the literature[8]. As the riser angle increases from 45° to 90°, maximum wall shear stress rises substantially, reflecting greater fluid-induced forces acting on the pig. Previous studies suggest that lower riser inclination angles generally reduce structural and hydraulic stresses in pipelines [15]; consequently, higher riser angles tend to increase stress levels during pigging operations. However, in offshore pipeline systems, excessively low riser angles can introduce stronger hydrodynamic effects such as increased wave- and current-induced loading and longer seabed interaction lengths which may adversely affect pipeline stability and pigging performance. Therefore, riser angle selection represents a trade-off between minimizing pig-induced hydraulic stresses and managing offshore hydrodynamic loading.

This trend is consistent with the physics of flow in inclined pipelines: in more vertical risers, gravity opposes fluid movement less effectively, requiring higher pressure gradients to drive flow past the pig. These elevated pressure differentials generate larger shear stresses at the pig-disc interface, increasing the likelihood of partial or complete stalling. Disc 1, positioned at the fluid-approach inlet, experiences the highest fluid impact and therefore provides the most sensitive measure of stalling severity. The results show that at 45°, maximum shear stress is only 15 kPa, corresponding to a very low likelihood of stalling. At 60°, shear stress rises to 80 kPa, indicating a low but notable risk, while at 90°, the maximum shear stress reaches 160 kPa, representing a high stalling potential. This demonstrates that stalling risk is strongly dependent on riser angle, with vertical or near-vertical configurations being particularly critical for subsea operations.

The initial spike in shear stress observed in all riser configurations is attributable to the sudden impact of fluid on the pig as it enters the riser section. This is followed by a decline as flow partially stabilizes around the pig, suggesting a transient interaction dominated by local acceleration and deceleration zones [5], [8]. These dynamics highlight the importance of transient modeling in predicting operational behavior, as steady-state approaches would fail to capture these critical spikes and the associated stalling risk. From an operational perspective, the findings suggest that lowering riser inclinations where feasible or designing pigging procedures that account for vertical sections can significantly reduce stalling likelihood [16]. Furthermore, the results emphasize the importance of realistic CFD modeling combined with hydraulic baseline data from PIPESIM, which allows engineers to capture both the transient fluid forces and the structural response of the pig in complex subsea riser geometries.

Overall, this study reinforces the critical role of riser angle, fluid properties, and pig design in subsea pipeline integrity and flow assurance. By quantifying wall shear stress on the leading disc, operators can better anticipate stalling events, optimize pigging schedules, and implement preventive measures such as pressure management or bypass strategies to mitigate operational downtime. The observed increase in wall shear stress and stalling likelihood with riser inclination agrees with prior experimental and analytical studies on inclined pipeline hydraulics and pigging dynamics [15]. However, this study extends existing knowledge by providing transient, disc-resolved CFD evidence linking shear stress evolution to pig stalling mechanism.

5. Conclusion

The time-dependent wall shear stress analysis demonstrates that riser inclination is a key factor influencing pig stalling risk in subsea pipelines. Maximum shear stress on Disc 1 increases with riser angle, with 45° showing very low stalling potential, 60° moderate risk, and 90° high likelihood of pig stalling. These results indicate that vertical or near-vertical risers are most susceptible to operational interruptions due to elevated localized pressure gradients. From a design perspective, maintaining lower riser inclinations where feasible can reduce wall shear stress and minimize stalling risk. Operationally, pigging schedules should account for riser geometry, with careful pressure management and, if necessary, bypass or auxiliary flow strategies in steep risers. Furthermore, pig design optimization—such as adjusting disc size, sealing force, or mass distribution can help mitigate stalling in high-angle risers. This analysis underscores the importance of combining transient CFD modeling with hydraulic baseline data to predict pig performance accurately, enabling engineers to implement targeted strategies that enhance subsea pipeline integrity and maintain uninterrupted flow assurance.

Compliance with ethical standards

Disclosure of conflict of interest

All authors declared they have no conflicts of interest related to this research.

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