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New Insights into Slug Frequency for High-Viscosity Liquid in Inclined Pipes

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New Insights into Slug Frequency for High-Viscosity Liquid in Inclined Pipes

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Abstract

Slug frequency is a key parameter in the modeling and flow assurance management of gas–liquid slug flow encountered in the petroleum industry. While slug frequency has been extensively investigated in horizontal and vertical pipes, its behavior in inclined flows with high-viscosity liquids remains less documented. In this short communication, experimental datasets reported in the literature are re-analyzed to investigate the combined effects of pipe inclination and liquid viscosity on slug frequency. The results show that, for a given liquid viscosity, slug frequency increases with pipe inclination. In contrast, the influence of liquid viscosity depends largely on the regime, showing opposite trends in flows dominated by gravity and inertia. The transition between these regimes is observed at a mixture Froude number of approximately 1.2. Further experimental investigations of slug frequency in inclined gas–liquid flows with high-viscosity liquids are required to better explain this behavior and to develop more robust slug frequency models for gas-high-viscosity liquid two-phase flow in inclined pipes.

Keywords: Slug flow; slug frequency; high-viscosity liquid; pipe inclination; liquid viscosity.

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Nomenclature

D	Pipe diameter (m)
Fr_M	Mixture Froude number (-)
Fr_{SL}	Liquid Froude number (-)
f_s	Slug frequency (Hz)
g	Gravitational acceleration (m/s^2)
Re_{SL}	Liquid Reynolds number (-)
St_M	Strouhal number based on mixture velocity (-)
V_M	Mixture velocity (m/s)
V_{SG}	Gas superficial velocity (m/s)
V_{SL}	Liquid superficial velocity (m/s)

Greek letters

Θ	Dimensionless parameter (-)
θ	Pipe inclination (rad)
λ_L	Homogenous liquid holdup (-)
μ_L	Viscosity (Pa.s)
ρ_G	Gas density (kg/m^3)
ρ_L	Liquid density (kg/m^3)
Φ	Dimensionless parameter (-)
Ψ	Dimensionless parameter (-)

Conversion

1 cP = 0.001 Pa.s

1. Introduction

Gas–liquid slug/intermittent flow is commonly encountered in the petroleum industry, as it occurs during both hydrocarbon production in wells and transportation through pipelines (Ali et al., 2024; Nydal, 2012; Shippen and Bailey, 2012). It should be noted that both wells and pipelines may be inclined, making the characterization of slug flow under inclined conditions particularly relevant (Ali et al., 2024; Beggs and Brill, 1973; Brito et al., 2018).The slug/intermittent regime exhibits specific hydrodynamic features in which the gas phase is mainly transported as elongated/Taylor bubbles separated by liquid slugs (Abdul-Majeed et al., 2024; Arabi et al., 2025b; Holagh and Ahmed, 2024; Morgado et al., 2016; Syikilili et al., 2022). The interface between the elongated/Taylor bubble and the liquid slug is where complex phenomena occur, including gas bubble shearing, recirculation zones and liquid turbulence (Arabi et al., 2025b; Holagh and Ahmed, 2024; Shi et al., 2017). Understanding slug flow requires a reliable prediction of intrinsic flow parameters, such as slug translational velocity, liquid slug length, liquid slug holdup, and slug frequency.

Slug frequency, defined as the number of liquid slugs passing at a given pipe location per unit time, is of particular importance because it is widely used as a closure relationship in mechanistic models implemented in simulation codes used in the petroleum industry to design well and piping system (Shippen and Bailey, 2012). Accurate estimation of slug frequency is also crucial for flow assurance issues, as it directly affects corrosion rates, wax deposition, and sand transport, as recently reviewed by Arabi et al. (2025a). Due to the complex nature of slug flow generation (Taitel and Dukler, 1977; Tronconi, 1990), the theoretical prediction of slug frequency remains challenging and a relatively large number of empirical correlations have been proposed in the literature (Arabi et al., 2020; Mohmmed et al., 2025). However, the reliability and applicability of such correlations strongly depend on the database used for their development and the specific range of physical conditions used in the experiments.

With the decline in conventional low-viscosity oil production, oil exploitation has increasingly shifted toward unconventional resources, including heavy oils (Pan et al., 2024; Wang et al., 2024), which are characterized by their high viscosity. Multiphase flows with high-viscosity liquids exhibit flow behaviors that differ significantly from those observed with low-viscosity liquids (Al-Ruhaimani et al., 2018a; Al-Safran et al., 2013; Al-Safran and Ghasemi, 2025; Archibong-Eso et al., 2019; Zhang et al., 2012). In this context, several research groups have investigated slug frequency in air–high-viscosity liquid flows (Al-Ruhaimani et al., 2018b; Archibong-Eso et al., 2018; Baba et al., 2017; Gokcal et al., 2010; Losi et al., 2016; Zhao et al., 2013).

Experimental studies conducted in horizontal pipes by Gokcal et al. (2010) and Archibong-Eso et al. (2018), among others, reported that increasing liquid viscosity promotes slug formation and leads to higher slug frequencies. These studies also demonstrated that correlations developed using water as the liquid phase fail to accurately predict slug frequencies obtained with high-viscosity liquids. For vertical upward flow, Al-Ruhaimani et al. (2018b) proposed an empirical correlation based on experiments performed in a 50.8 mm ID pipe with liquid viscosities ranging from 127 to 586 cP. As discussed in Abdul-Majeed et al. (2020), this correlation predicts a decrease in slug frequency with increasing liquid viscosity. This opposite trend, compared to horizontal flow, indicates that pipe inclination strongly influences how liquid viscosity affects slug frequency.

Compared to horizontal and vertical configurations, relatively few studies have investigated slug frequency in inclined upward flows (Hernandez-Perez, 2008; van Hout et al., 2003). For air–water flow, van Hout et al. (2003) reported that increasing the pipe inclination tends to increase slug frequency up to inclinations between 50° and 70°, beyond which further inclination increases tend to decrease slug generation. More recently, Fayyaz (2022) conducted experimental measurements of slug frequency using high-viscosity liquids at different pipe inclinations. To the best of the authors' knowledge, this work represents the only experimental investigation of this type. However, the study

focused exclusively on the effects of gas and liquid superficial velocities, with slug frequency plotted separately for each liquid viscosity and pipe inclination.

In summary, the combined effects of pipe inclination and liquid viscosity on high-viscosity gas–liquid inclined flows remain largely unexplored. Although Fayyaz (2022) provides the only available experimental dataset for inclined pipes with high-viscosity liquids, it has not been analyzed to elucidate the coupled roles of inclination and viscosity. The present short communication addresses this gap by re-analyzing these datasets using alternative representations that reveal previously unreported trends. The results provide new physical insight into slug frequency in inclined pipes by highlighting the evolving competition between gravitational and inertial forces.

2. Analysis and discussion

As discussed above, the present analysis is based on the experimental data reported by Fayyaz (2022). The experiments were conducted at the University of Nottingham using a 67 mm inner diameter and 6 m long acrylic pipe, with an air–silicone oil mixture. Three mixtures were prepared for achieving viscosities (μ_L) of 64, 91.5, and 236 cP. The properties of the fluids are summarized in Table 1. Measurements were performed for pipe inclinations (θ) of 0°, 5°, 15°, 25°, 35°, 45°, 65°, 75°, and 90° relative to the horizontal. It should be noted that different liquid superficial velocities were investigated for each liquid viscosity, and that for viscosities 91.5 cP and 236 cP, experiments were conducted only at pipe inclinations of 0°, 15°, 45°, 65°, and 90°. For clarity, Figure 1 shows the experimental matrix in terms of pipe inclination and liquid superficial velocity explored in this study for the three liquid viscosities.

Table 1 Physical properties of silicone oil-air mixtures employed by Fayyaz (2022).

Fluid		Viscosity [cP]	Density [kg/m^3]	Surface tension [N/m]
Silicone oil mixture	Mixture 1	64	922.5	0.0202
	Mixture 2	91.5	922.5	
	Mixture 3	236	922.5	
Air		0.0185	1.225	

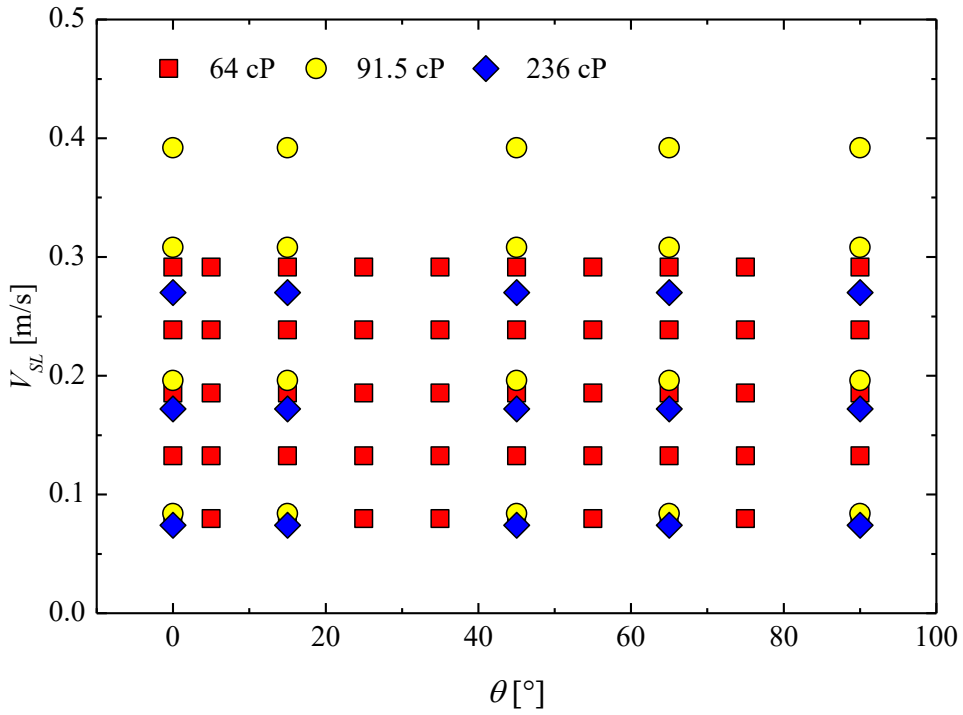


Fig. 1 Experimental matrix showing the pipe inclination and liquid superficial velocities for the three liquid viscosities investigated by Fayyaz (2022).

Fayyaz (2022) extracted the slug frequency from void fraction time series obtained using electrical capacitance tomography (ECT) by employing the double-threshold method proposed by Hazuku et al. (2008). In the present study, the slug frequency values were obtained by digitizing the corresponding plots presented in the doctoral thesis of Fayyaz (2022). It should be noted that, due to

the limited resolution of some figures, not all data points could be digitized. These points only concern the low gas superficial velocity range. The digitized datasets are provided as supplementary material. Figure 2 presents the results of slug frequency (f_s) obtained for a liquid viscosity of μ_L = 64 cP at different liquid and gas superficial velocities, plotted as a function of pipe inclination. The results clearly show that slug frequency follows the increasing trend as the pipe inclination increases, for all the superficial velocities investigated. This behavior contrasts with that observed for low-viscosity liquids, where, as discussed in Section 1, slug frequency first increases and then decreases with increasing pipe inclination. A similar trend is observed for the two other liquid viscosities investigated.

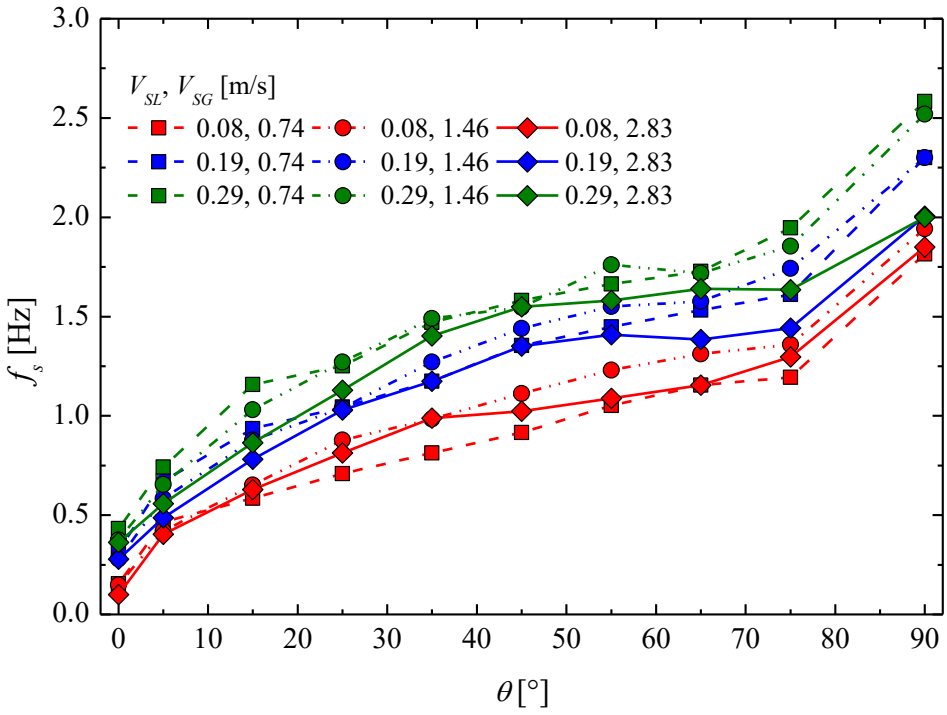


Fig. 2 Slug frequency measured by Fayyaz (2022) as a function of pipe inclination obtained with μ_L = 64 cP.

To illustrate the influence of liquid viscosity, only the results obtained at a liquid superficial velocity of V_{SL} = 0.29 ± 0.02 m/s were considered. First, the data corresponding to horizontal and

vertical pipe configurations are presented in Fig. 3 as a function of the mixture velocity ($V_M = V_{SL} + V_{SG}$). The results clearly reveal opposite effects of liquid viscosity on slug frequency in horizontal and vertical pipes. This observation is consistent with trends reported in the literature, as discussed in Section 1.

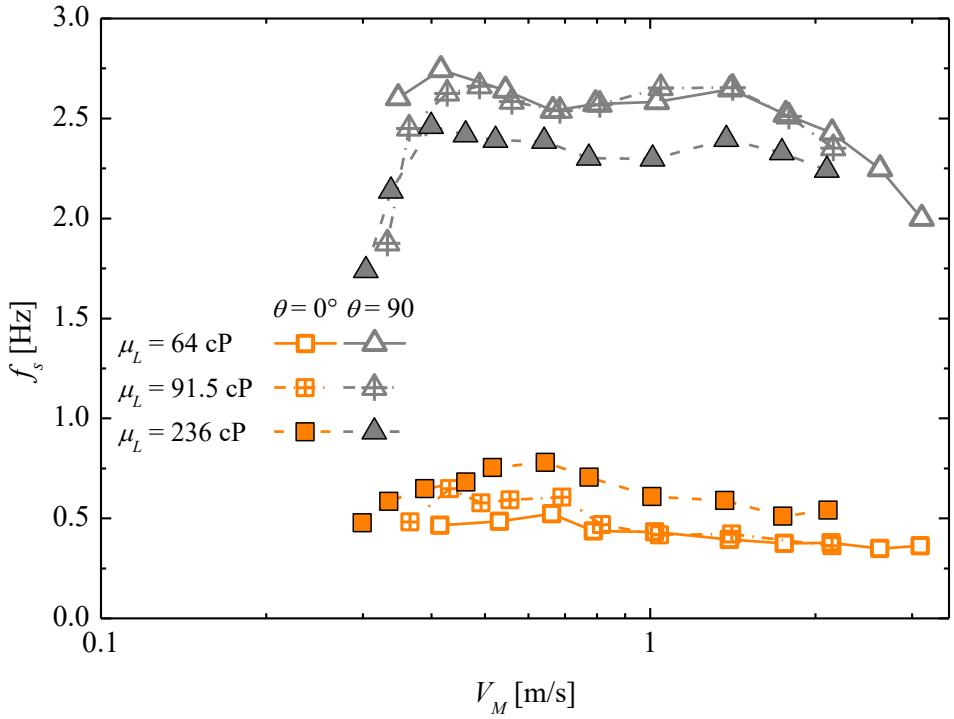
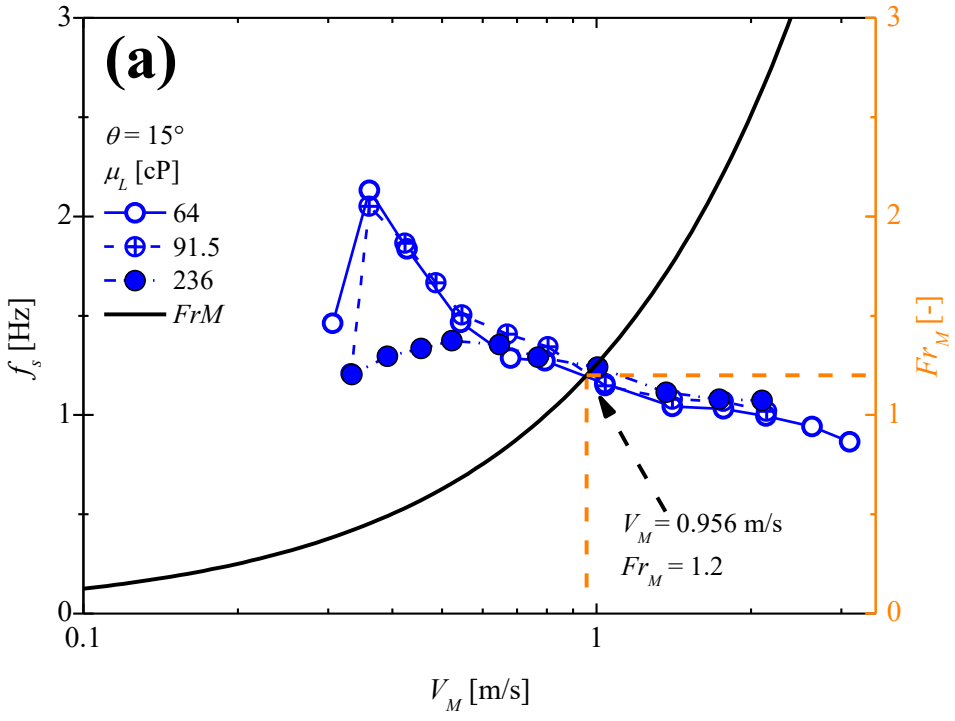


Fig. 3 Slug frequency reported by Fayyaz (2022) in horizontal and vertical pipes as a function of mixture velocity for the three investigated liquid viscosities and $V_{SL} = 0.29 \pm 0.02$ m/s.

Finally, the slug frequency results for pipe inclinations of $\theta = 15°$, 45°, and 65° are presented in Fig. 4 as function of mixture velocity. For clarity, the data for each inclination are shown separately. The results indicate that, at low V_M, increasing liquid viscosity leads to a reduction in slug frequency, whereas the opposite trend is observed at higher V_M values. These two regimes are more clearly distinguished for $\theta = 15°$ and 65°, where an increase in pipe inclination shifts the critical mixture velocity marking the transition between the two trends toward higher values. The absence of a clear

trend for θ = 45° is likely due to the relatively close values of slug frequency and the associated measurement uncertainties. Further discussion of this aspect can be found in Höhn et al. (2024).

At low V_M, the influence of liquid viscosity on slug frequency is similar to that observed in vertical pipes, which can be attributed to the dominant role of gravitational forces. As the mixture velocity increases, inertial effects become more significant and progressively reduce the influence of gravity, leading to a change in the way liquid viscosity affects slug frequency. This indicates that the impact of liquid viscosity on slug frequency is governed by whether the flow is predominantly gravity- or inertia-dominated. This gravity–inertia flow transition can be physically interpreted through changes in the shape of the elongated/Taylor bubbles, which are governed by the competition between inertial and gravitational forces, as discussed by Grenier (1997), Maldonado et al. (2024), and Höhn et al. (2025). Variations in bubble shape directly affect the interface between the elongated bubble tail and the nose of the following liquid slug, thereby influencing liquid slug length, which is inversely proportional to slug frequency (Al-Safran et al., 2013; Zitouni et al., 2021).



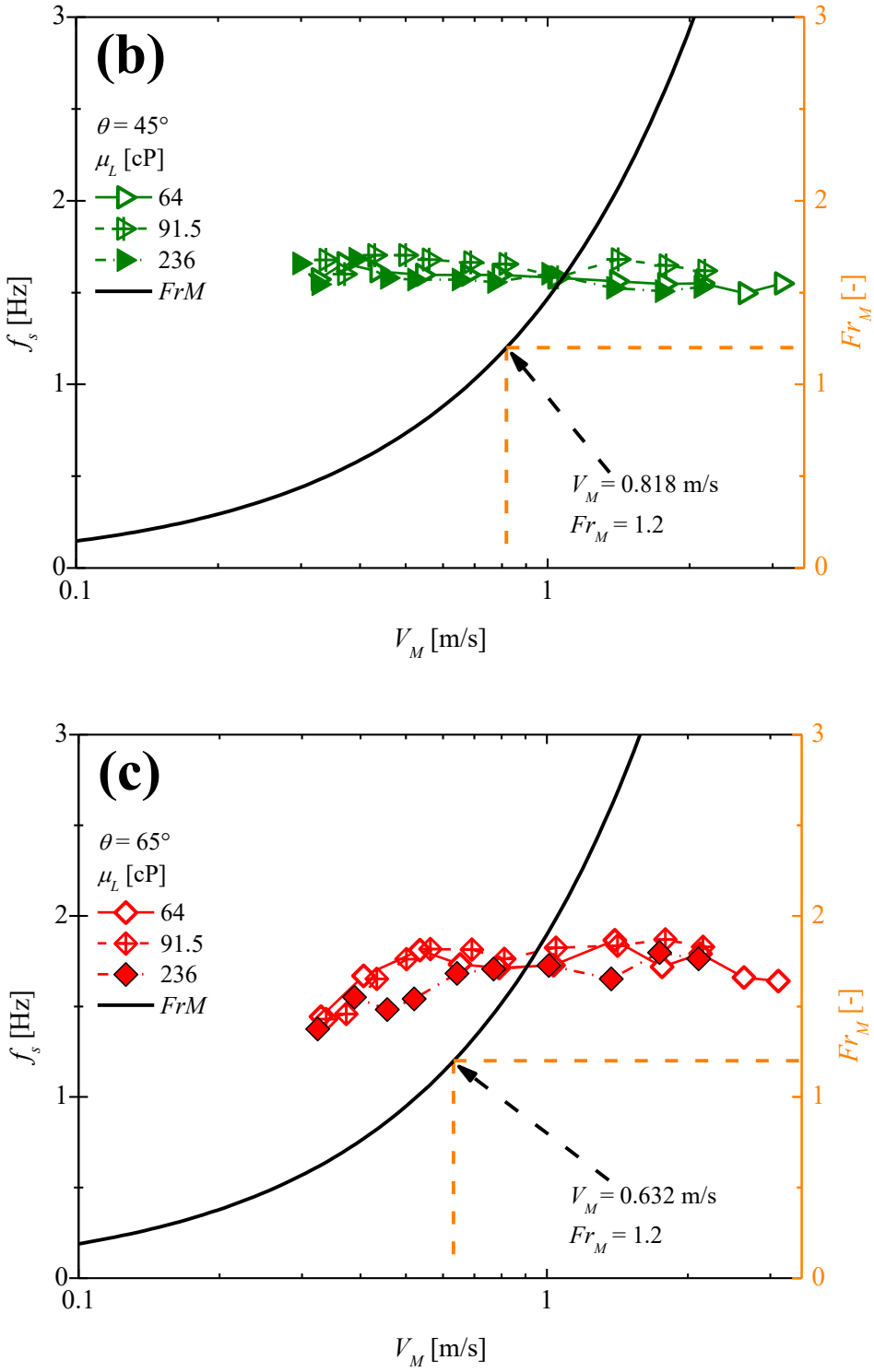


Fig. 4 Simultaneous plots of slug frequency measured by Fayyaz (2022) and the calculated mixture Froude number as functions of mixture velocity for the three investigated liquid viscosities, V_{SL} = 0.29 ± 0.02 m/s, and pipe inclinations of (a) 15°, (b) 45°, and (c) 65°.

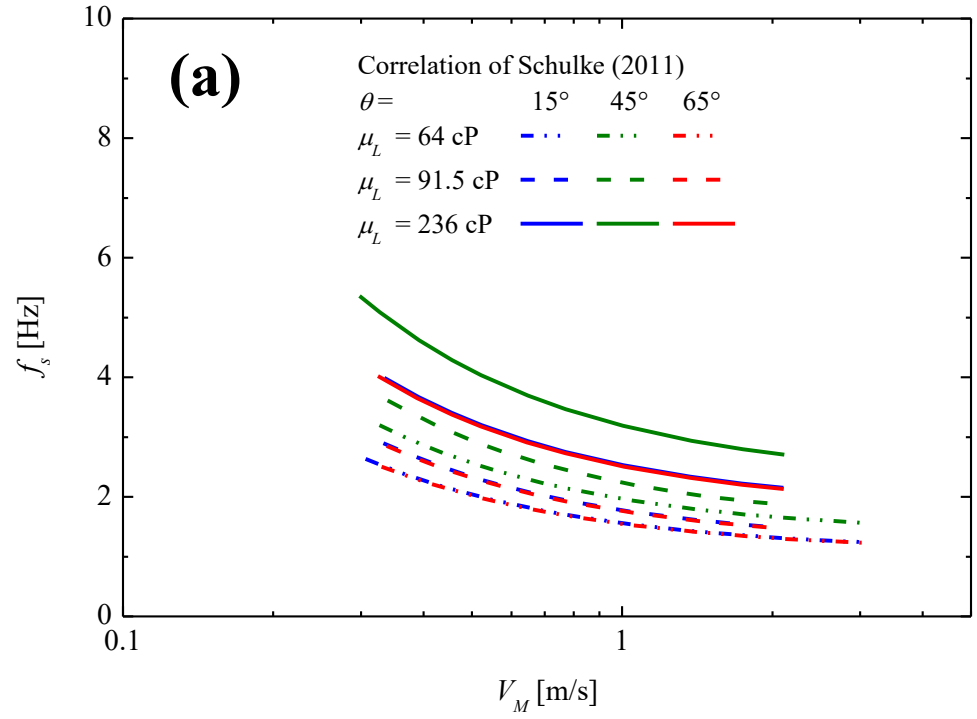
Based on the above force analysis, it appears that the mixture Froude number $\left(Fr_M = \sqrt{\frac{\rho_L}{\rho_L - \rho_G}} \frac{V_M}{\sqrt{gDcos\theta}}\right)$ based on the effective gravitational acceleration ($g\cos\theta$), appears to be the most appropriate dimensionless parameter for characterizing the transition between gravity- and inertia-dominated flow regimes. Figure 4 suggests that the transition between gravity-dominated and inertia-dominated regimes occurs at $Fr_M \approx 1.2$, where a change in the trend of the liquid viscosity effect on slug frequency can be noted.

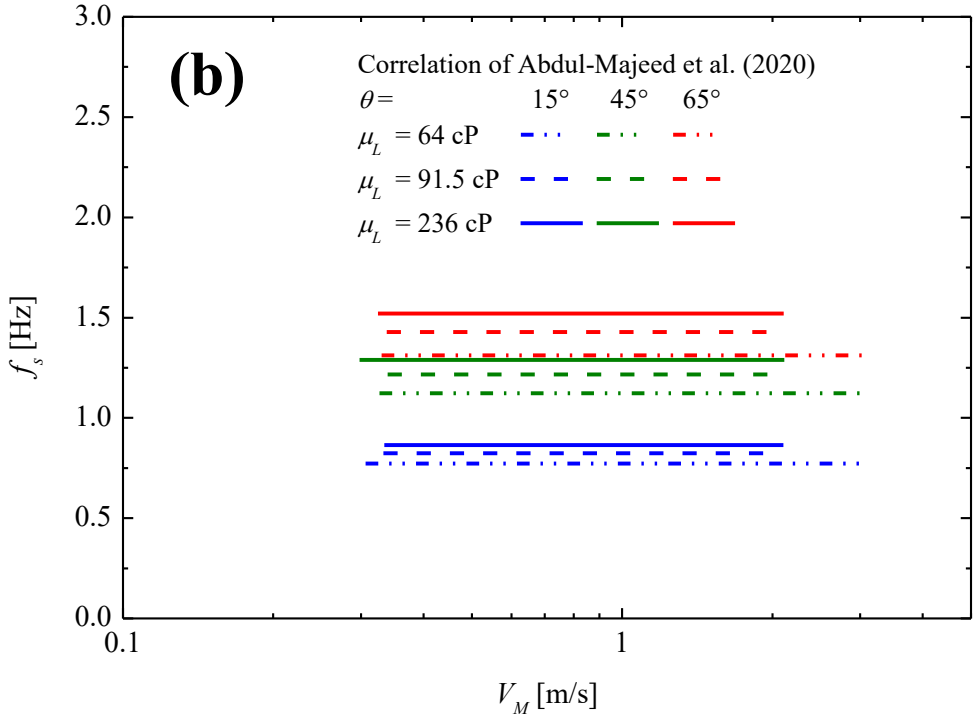
The reported findings confirm the importance of considering the mixture Froude number range when correlating slug frequency for high-viscosity liquids in inclined pipes. As shown in Fig. 5, existing slug frequency correlations that account for both liquid viscosity and pipe inclination (namely those proposed by Schulkes (2011), Abdul-Majeed et al. (2021), and Garcia et al. (2023), and summarized in Table 2) capture only inertia-dominated behavior. This limitation can be attributed to the restricted experimental databases used in the development of these models, particularly the limited number of data obtained in inclined pipes and for different liquid viscosities. In the case of Schulkes (2011), the predominance of low-viscosity liquid data explains the observed increase in slug frequency from 15° to 45°, followed by a decrease from 45° to 65°, as shown in Fig. 5a.

Table 2 Summary of existing slug frequency correlations accounting for both pipe inclination and liquid viscosity.

Authors and year	Correlation	Pipe diameter range* [mm]	Pipe inclination range* [°]	Liquid viscosity range [cP]
Schulkes (2011)	$St_M = \Psi(\lambda_L) * \Phi(Re_{SL}) * \Theta(\theta, Fr)$ $St_M = \frac{f_s D}{V_M}$ $\Psi(\lambda_L) = 0.016\lambda_L(2 + 3\lambda_L)$ $\Phi(Re_{SL}) = \begin{cases} 12.1 Re_{SL}^{-0.37} for\ Re_{SL} < 4000 \\ 1\ for\ Re_{SL} \geq 4000 \end{cases}$ $\Theta(\theta, Fr_{SL}) = \begin{cases} 1 + \frac{2}{Fr_{SL}} sgn(\theta)\sqrt{\theta}\ for \lvert\theta\rvert \leq 0.17 \\ \frac{1.8}{Fr_{SL}} * (0.6 + 2\theta - \theta^2) for \lvert\theta\rvert > 0.17 \end{cases}$ $\lambda_L = \frac{V_{SL}}{V_M}$ $Re_{SL} = \frac{\rho_L V_{SL} D}{\mu_L}$ $Fr_{SL} = \frac{V_{SL}}{\sqrt{gDcos\theta}}$	19-100	-1-80	1-589
Abdul-Majeed et al. (2020)	$f_S = 0.1867 \frac{V_{SL}^{0.8} \mu_L^{0.2}}{D^{1.2} \rho_L^{0.2}} \left(1 + sin(\theta)\right)^2 + 0.3561$	50.8	5-85	213
Garcia et al. (2023)	$St_M = \Psi\left(\lambda_L, Fr_{SL,\theta=0}\right)\Phi\left(Re_{SL}, Fr_{M,\theta=0}\right)\Theta(\theta)$ $\Psi\left(\lambda_L, Fr_{SL,\theta=0}\right) = 0.016\lambda_L(2 + 3\lambda_L)\left(0.80167 {Fr_{SL,\theta=0}}^{0.28195}\right)$ $\Phi\left(Re_L, Fr_{M,\theta=0}\right) = \begin{cases} 20 Re_L^{-0.388} & for\ Re_L < 2000 \\ 1 + 0.0017237 Fr_{M,\theta=0}^{2.68958} & for\ Re_L \geq 2000 \end{cases}$ $\Theta(\theta) = 1 + 2.059 sin^{2.103}(\theta)$ $Fr_{SL,\theta=0} = \frac{V_{SL}}{\sqrt{gD}}$ $Fr_{M,\theta=0} = \frac{V_M}{\sqrt{gD}}$	50.8-155.7	0-90	1-601

*refers to the datasets employed in the model development.


(a)
Correlation of Schulke (2011)
θ= 15° 45° 65°
μL = 64 cP
μL = 91.5 cP
μL = 236 cP
fs [Hz]
VM [m/s]
0
2
4
6
8
10
0.1
1


(b)
Correlation of Abdul-Majeed et al. (2020)
θ= 15° 45° 65°
μL = 64 cP
μL = 91.5 cP
μL = 236 cP
fs [Hz]
VM [m/s]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.1
1

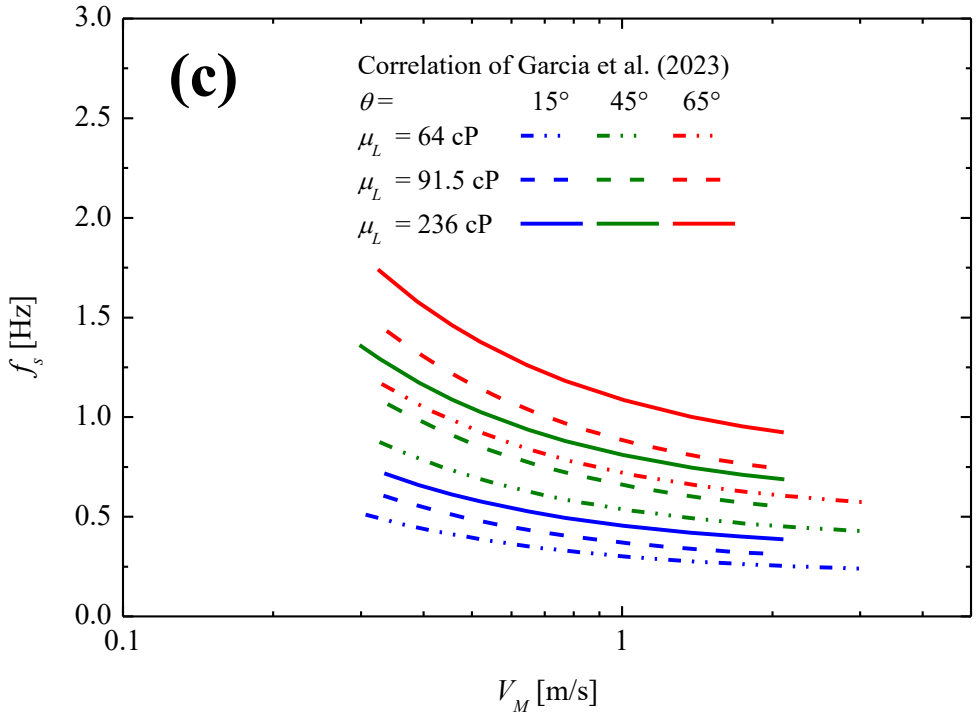


Fig. 5 Slug frequency calculated using the correlations of (a) Schulkes (2011), (b) Abdul-Majeed et al. (2021), and (c) Garcia et al. (2023) as a function of mixture velocity for pipe inclinations of 15°, 45° and 65° and V_{SL} = 0.29 ± 0.02 m/s, and for the three liquid viscosities investigated by Fayyaz (2022).

3. Concluding remarks and future works

This short communication re-analyzed the experimental data of Fayyaz (2022) to investigate the combined effects of pipe inclination and liquid viscosity on slug frequency in high-viscosity gas–liquid flows. The results show that, for a given liquid viscosity, slug frequency increases with pipe inclination. In contrast, the influence of liquid viscosity depends on whether the flow is gravity- or inertia-dominated, with an inversion of trends occurring at a mixture Froude number, based on the effective gravitational acceleration, of about 1.2. The present study also shows that existing slug frequency correlations developed for high-viscosity liquids in inclined pipes consider only inertia-dominated flow conditions.

Since the reported findings are based on data obtained using a single fluid system (air–silicone oil), one pipe diameter (67 mm), three pipe inclinations (15°, 45°, and 65°), and a limited liquid viscosity range (64–236 cP), further experiments under different operating conditions are needed to validate these results. The authors also encourage coupling slug frequency measurements with visualization of other flow parameters, particularly slug length and elongated bubble interface morphology. This approach would help improve understanding of the underlying physical mechanisms and allow for more accurate determination of the critical mixture Froude number associated with the transition from gravity-dominated to inertia-dominated flow.

These findings provide a clearer framework for improving slug frequency modeling in two-phase flows involving high-viscosity liquids.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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