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Practical aspects of multiphase slug frequency: An overview

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Abstract

Slug frequency, the number of liquid slugs passing through a point per unit of time, is an intrinsic parameter that is used to characterize multiphase slug flows in pipes. In this review we discuss practical aspects of slug frequency for industrial purposes from an examination of published literature and available experimental data. The review shows that slug frequency appears to play a key role in the modelling of intermittent flow using 1-D mechanistic slug models and 3-D computational fluid dynamics tools. In addition, various global parameters and phenomena used to design, optimize, and control industrial pipelines are directly impacted by slug frequency. This manuscript highlights the importance of slug frequency not only for petroleum engineering but also for chemical, nuclear, and mechanical engineering.

KEYWORDS
multiphase flow, slug flow, slug frequency

1 | INTRODUCTION

The simultaneous flow of liquid and gas phases in pipe systems, commonly referred to as gas–liquid two-phase flow, is found in industrial applications such as petroleum and oil production systems, nuclear power plants, heat exchangers, and chemical and biochemical processes.[1–5] According to AlSaif and Al-Sarkhi,[6] gas–liquid two-phase flow is involved in four fields of engineering, that is, petroleum, chemical, nuclear, and mechanical engineering. Slug flow refers to a situation in which two phases are distributed as two structures (elongated bubble and liquid slug) that flow alternately, forming a slug unit cell.[7] A sketch of slug unit highlighting the more important slug parameters is depicted in Figure 1. These parameters are the slug length (L_L), the elongated bubble length (L_G), the slug unit cell length (L_T), the slug liquid holdup (H_{ls}), and the elongated bubble liquid holdup (H_{leb}). These latter parameters refer to the liquid holdup in the liquid slug and elongated bubble regions, respectively. This flow configuration is also present in gas–liquid–liquid and gas–liquid–solid three-phase flows.

This flow regime has unwanted consequences in industrial applications. According to Hill and Wood,[8] Havre et al.,[9] Abdullahi,[10] Arabi,[11] and Arabi et al.,[12] these include:

- Liquid overflow and high pressure in upstream separators,
- Shutdowns,
- Poor oil/water separation,

Abbreviations: CFD, computational fluid dynamics; CMFD, computational multiphase flow dynamics; DNS, direct numerical simulation; FIV, flow-induced vibration; FSI, fluid–structure interaction; GLCC, gas–liquid cylindrical cyclone; ID, inner diameter; LES, large eddy simulation; RANS, Reynolds-averaged Navier–Stokes.

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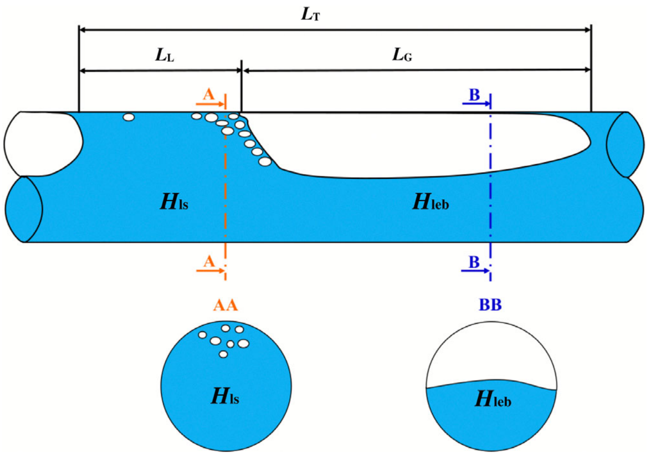

FIGURE 1 Sketch of slug unit showing the most important slug parameters. Flow direction: From left to right.

- Overload on gas compressors,
- Amplification of corrosion–erosion phenomena,
- Destruction of the pipeline protective inhibitor film,
- Mechanical damage in pipeline connections and supports,
- Large pressure drops,
- Instability in the heat and mass transfer processes,
- Unwanted flaring, and
- Difficulty for the flowmeters to correctly operate.

On the other hand, slug flow is preferred in several chemical engineering applications. Indeed, the high liquid velocities characterizing this flow pattern cause a transport of larger liquid quantities as well as very high convective heat and mass transfer coefficients, which enhances the heat and mass transfer efficiencies.[13] The increasing of heat and mass transfer is also due to the large gas–liquid interfacial area.[14]

Slug frequency (f_s), that is, the number of liquid slugs passing at one axial position of the pipe per unit of time, is a parameter used to characterize slug flow. This parameter has been widely studied in the literature mainly for petroleum and gas applications, where several theoretical and empirical models have been proposed to predict it. In this last decade, the characteristics and implications of the slug frequency has been reported in review papers on slug flow[14,15] as well as in the studies of Al-Safran,[16] Arabi et al.,[17,18] Sassi et al.,[19] and Cao et al.[20] These papers presented notably the influencing parameters and the existing predictive models, and discussed the difficulty involved in correctly predicting and satisfactorily measuring this parameter.

One of the preliminary questions that can arise in discussing slug frequency is why it is important to study it, including in particular, its practical aspects. This question was not discussed in much detail in the aforementioned papers as well as in the previous ones.[21,22] Indeed, these references only mention that slug frequency is used as input parameter of the slug models and that it is related to serious operational problems including severe pipe corrosion. The present review aims to fill the pointed-out lack in the literature related to slug frequency through an analysis and discussion of their practical aspects illustrated in Figure 2. Specifically, we analyze the following:

1. The role slug frequency can play in the modelling of intermittent flow using 1-D mechanistic slug models and 3-D computational fluid dynamics (CFD); and
2. The impact of slug frequency on several parameters or phenomena (i.e., pressure drops, heat transfer, flow assurance issues, flow-induced vibration, and the design and optimization of facilities and processes) related to the design and optimization of industrial pipelines and equipment.

This overview was conducted by critically reviewing current open literature and analyzing or re-examining publicly available data. In view of the importance of these seven aspects for petroleum, chemical, nuclear, and mechanical engineering, this review also aims to highlight the importance of slug frequency in these fields of engineering.

2 | 1-D MECHANISTIC SLUG MODELS

The design and operation of industrial equipment associated with multiphase flow requires accurate prediction and adequate control of parameters such as pressure drop, mass flow rates, and temperature in case of non-isothermal flow conditions. For some applications, such as chemical reactors, residence time is also a key variable.[13] Predicting these parameters is difficult—partly because of the relatively large number of flow variables involved compared to single-phase flows. For instance, in two-phase flows, up to seven dimensionless groups can be involved.[23] This number, obtained from dimensional analysis, can increase to 12 in the case of gas–liquid–liquid three-phase flows.[23] The complexity involved in predicting the design parameters may also be attributed to the unsteady nature of multiphase flows, especially in the case of slug flow, and to the presence of several flow regimes. The mechanistic approach, which is primarily based on the flow regimes,[24] is still the most reliable option for constructing the predictive models.[25,26] These models are based on 1-D momentum balance equations combined with the continuity equations for each phase.[27]

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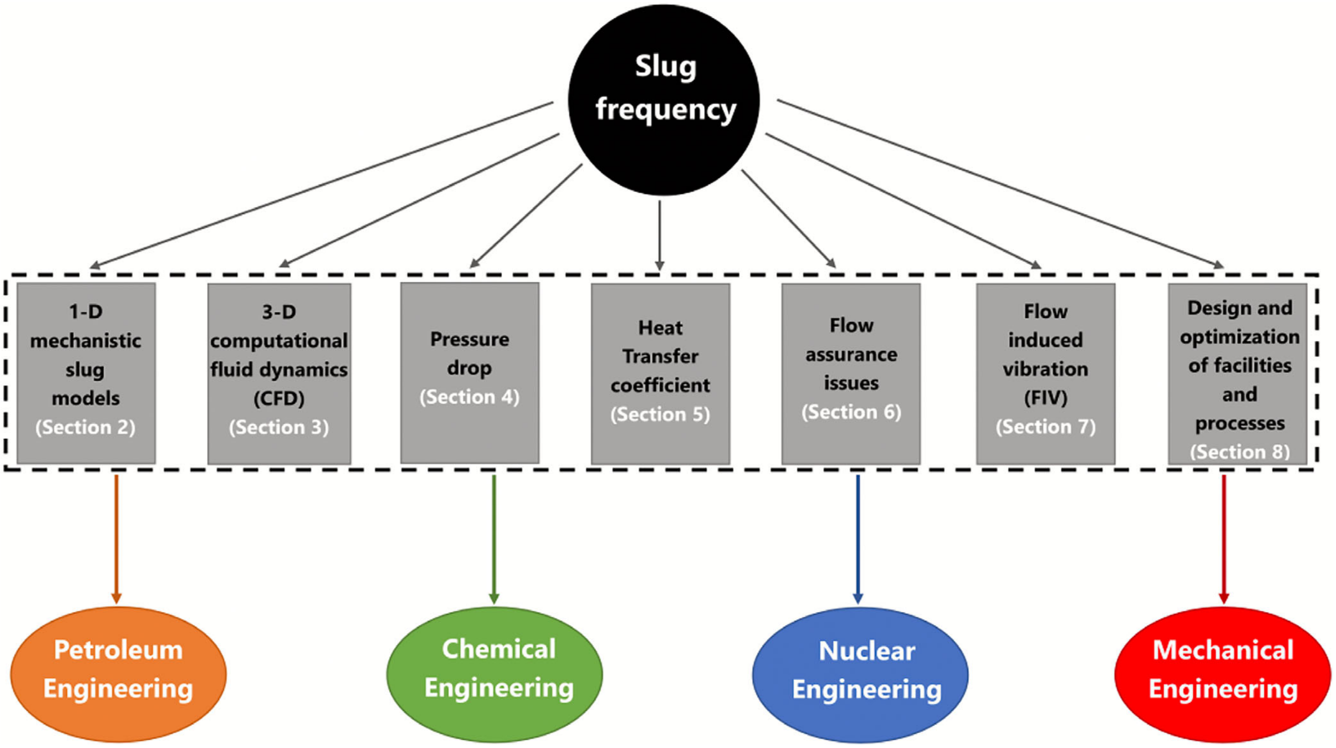

FIGURE 2 Tools and parameters impacted by slug frequency discussed in this review. These tools and parameters are directly related to petroleum, chemical, nuclear, and mechanical engineering.

Over the years, pioneering gas–liquid slug flow mechanistic models, such as those proposed by Dukler and Hubbard,[28] Nicholson et al.,[29] and Fernandes et al.,[30] led to the development of more advanced models for predicting the various hydrodynamic parameters.[31–40] Some of these models have also been extended to take into account the presence of a third phase,[41–43] heat transfer,[44–49] or flow assurance phenomena such as the formation and deposition of wax[50] or hydrates.[51–53] The challenges involved in modelling slug flow were discussed in detail by Fabre and Liné.[54] Modern slug models have directly benefited from advances in computer technology, which have led to the development of highly sophisticated transient approaches.[23] These models have generally been developed for petroleum applications,[4] but they have also been used in chemical engineering.[55,56]

Since there are more variables than equations, slug flow models, like all mechanistic models, require closure relations to initiate the calculation. The results provided by this kind of model are therefore sensitive to the input parameters.[8,57,58] For slug flow models, slug parameters such as liquid slug holdup, slug translational velocity (V_t), and slug length or slug frequency are generally used as input parameters.[59] Note that slug length and slug frequency are interrelated through the slug translational velocity.

Whether slug length or slug frequency should be used as an input parameter has been debated by the multiphase flow community. Taitel and Barnea[60] recommended using slug length because it is modelled better theoretically. Indeed, the theoretical works of Taitel et al.[61] and Barnea and Brauner[62] reported that, for a long pipe, slug length reaches a constant value and depends only on the pipe's diameter. For instance, the minimum stable slug lengths for vertical and horizontal pipes are equal to 16D and 32D, respectively, while Dukler et al.[63] reported a theoretical value of 20D. However, these values were questioned by Fréchou,[64] Scott et al.,[65] and Tronconi,[66] among others. In this paper, we would also like to attract the attention about the correlation for predicting slug length presented by Brill et al.[67] given by Equation (1).

$$\mathrm{Ln}(L_s) = 0.059\mathrm{Ln}\left(\frac{V_M}{0.3048}\right) + 5.445\left(\mathrm{Ln}\left(\frac{D}{0.0254}\right)\right)^{0.5} - 3.851 \tag{1}$$

where V_{M} is the mixture velocity which refers to the mean velocity of the gas–liquid mixture inside the pipe. It is computed as the sum of liquid and gas superficial velocities (Equation (2)).

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$$V_M = V_{SL} + V_{SG} \tag{2}$$

According to this correlation, the mixture velocity has an influence on the slug length only in the range of low values of V_M, as shown in Figure 3. Note that this correlation was developed from field data acquired at Prudhoe Bay Field (Alaska, USA) with a pipe 4.83 km long. The measurements were taken on a long horizontal section 45.72 m in length, where one can assume that the flow was fully developed.

Furthermore, in Figure 4A, we can see from the results obtained by Kokal,[68] who used three pipe diameters, that an increase in mixture velocity led to a decrease in slug length for the range of low mixture velocities. After a critical mixture velocity was reached, slug length became insensitive to mixture velocity. Similar behaviour can be observed in the work of Al-Safran et al.[69] Moreover, Cao et al.[70] reported that the transition between the two trends occurs at a critical gas superficial velocity of 1 m/s (Figure 4B). The change of slug length behaviour can be explained by the plug-to-slug flows transition.[71] Note that the experiments of Cao et al.[70] were conducted on a 1657 m horizontal pipeline. By analyzing the data obtained from the Kouba's thesis[72] with a 76.2 mm ID and 417.6 m horizontal pipe, Scott and Kouba[73] reported that the maximum slug length was measured in the region of low gas and liquid superficial velocities. The experimental/field findings reported by Brill et al.,[67] Kokal,[68] Scott and Kouba,[73] Al-Safran et al.,[69] and Cao et al.[70] clearly demonstrate that the theoretical assumption that slug length becomes independent of liquid and gas superficial velocities for long pipelines is not valid for the range of low gas superficial or mixture velocities.

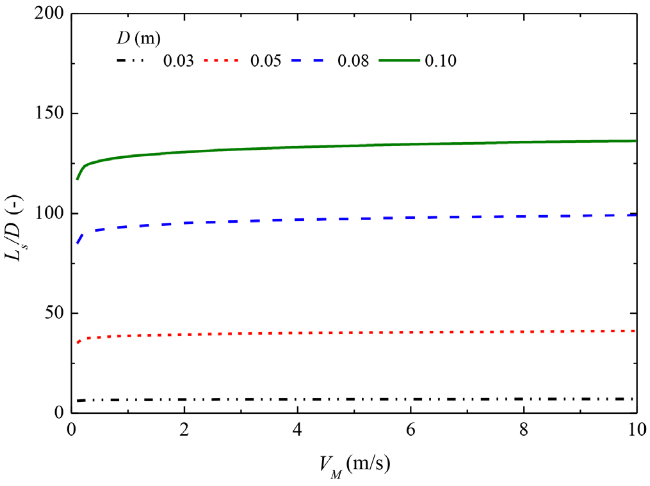

FIGURE 3 Influence of mixture velocity on the prediction of slug length given by the correlation of Brill et al.[67] for different pipe diameters.

Mohammadi et al.[58] used a genetic algorithm to obtain a set of closure relations for experimental (field) data that minimized the error between the measured and the predicted pressure gradient provided by the Tulsa Unified Fluid Flow Project (TUFFP) unified model.[35] For slug frequency and slug length, 12 models (five for slug length and seven for slug frequency) were studied. Results were in better agreement with the slug frequency model of Hill and Wood.[8] Note also that slug frequency was used as an input parameter for the development of recent slug length models of Al-Safran et al.[69] and Shaaban and Al-Safran.[74] As well as asserting that slug length exhibits greater randomness than slug frequency,[75,76] all findings above suggested there is no advantage to using slug length instead of frequency as an input parameter.

Regarding the effect of slug frequency on the performance of slug models and the reliability of output results, Gonçalves et al.[77] reported that the feasible domain of the model of Dukler and Hubbard[28] changes as the type of slug frequency correlation used as a closure relation changes. Feasible domain refers to the conditions, in terms of gas and liquid superficial velocities, when the mathematical operations are justified and the physical parameters are consistent with their definition. Bassani et al.[78] compared the effect of the slug frequency correlations selected on the slug and elongated bubble lengths obtained by their slug model. Indeed, large discrepancies (up to 40%) were obtained. On the other hand, no great difference was observed for the pressure drop and mixture heat transfer coefficient.

3 | 3-D COMPUTATIONAL FLUID DYNAMICS (CFD)

The progress made in recent decades regarding modern computer architectures and software engineering and understanding of the underlying physics of flow phenomena have directly benefited the field of CFD.[79] Extending CFD methods from single-phase flow to multiphase flow is still a complex task and, according to Yadigaroglu and Hewitt,[80] constitutes a step beyond. This complexity is notably due to the strong multiscale character of multiphase turbulence, which spans over eight to nine orders of magnitude.[81] Thus, only limited spatial and temporal resolution can be obtained for the case of turbulent multiphase flow.[81–84] When applied to multiphase flows, CFD is often referred to as computational multiphase flow dynamics (CMFD).[85] Compared to 1-D mechanistic models, CFD can predict detailed 3-dimensional physical phenomena,[86–88] which can be highly useful when experiments cannot be conducted.[79,89,90] Thanks to its

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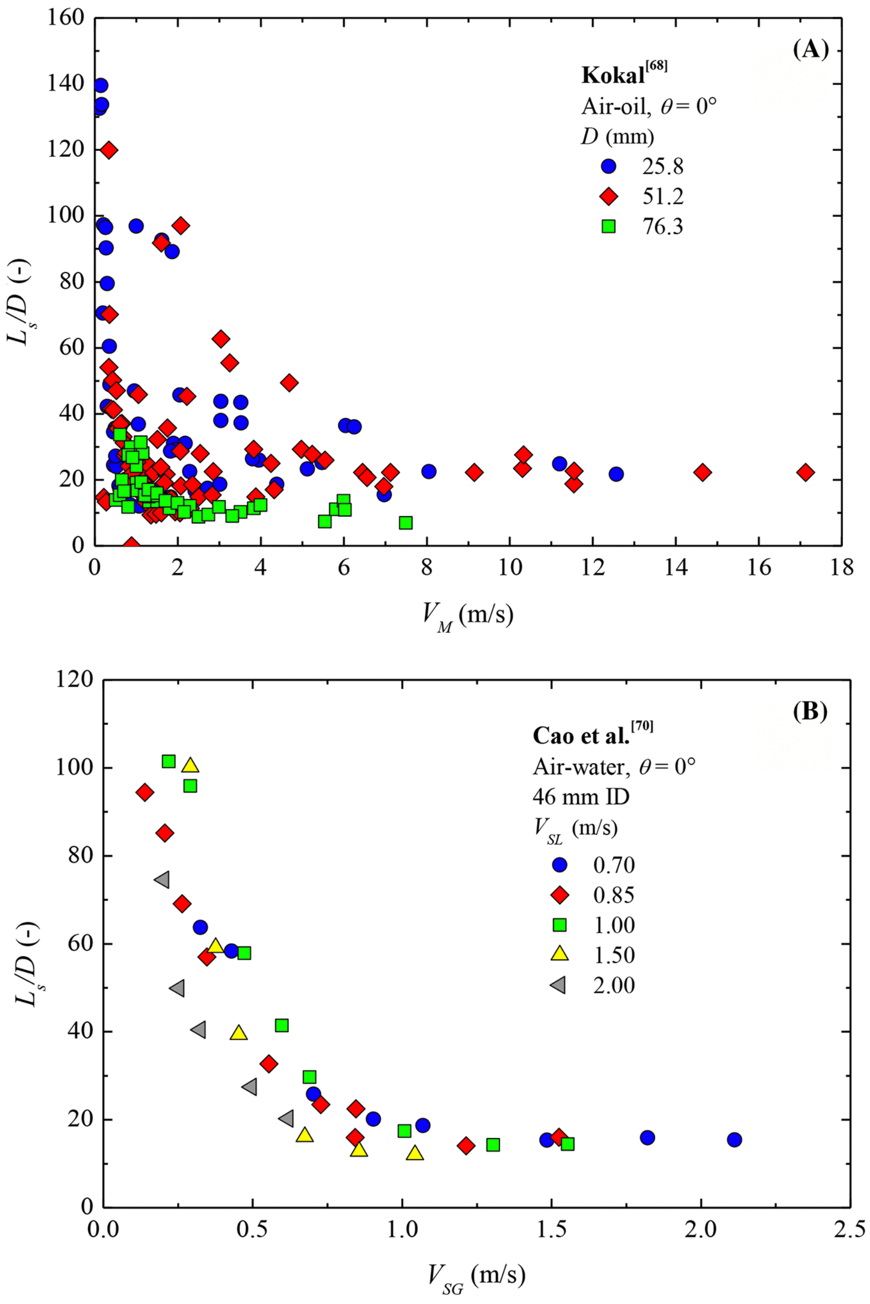

FIGURE 4 Evolution of mean slug length as a function of (A) the mixture velocity obtained by Kokal[68] and (B) the gas superficial velocity obtained by Cao et al.[70] The data are taken from Kokal[68] and Cao et al.[70]

capacity to simulate hydrodynamic heat and mass transfer as well as flow assurance phenomena, 3-D CFD is currently employed in a wide range of applications in, for example, the gas and oil industries, chemical and biochemical engineering, nuclear thermal hydraulics, and heat exchangers.[87,91–103] CFD can also be used to study flow-induced vibration (FIV) phenomena by coupling the fluid and solid domains.[104,105] The 3-D CFD simulations are generally coupled with Reynolds-averaged Navier–Stokes (RANS), large eddy simulation (LES), or direct numerical simulation (DNS) approaches.[92,97] The utilization of hybrid turbulent models based on RANS, LES, and DNS is an effective method to optimize between computational accuracy and efficiency.[88]

Slug frequency is a key parameter for the numerical 3-D simulation of intermittent flows. Indeed, it has already been used for the mesh independence study[106–108] and as a validation parameter.[109–111]

On the other hand, a time dependent inlet condition can be defined in order to reduce the computational cost and better describing the slug flow behaviour. This approach was initially proposed by Frank.[112] Afterwhile, Akhlaghi et al.[113] defined a simplified unit slug as inlet condition. This was done through a simplification of the slug flow by neglecting the small bubbles present inside

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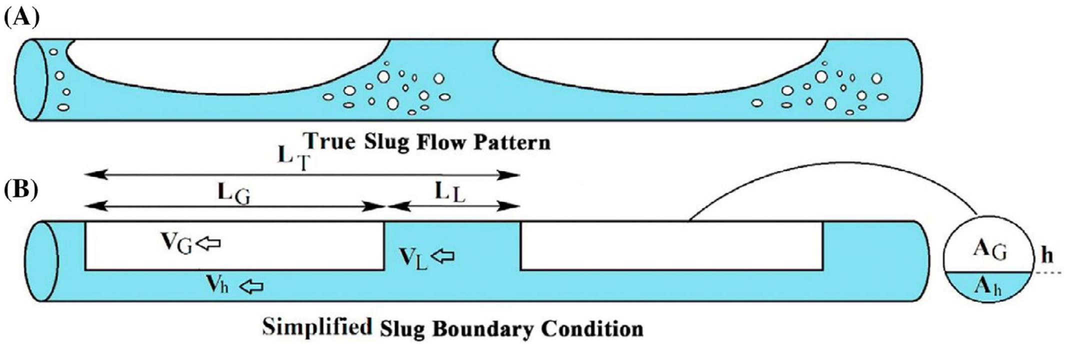

FIGURE 5 Scheme of (A) a slug unit and (B) a simplified slug unit considered by Akhlaghi et al.[113] Flow direction: From right to left. Reprinted from Journal of Natural Gas Science and Engineering, vol. 211, Mohammad Akhlaghi, Morteza Taherkhani, Nowrouz Mohammad Nouri, Study of intermittent flow characteristics experimentally and numerically in a horizontal pipeline, page 6, Copyright © 2020, with permission from Elsevier.

the liquid slugs and the curvature of the interfaces, as shown in Figure 5. The inlet parameters L_T, L_L, L_G, and V_L are extracted from the experiments, while A_G, A_h, h, V_h, and V_g are calculated from the mass conservation equations of each phase. The experimental value of the slug frequency is used to calculate the elongated bubble and liquid slug translational times. This strategy allowed them to obtain a significantly reduces in the size of the computational domain. On the other hand, Schmelter et al.[114] showed that the initial defined inlet frequency influences the obtained slug frequency. Thus, it has to be chosen carefully. This fact explains the necessity to accurately estimate the slug frequency.

4 | PRESSURE DROP

Accurately predicting pressure drop is extremely important in systems involving multiphase flows.[115] In the petroleum and gas industries, it is common to transport multiphase flow in pipelines from production sites to separation sites, which may be located several kilometres away.[67] Slug flow is often present in these pipelines due to the operating conditions and is known to be one of the flow regimes that generate the largest frictional pressure drops. Moreover, as it appears in Figure 6, the pressure drop time series exhibit fluctuations with a relatively large amplitude due to the intermittent passage of liquid slugs and elongated bubbles. According to Lin et al.,[116] Arabi et al.,[17] and Sassi et al.,[19] the peak number is directly related to slug frequency.

Using their own data and those of Kokal,[68] Arabi et al.[117] asserted that the mean pressure drop (dP/dL) is linearly related to slug frequency. The authors explained that the linear coefficient depends on the aeration within the liquid slugs. In Figure 7, we plot pressure drop as a function of both the slug frequency and the liquid slug holdup obtained by Kokal[68] using three pipe diameters. We can see that an increase in slug frequency produces an increase in pressure drop and that, via a reduction in slug liquid holdup, this effect becomes stronger as aeration increases within the liquid slugs.

5 | HEAT TRANSFER COEFFICIENT

Heat transfer in slug flow occurs notably in direct-contact heat exchangers (DCEs), some chemical engineering applications, and offshore petroleum pipelines. In the latter case, the difference between the temperatures inside and outside the production pipelines can be considerable (up to 71°C, according to Trevisan et al.[118]). This can lead to the formation and deposition of hydrate and wax on the pipe wall as well as to a change in pressure drop through the change in liquid viscosity.[45] It is therefore important to estimate the heat transfer coefficient (h_{TP}) in order to correctly predict temperature distribution along the pipeline. As stated recently by Holagh and Ahmed,[14] heat transfer phenomena in slug flow are less well understood and less often studied than the flow hydrodynamics.

The presence of elongated bubbles and liquid slugs implies that the heat transfer coefficient and wall temperatures are unsteady.[119–121] This complicates modelling of the heat transfer mechanism in relation to intermittent flow. Using air–water and air–oil mixtures, Dong et al.[122] found that heat transfer is enhanced as slug frequency increases (as shown in Figure 8). This is due to an increase in the number of liquid slugs and elongated bubbles that pass per unit of time, which leads to an increase in flow turbulence and a decrease in thermal boundary layer.[48] We can observe from Figure 8 that compared to

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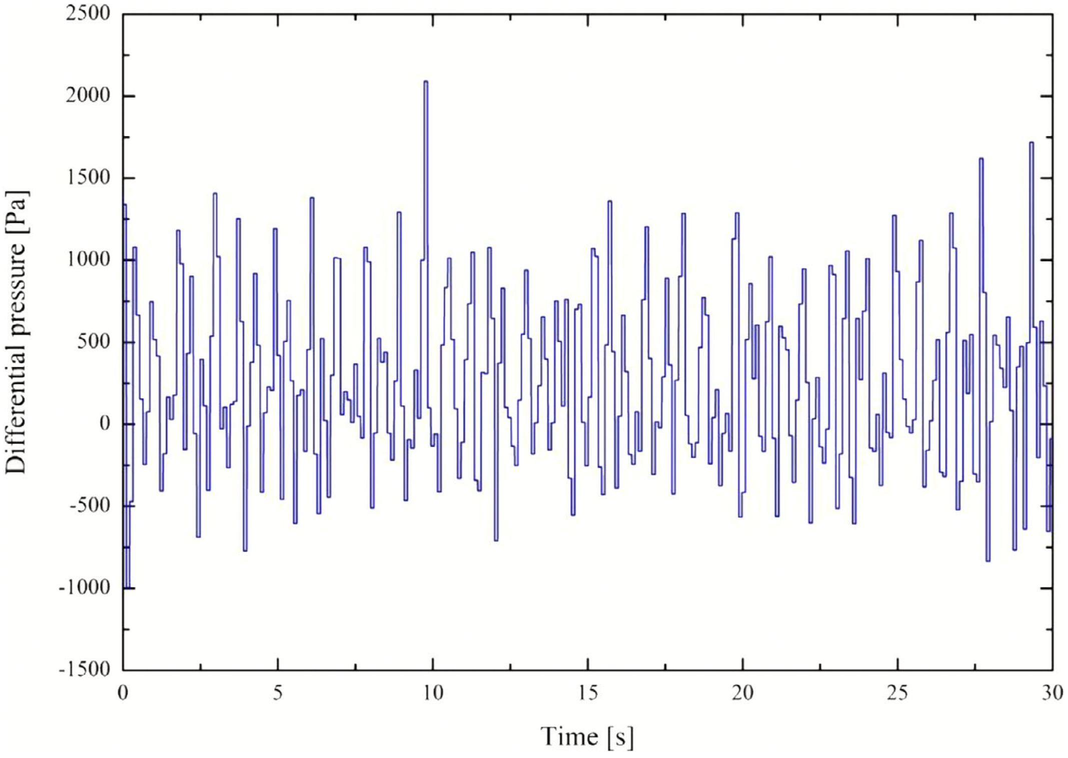

FIGURE 6 Example of time signals of the pressure drop between two points of the pipe obtained for the slug flow by Arabi et al.[17] (air–water mixture, $\theta = 0°$, 30 mm ID, $V_{SL} = 0.637$ m/s, and $V_{SG} = 1.572$ m/s). Reprinted from Chemical Engineering Science, vol. 211, A. Arabi, Y. Salhi, Y. Zenati, E-K. Si-Ahmed, (J). Legrand, On gas–liquid intermittent flow in a horizontal pipe: Influence of sub-regime on slug frequency, page 7, Copyright © 2019, with permission from Elsevier.

air–oil mixture, liquid superficial velocity has a lower influence on how the slug frequency impacts the heat transfer in the case of air–water. This can be explained by the higher values of density (992 and 852 kg/m^3), surface tension (69.3 and 28.7 mN/m), heat conductivity (0.635 and 0.126 W/m · K), and specific heat capacity (4.17 and 2.50 kJ/kg · K) as well as lower viscosity (0.653 and 58.8 mPa · s) of water compared to oil. Up to the authors' best current knowledge, this study is the only experimental one that investigates the relation between heat transfer coefficient and slug frequency.

6 | FLOW ASSURANCE ISSUES

In the petroleum industry, 'flow assurance' is defined according to Danielson[23] as '*any issue arising in the production system between the reservoir and the central facility that has the potential to impede production*'. The main flow assurance problems are hydrate blockage or deposition, wax deposition, asphaltene deposition, scale formation, sand transport, and corrosion, as well as various kinds of slugging (terrain or riser slugging, ramp-up slugs, and pigging/sphering slugs).[23,123] Given the financial impact of these issues,[124] scientific methods are used in flow assurance studies to optimize the design of systems and infrastructures in order to manage risk and optimize cost.[125] Since multiphase flows are associated with the vast majority of flow assurance problems,[126] it is important to understand multiphase flow phenomena correctly before tackling these issues.[23]

Slug flow can reduce the efficiency of the corrosion inhibitor film.[127] This phenomenon is caused by high shearing forces destroying the liquid boundary layer close to the pipe wall, thus complicating the formation of a stable inhibitor film.[128,129] The influence of slug frequency on corrosion rate has been studied by several research groups. The Institute for Corrosion and Multiphase Technology (Ohio University), for example, measured the corrosion rate for carbon dioxide–water two-phase and carbon dioxide–oil–water three-phase slug flows for various pipe inclinations.[130–132] By representing the measured corrosion rate as a function of slug frequency, the authors found that for each value of the liquid film Froude number (Fr_s) (given in Equation (3)), the corrosion rate increases approximatively linearly with the increase in slug frequency before reaching a constant value.

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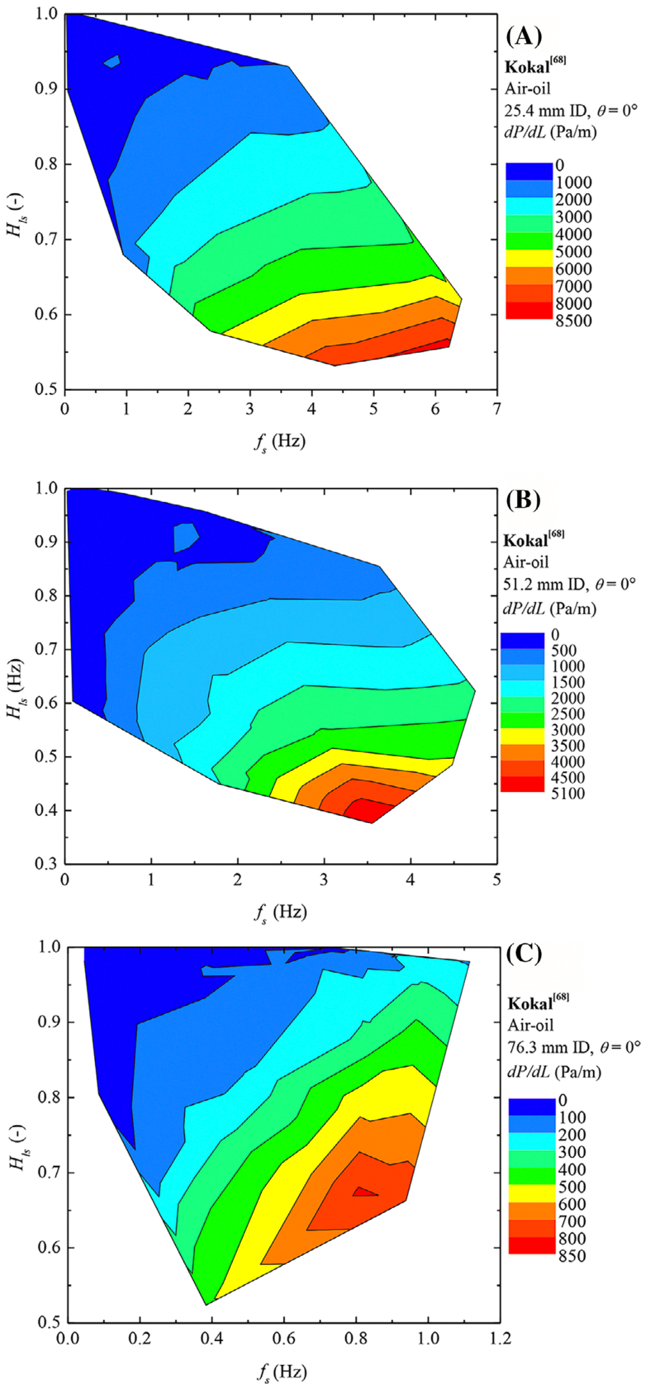

FIGURE 7 Isogram showing the simultaneous influence of slug frequency and liquid slug holdup on pressure drop. The data are taken from Kokal.[68]

$$Fr_{\mathrm{s}} = \frac{V_t - V_{\mathrm{lf}}}{\sqrt{g h_{\mathrm{L,eff}}}} \tag{3}$$

In Equation (3), V_t, V_{lf}, g, and $h_{\mathrm{L,eff}}$ are the translational velocity of the slug, the velocity of the liquid film ahead of the slug, the gravitational acceleration, and the effective height of the liquid film ahead of the slug, respectively.

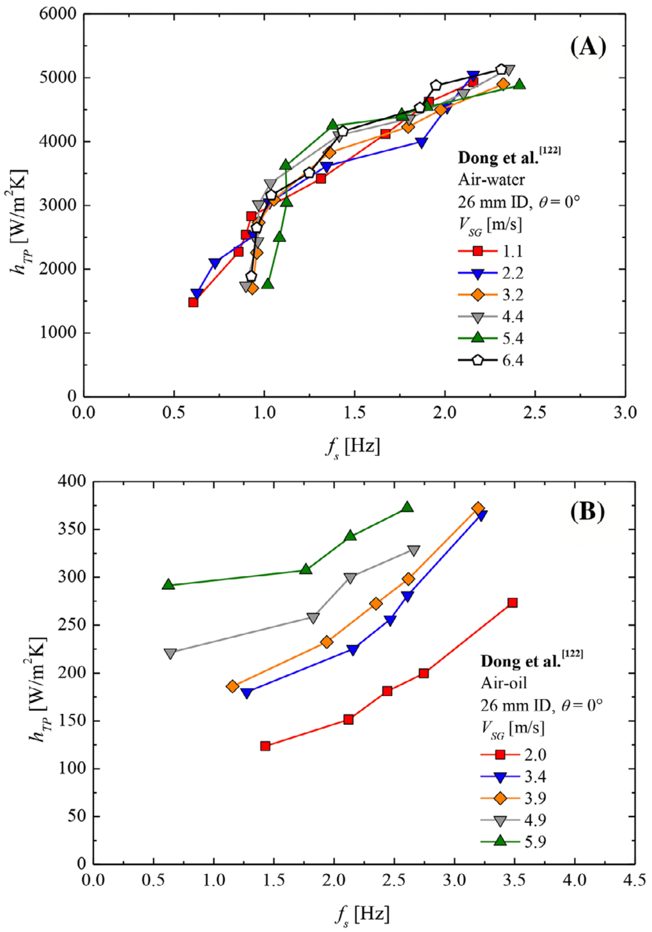

FIGURE 8 Effect of slug frequency on the heat transfer coefficient for (A) an air–water mixture and (B) an air–oil mixture. Reproduced from Dong et al.[122]

Examples of the results obtained are shown in Figure 9. Note that WC in Figure 8 refers to water cut, which is given as follows:

$$\mathrm{WC} = \frac{V_{\mathrm{SW}}}{V_{\mathrm{SL}}} = \frac{V_{\mathrm{SW}}}{V_{\mathrm{SW}} + V_{\mathrm{SO}}} \tag{4}$$

in the above equation, V_{SW} and V_{SO} stand for water and oil superficial velocities, respectively.

Based on this result, Jepson et al.[132] considered the slug frequency as input parameter in its predictive correlation of the corrosion rate. Villarreal et al.[133] found that an increase in slug frequency induces a decrease in corrosion rate (see Figure 9). They explained that the difference in trend between their study and that of Jepson et al.[132] was due to the range of Fr_{s}. The latter parameter is dependent on the amount of aeration within the liquid slugs, which, in turn, is correlated with V_{SG}. Villarreal et al.[133] pointed out that their study involved lower values of V_{SG} than that conducted by Jepson et al.[132] By analyzing this trend and data from

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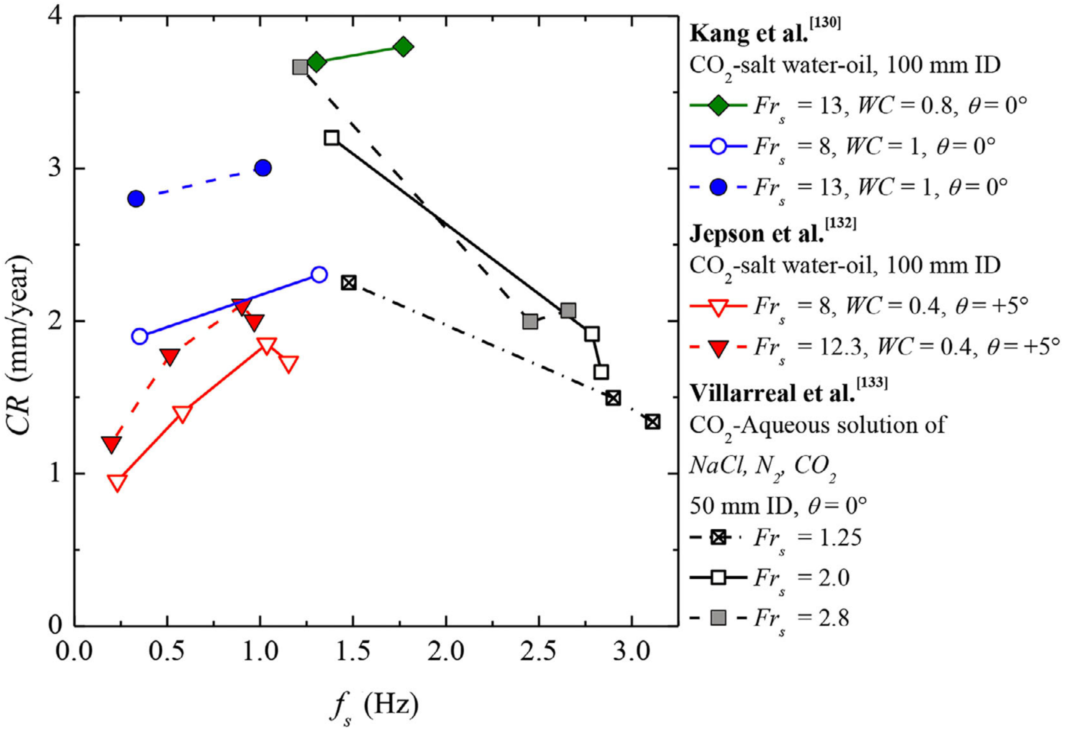

FIGURE 9 Effect of slug frequency on corrosion rate. The data are taken from Kang et al.,[130] Jepson et al.,[132] and Villarreal et al.[133]

Kang et al.[130] and Jepson et al.,[132] we find that the slug frequency generates an increase before a decrease in the corrosion rate. Further experiments to cover larger ranges of operating conditions could help to reach a more general conclusion. More recently, Thaker and Banerjee[134] explained that shear stress-induced erosion (SSIE) occurs because of frequent and large fluctuations in gas and liquid velocities and is therefore directly related to both slug frequency and slug translational velocity. They explained that this mechanism occurs for f_s >1.35 Hz and V_t > 1 m/s, though the justification for these critical values is still unknown.

Wax and asphaltene are high-molecular-weight compounds that lead to steadiness of oil in a dispersed state.[135] Deposition of wax along the wall of the pipe can lead to blockage of pipeline production, shutdown, and financial losses.[136,137] Wang et al.[138] recently suggested that wax deposition in the gas–liquid two-phase is not fully understood. As mentioned in the review presented in Sarica and Panacharoensawad,[139] the thickness and hardness of wax deposition depend on the flow regimes. For the horizontal configuration, the flow regime also influences the thickness distribution. According to Liu et al.,[140] the flow-regime-dependent predictive model of wax deposition thickness (TWD) developed by Matzain et al.[141] can be improved by considering the influence of slug frequency. This influence has rarely been studied in the literature. Gong et al.[142] investigated wax deposition for horizontal stratified and slug gas–oil two-phase flow. Different results were reported for both flow regimes. To explain the parameters influencing wax deposition for slug flow, the authors also studied slug frequency. Figure 10 shows their results for average wax-deposition thickness as a function of slug frequency for the three gas superficial velocities studied. Note that the authors plotted the results for the two parameters separately as a function of liquid superficial velocity but not as a function of slug frequency. Figure 10 suggests that, for low values of slug frequency, an increase in slug frequency induces an increase in wax-deposition thickness, while for large values it induces a decrease. Gong et al.[142] explained that an increase in slug frequency produces two opposite effects: (1) an increase in heat transfer coefficient (as explained in Section 5) and therefore an increase in radial temperature gradient, which enhances wax deposition, and (2) an increase in the average wall shear stress at the liquid deposit interface, which induces an increase in the intensity of shear stripping but does not promote wax deposition. From Figure 10, it appears that the first effect is stronger for low values of slug frequency but that the second effect is stronger for larger values (roughly 2.0 Hz).

The effect of slug frequency on sand transport in multiphase flow has not been widely studied. We can cite the work of Stevenson and Preston[143] who derived a model for predicting average particle velocity in slug flow which uses slug frequency as input parameter. Yan[144] observed that low slug frequencies are associated with a decrease in sand deposition for a horizontal pipe.

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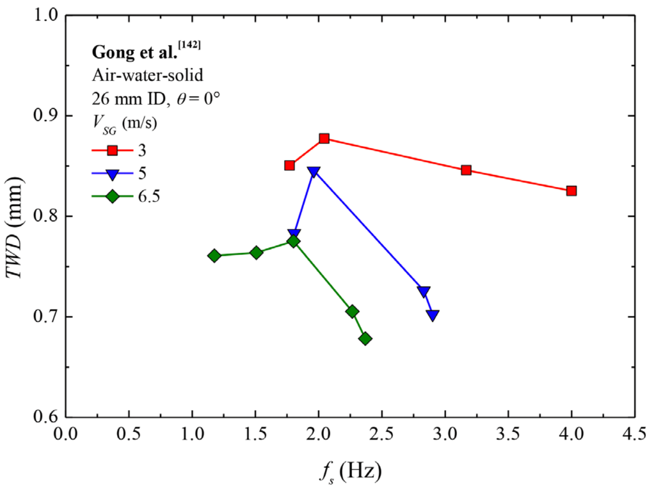

FIGURE 10 Effect of slug frequency on the average thickness of wax deposition. The data are taken from Gong et al.[142]

7 | FLOW-INDUCED VIBRATION (FIV)

According to Moussou et al.,[145] flow-induced vibration (FIV) refers to '*stationary flow inducing pipe vibration. The interaction normally is one-way (fluid → pipe)*'. They also specified that '*the stationary (or steady) flow is considered time-averaged: it includes turbulence and vorticity*'. This terminology is often used interchangeably with the concept of fluid–structure interaction (FSI). FIV is a major concern for piping systems, power plants, nuclear installations, and heat exchangers.[146–148] Indeed, vibrations of pipe components lead to fluctuating stresses, which cause pipe failures.[149] In their review of FIV induced by the two-phase flow, Miwa et al.[148] reported that the mechanisms of vibrations caused by two-phase flow and single-phase flow are quite different. This difference is mainly due to the complex interaction between the phases, the difference in physical properties of the flowing fluids, and the phase change that may occur during evaporation/condensation in the case of non-isothermal flow. According to JSME,[150] FIV in the case of two-phase flow is divided into three categories: (1) momentum fluctuation produced by the difference in density between the two phases; (2) thermal–hydraulic vibration associated with phase change occurring in flow involving heat transfer with substantial condensation or boiling phenomena; and (3) bubble-induced vibration caused by the dynamics of bubbles with different shapes and sizes. These three categories are coupled with the fluctuations of momentum, pressure, and void fraction that characterize the two-phase flow.

Intermittent flow is the most critical flow pattern regime for FIV because of its hydrodynamic characteristics.[151] According to Miwa et al.,[148] the two physical aspects of intermittent flow that should be considered for FIV purposes are: (1) the relationship between the values of the frequency of momentum/pressure fluctuations and the natural frequency of the pipe, and (2) collision of the liquid slugs onto a structural surface, which induces the transmission of a large excitation force. These two aspects are directly related to slug frequency, as we discuss below.

With regard to the first aspect, if the slug frequency and piping natural frequency collapse, the response of the structure increases linearly, thus causing the resonance problem.[148] The low values of slug frequency (of the order of a few Hz) increase the chances of this phenomenon occurring. Because of the negative consequences of resonance on the safety of industrial facilities,[152–154] piping systems are designed to have a higher natural frequency than two-phase flow systems frequency.[148] This can be achieved by correctly designing the piping system with appropriate pipe dimensions, supports, and materials. On the other hand, the results obtained by Mohmmed et al.[155] showed that, for a constant V_{SL}, an increase in slug frequency induces a linear decrease in mean stresses. An opposite trend was reported in the developing flow region. A correlation for predicting the mean value of stress using slug frequency as the input parameter was proposed by the above authors. More recently, Porter et al.[156] investigated the relationship between the slug parameters and the structural responses for horizontal pipes. Their study demonstrated that an increase in slug frequency causes an increase in pipe excitation through an augmentation of structural response and structural frequency. Porter et al.[157] reported the need to correctly estimate the slug parameters, especially slug frequency, to predict pipe fatigue life due to stresses caused by the slug flow. Because slug flow exhibits stochastic fluctuations, it induces several frequencies in the vibrations of flexible catenary risers used in offshore petroleum and natural gas production.[158]

With regard to the impact force of liquid slugs on the piping components, this occurs mainly in fittings such as T-junctions, bends, and orifices. According to Riverin and Pettigrew,[159] the impact frequency of liquid slugs on the piping components is directly related to slug frequency. Bamidele et al.[160,161] showed the positive relationship between vibration amplitude and slug frequency in flows through orifices and U-bends. By studying the impact of slug and pseudo-slug flow on horizontal bend, Garcia et al.[162] reported that their results for hydrodynamic force frequency matched those of slug and pseudo-slug frequencies collected upstream from the bend.

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8 | DESIGN AND OPTIMIZATION OF FACILITIES AND PROCESSES

As we reported in Sections 4–7, slug frequency is directly related to several parameters that must be taken into account when designing multiphase flow pipelines. Slug frequency must also be taken into account when designing petroleum downstream facilities such as slug catchers, horizontal gas–liquid separators, and gas–liquid cylindrical cyclone (GLCC) separators.[163] Indeed, the liquid slugs passing through this equipment produce sudden increase in liquid levels, which can affect separation efficiency and cause separator flooding. Lee et al.[164] showed that the entry of liquid slugs into a horizontal gas–liquid separator leads to severe turbulence that may generate sloshing. Sloshing impacts separator stability and generates an increase in the liquid that carries over into the gas outlet. Intuitively, we expect an increase in slug frequency to intensify these phenomena. For these reasons, it is important to accurately predict the input flow, including slug frequency, when designing gas–liquid separation devices.[165,166]

Slug mitigation in the pipeline and downstream facilities requires a reduction in the frequency and volume of the liquid slug.[167,168] Slug control methods are therefore oriented towards the manipulation of slug frequency. Haghighishahmirzadi[169] recently evaluated two slug mitigation techniques (gas-lifting and topside choking) for two pipeline-riser offshore systems (4.5 and 19.5 km in length) located at the Bøyla field in the North Sea by comparing slug frequencies. This highlights the huge importance of correctly estimating and predicting slug frequency.

In several wastewater, chemical, biochemical, food, and pharmaceutical processes, a gas phase is injected to generate a gas–liquid two-phase flow for improving the efficiency of processes as membrane filtration.[101,170–175] Hwang and Hsu[176] showed that for cross-flow microfiltration of yeast suspension, the best flux enhancement is achieved with slug flow. The same observation for filtration improvement performance was reported by Jianxin et al.[177] for the spiral wound membrane module. According to Mercier et al.[170] and Wu et al.,[56] this is explained by substantial variation in the wall shear stress (produced by the alternating passage of liquid slugs and Taylor bubbles) and the high level of turbulence in the wake region behind the Taylor bubble. Li et al.[178] reported that bubble frequency has a significant influence on the permeate flux of the sparged ultrafiltration. They explained that the increase in bubble frequency increases the passage of wakes behind the Taylor bubbles, which enhances the permeate flux. Mercier-Bonin et al.[179] asserted that the ability to control the frequency of passage of liquid slugs and Taylor bubbles can be extremely valuable for enhancing filtration performance.

On the other hand, mixing is used to reduce the inhomogeneity in several chemical engineering systems caused by gradients of phase volume fractions, viscosity, concentration, or temperature.[180] Static mixers are widely used for these purposes thanks to several advantages, including the absence of moving parts, easy maintenance, low residence time, and low energy consumption.[181] Recent investigations carried out by Hosni et al.[182] and Yu et al.[183] showed that both the mean and fluctuations of pressure drop are directly related to several parameters used to characterize the mixing phenomena generated by the passage of the multiphase flow through static mixers. As we discussed in Section 4, the mean and fluctuations of pressure drop are directly related to slug frequency. We can therefore estimate the direct impact of slug frequency on the characteristic mixing parameters.

9 | CONCLUSIONS

In this paper we have presented an overview of the practical aspects of multiphase slug frequency and discussed how slug frequency acts on the tools and parameters used to design and monitor industrial pipelines and facilities. The review was carried out by critically analyzing publicly available research works and examining available data. The outcomes of this survey are as follows:

- 1-D mechanistic slug models generally use slug length or slug frequency as the input parameter. The state-of-the art on slug length and, in particular, the difficulty involved in estimating it for some cases suggest that slug frequency could be a highly interesting alternative. The outputs given by these models are sensitive to slug frequency.
- Accurate estimation of slug frequency is important for the mesh independence study and reducing the computational costs of the numerical simulations carried out with 3-D CFD.
- The mean and fluctuations of pressure drop, the heat transfer coefficient, and FIV are directly related to slug frequency. Slug frequency is also a key parameter for designing and monitoring industrial pipelines, facilities, and processes.
- Slug frequency impacts directly on flow assurance issues such as corrosion rate, wax deposition, and sand transportation.

This review also enabled us to highlight the lack of studies and comprehension regarding the relationship between slug frequency and both corrosion rate and wax

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deposition. Further experiments are therefore strongly recommended in order to more thoroughly understand these aspects. Efforts should also be made to measure, estimate, and predict slug frequency more accurately. As well as stressing the importance of slug frequency in petroleum engineering, this overview has highlighted the importance of this parameter in the chemical, nuclear, and mechanical engineering fields.

NOMENCLATURE

A_G	cross section area occupied by the gas phase in the elongated bubble region (m^2)
A_h	cross section area occupied by the liquid phase in the elongated bubble region (m^2)
CR	corrosion rate ($m \cdot s^{-1}$)
D	pipe diameter (m)
dP/dL	pressure drop ($Pa \cdot m^{-1}$)
Fr_s	slug Froude number (–)
f_s	slug frequency (s^{-1})
g	gravitational acceleration ($m \cdot s^{-2}$)
h	liquid height in the elongated bubble region (m)
$h_{L,eff}$	effective height of the liquid film ahead of the slug (m)
H_{ls}	liquid slug holdup (–)
h_{TP}	two-phase heat transfer coefficient ($W \cdot m^{-2}\ K^{-1}$)
L_G	elongated bubble length (m)
L_L	liquid slug length (m)
L_s	slug length (m)
L_T	slug unit length (m)
TWD	average thickness of the wax deposition (m)
V_g	elongated bubble velocity ($m \cdot s^{-1}$)
V_h	liquid film velocity ($m \cdot s^{-1}$)
V_L	liquid slug velocity ($m \cdot s^{-1}$)
V_s	slug translational velocity ($m \cdot s^{-1}$)
V_{SG}	gas superficial velocity ($m \cdot s^{-1}$)
V_{SL}	liquid superficial velocity ($m \cdot s^{-1}$)
V_{SO}	oil superficial velocity ($m \cdot s^{-1}$)
V_{SW}	water superficial velocity ($m \cdot s^{-1}$)
V_M	mixture velocity ($m \cdot s^{-1}$)
WC	water cut (–)

Greek letters

θ	pipe inclination (°)

AUTHOR CONTRIBUTIONS

Abderraouf Arabi: Conceptualization; data curation; funding acquisition; methodology; visualization; writing – original draft; validation. **Ronaldo Luis Höhn:** Writing – review and editing. **Jordi Pallares:** Funding acquisition; writing – review and editing. **Youssef Stiriba:** Conceptualization; visualization; writing – review and editing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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