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CHARACTERIZATION OF SUBREGIMES IN TWO-PHASE SLUG FLOW

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Abstract—A new subdivision of the slug flow region, determined on the basis of different flow features, is presented. The characteristic features of each subregime have been shown by diffusional analysis of experimental time series relative to intermittent flow. It is found that, at low values of the mixture velocity, $V_m = j_L + j_G$, a subregime (elongated bubble with dispersed bubble, EDB) with structural characteristics different from those usually attributed to slug flow (slug, SL) exists. It is demonstrated that the application of slug flow models to the whole slug flow region may lead to errors in the estimation of flow parameters, especially in large-diameter pipes (industrial application). A modification of the existing models for the flow variables (slug translational velocity, slug length and slug void fraction) is proposed in the light of the results obtained and confirmed against present and existing data. Copyright © 1996 Elsevier Science Ltd.

Key Words: two-phase flow, slug flow, transitions, diffusional analysis, subregimes.

1. INTRODUCTION AND BACKGROUND

Given a horizontal pipeline with a gas and a liquid flowing together, different flow regimes may occur depending on the flow rate of the two individual phases. The superficial phase velocities (j_i for the ith phase), representing the phase volumetric flux along the axis of the pipe, are customarily used to classify the different flow regimes in form of a map (see Mandhane *et al.* 1974, for an example). The two phases may flow separately, as in annular and stratified flow, dispersed into one another, as in annular mist or bubbly flow, or alternatively, as in intermittent flow. The intermittent-flow region occupies a rather large portion of the map and is usually divided into plug flow, which occurs at lower superficial gas velocity, and slug flow. In this paper it will be shown that the region usually labeled as slug flow may be more conveniently divided into two subregions with different characteristics: slug flow and elongated bubble with dispersed bubble flow (EDB). EDB flow is more or less intermediate between plug and slug flow.

Slug flow is characterized by the stochastic alternation of large bubbles flowing over a thin liquid film and liquid slugs containing small gas bubbles (aerated slug). As pointed out by other researchers (Gregory *et al.* 1977; Kokal & Stanislav 1989), slug flow exhibits different features depending on the value of the superficial velocities. These features have not yet been fully characterized. Like the other two-phase flow regimes, slug flow is usually investigated by analysing experimental results and developing models to interpret data. In this work, experimental time series relative to characteristic properties of slug flow (pressure drop and liquid hold-up) are carefully examined by using diffusional analysis to disclose the intrinsic features of the flow regime in the first place. Existing correlations are then modified and applied to present and previous experimental data in order to characterize the two flow subregimes.

Several types of analysis have been applied with the aim of achieving an adequate characterization of multiphase flows. The objective of these analyses is to evaluate the short and long-range behavior of experimental time series (e.g. pressure fluctuation measurements, void fraction measurements). Saether *et al.* (1990) and Fan *et al.* (1990, 1993a) employed rescaled-range

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(R/S) analysis and fractional Brownian motion (fBm) characterization of time series to carry out a quantitative analysis of slug-length statistics in two-phase flow and pressure fluctuation in a fluidized bed. A similar approach was followed by Bernicot *et al.* (1990) to characterize slug/bubble regimes, by Drahos *et al.* (1993) to analyse pressure fluctuations in bubble columns, and by Franca *et al.* (1991) who, in addition to R/S techniques, discussed the possibility of determining the correlation dimension associated with pressure fluctuations in order to discriminate between deterministic and stochastic flows. In a recent paper, Giona *et al.* (1994b) demonstrated that diffusional analysis may be of great assistance in examining the characteristics of two-phase flow experimental time series and, in particular, that the quality of the information obtained could be higher than that provided by the R/S technique.

Flow regime differences in the slug flow region were observed in previous works by Kokal & Stanislav (1989), who noticed them as connected with the value of the void fraction in the slug body, α_s. They proposed to use such α_s to distinguish between slug flow and what they called elongated bubble with dispersed bubble flow (EDB). They suggested empirically that EDB flow occurs for $\alpha_s < 0.1$. Ruder & Hanratty (1990) studied the characteristics of the gas bubble in the whole region of intermittent flow using photographic techniques. They observed that at low gas superficial velocity the gas bubble is symmetrical, thus identifying plug flow, while at higher velocity the tail of the gas bubble appears as a hydraulic jump, characteristic of slug flow. They also observed that in the intermediate region between plug and slug flow the tail of the gas bubble assumes a *staircase* shape with two steps and that, in this intermediate region, the slug body is very little aerated in comparison with slug flow. Furthermore, Bontozoglu & Hanratty (1990) and Fan *et al.* (1993b) proposed different mechanisms at the base of slug flow initiation depending on the superficial gas velocity being above or below the threshold value $j_G = 3$ m/s. At all velocities it is the fastest growing wave which, occupying the whole pipe section, initiates slug flow. However, at low j_G short-wavelength gravity waves seem to control the interface shape and slug flow initiation, while at larger j_G capillary-gravity waves give rise to irregular waves which eventually generate liquid slugs.

A discontinuity in the behavior of the physical quantities characteristic of slug flow was also observed by Bendiksen (1984), who suggested characterizing the flow by the Froude number of the mixture, $Fr_m = V_m/\sqrt{gD}$ and found a discontinuity in the translational velocity, V_t (the average velocity at which the whole formed by the liquid slug and the following bubble moves), appearing at $Fr_m \simeq 3$ for air–water flow.

In this work, the application of diffusional analysis to intermittent flow regime data is presented in order to identify the two different subregimes existing in the slug flow region. The two subregimes are then characterized by analysing the behavior of void fraction, translational velocity and slug length and extending the analysis to data available from the literature.

2. EXPERIMENTAL DATA SET

The data presented in this work were obtained in the loop assembled at the Institute for Energy Technology (IFE) at Kjeller (Norway). The experimental rig operates at atmospheric pressure: an inclinable bench of 13 m in length supports the test section. The pipeline, made of transparent Perpex tubes with an inner diameter of 31.7 mm, was operated with air and light oil. The void fraction was measured by two capacitance probes, consisting of two ring electrodes mounted flush with the pipe wall, and one γ-densitometer. This test section containing the measuring devices is schematically represented in figure 1. It was located at a distance of 8.5 m from the inlet in order to reduce entrance disturbances and obtain a fully developed flow regime. This distance, equal to 265 diameters, is sufficient for the entrance disturbances and the developing slugs to be disregarded as shown by Nydal *et al.* (1992). The γ-densitometer was centered between the capacitance probes, which were placed 1.04 m apart. A detailed description of capacitance probes is given by Andreussi *et al.* (1988). The γ-densitometer is a one-shot-collimator γ ray developed at IFE which uses an Am^{243} source. The collimator is such that γ rays are distributed over the entire cross section and the sampling rate is 1000 Hz. For a more detailed description of the technique and of the collimator design, see Gardner *et al.* (1970).

Capacitance probes, developed at the University of Pisa, measure the capacitance of flowing

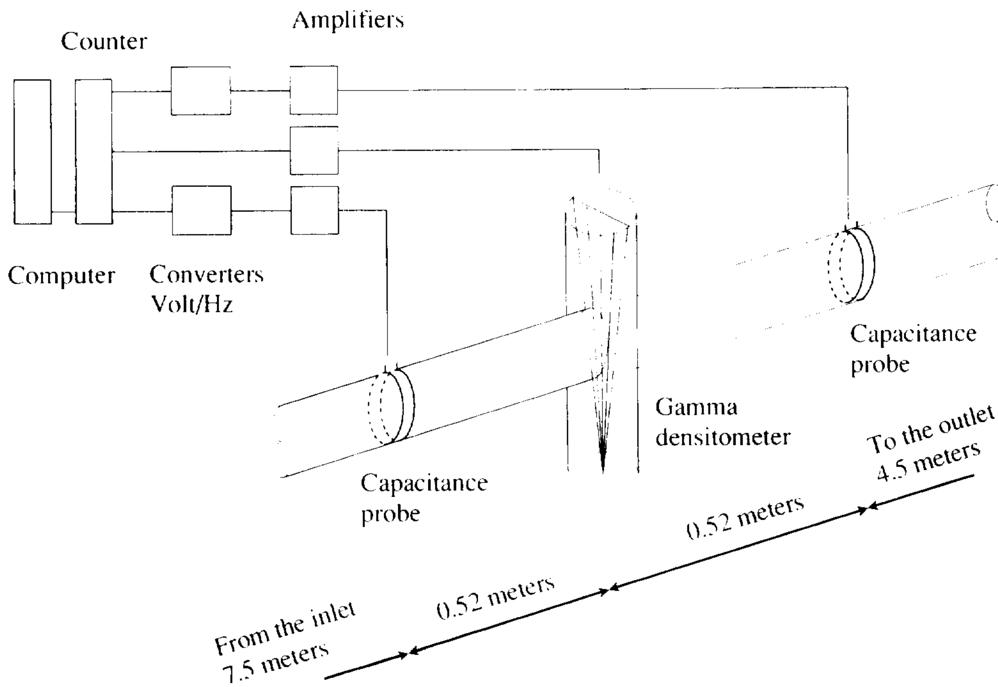

Figure 1. Configuration of gamma densitometer and conductance probes for the data-acquisition system.

mixtures between two conducting rings 0.1 diameters apart. For these instruments, as for the gamma densitometer, the sampling velocity is 1000 Hz.

The working fluids are air and light oil. The liquid phase was characterized by viscosity, $\mu = 1.6 \cdot 10^{-3}$ Ns/m^2, density, $\rho = 800$ kg/m^3 and surface tension, $\sigma = 0.027$ N/m.

Two different capacitance probes and one γ-densitometer were used. Diffusional analysis was applied to the all experimental signals and the results are comparable if analysis is restricted to the intermittent flow regime. The results presented in this paper were obtained by analysing γ-densitometer time traces.

3. DIFFUSIONAL ANALYSIS: IDENTIFICATION OF SLUG FLOW SUBREGIMES

3.1. *Diffusional analysis*

Diffusional analysis has already been applied in the study of statistical properties of chaotic flows (Geisel & Niertwetberg 1982; Grossmann & Fujisaka 1982; Prakash *et al.* 1991). A previous work (Giona *et al.* 1994b) shows that, when analysing time series with a persistent periodic/quasiperiodic oscillation mixed with random fluctuations (as is the case with slug flow), diffusional techniques furnish a better and more complete interpretation of the fluid dynamic conditions and can give a quantitative estimate of the characteristic parameters of the flow (e.g. slug frequency). A brief description of diffusional analysis is presented below.

Let $\{x_i\}$ be the time series to be analysed (wall pressure, pressure drop, density). From $\{x_i\}$ it is possible to generate a normalized time series $\{\xi_i\}$ with zero mean and unit variance:

$$\xi_i = (x_i - \langle x \rangle)/\sigma_x, \qquad [1]$$

where

$$\langle x \rangle = \frac{1}{N}\sum_{i=1}^{N} x_i, \quad \sigma_x^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x \rangle)^2 \qquad [2]$$

and N is the length of the series. A diffusional process on the real line driven additively by $\{\xi_i\}$ can be defined as

$$z_i = z_{i-1} + \xi_i \qquad [3]$$

with the initial condition, $z_0 = 0$. From the statistical theory of diffusive phenomena (Havlin & Ben-Avraham 1987), the most relevant quantity associated with the diffusion process [3] is the mean square displacement $R_z^2(n)$, defined as

$$R_z^2(n) = \langle (z_{k+n} - z_k)^2 \rangle = \frac{1}{N_{av}} \sum_{k=1}^{N_{av}} (z_{k+n} - z_k)^2, \qquad [4]$$

where the integer n stands for time and N_{av} is the number of averaging points. Obviously, if $\{\xi_i\}$ is a Brownian motion process then $R_z^2(n) \sim n$. Diffusional analysis based on the scaling of $R_z^2(n)$ is strongly related to the R/S method. In the case of fractional Brownian motion (fBm) we have

$$R_z^2(n) \sim n^{\beta} \quad \beta = 2H, \qquad [5]$$

and both diffusional and R/S analyses make it possible to estimate the Hurst exponent H.

The number of data points is $N = 8000$ and the sampling time $\Delta t = 10^{-3}$ s. Since the maximum value of n used in the evaluation of $R_z^2(n)$ is $n = 1000$. N_{av} appearing in [4] is 7000 data points.

Figure 2(a)–(c) shows the various steps involved in diffusional analysis, starting from the experimental normalized signal, $\{\xi_i\}$ [figure 2(a)], then obtaining the diffusive trajectory $\{z_i\}$ [figure 2(b)], and the corresponding mean square displacement $R_z^2(n)$ [figure 2(c)]. The data of figure 2 refer to slug flow regime, $j_L = 2.07$ m/s, $j_G = 2.58$ m/s. From figure 2(c), it is evident that the scaling of the mean square displacement exhibits a crossover behavior (which in the case of slug flow stems from the superposition of deterministic and stochastic fluctuations):

$$R_z^2(n) \sim \begin{cases} n^{\beta_1} & n < n_c \\ n^{\beta_2} & n \gg n_c \end{cases}, \qquad [6]$$

where the exponents β_1 and β_2 are related respectively to short-term and long-term properties of the signal $\{\xi_i\}$ and n_c is the crossover instant. In intermittent flow the value of the exponent β_1 is much higher than unity (in practical terms β_1 ranges between [1.5, 2.0]) and β_2 is close to zero (in practical terms β_2 ranges between [0.0, 0.6]).

The crossover instant n_c is related to the fundamental period of slug oscillation T_c by the equation, $T_c = 4n_c\Delta t$, where Δt is the sampling time. Of course, n_c depends on both gas and liquid superficial velocities. The values of T_c (or equivalently of the slug frequency) obtained from the estimate of the crossover instant n_c are consistent with the results obtained by spectral analysis (or correlation function analysis) and display an acceptable level of agreement with the model proposed by Tronconi (1976).

In this work we restrict our analysis to γ-densitometric traces. Diffusional analysis is performed without preprocessing or filtering the time series. In previous articles (Soldati *et al.* 1996; Giona *et al.* 1995a), we have shown that in slug and stratified flows the values of β_1, β_2 obtained by processing γ-densitometric traces are consistent within the range of experimental error ($\beta \pm 0.05$) with the corresponding values obtained from the analysis of pressure-drop and of capacitance probe traces. This indicates that the exponents β_1, β_2 are intrinsic properties of the flow regime and are independent of the choice of the physical quantity (density, pressure-drop, liquid hold-up) analysed.

Most of the literature on the fluctuation analysis of multiphase flow systems (Fan *et al.* 1990, 1993a; Drahos *et al.* 1993) applies rescaled-range analysis (R/S) to characterize the scaling properties of a fluctuating fluid-dynamic quantity in order to identify flow regimes. As discussed above, for all the stochastic processes, such as regular and fractional Brownian motions, which are characterized by a single scaling exponent, diffusional and R/S analysis provide comparable results [5]. In the case of mixed signals represented by the superposition of periodic/quasiperiodic oscillations and stochastic fluctuations, however, diffusional analysis provides clearer scaling results

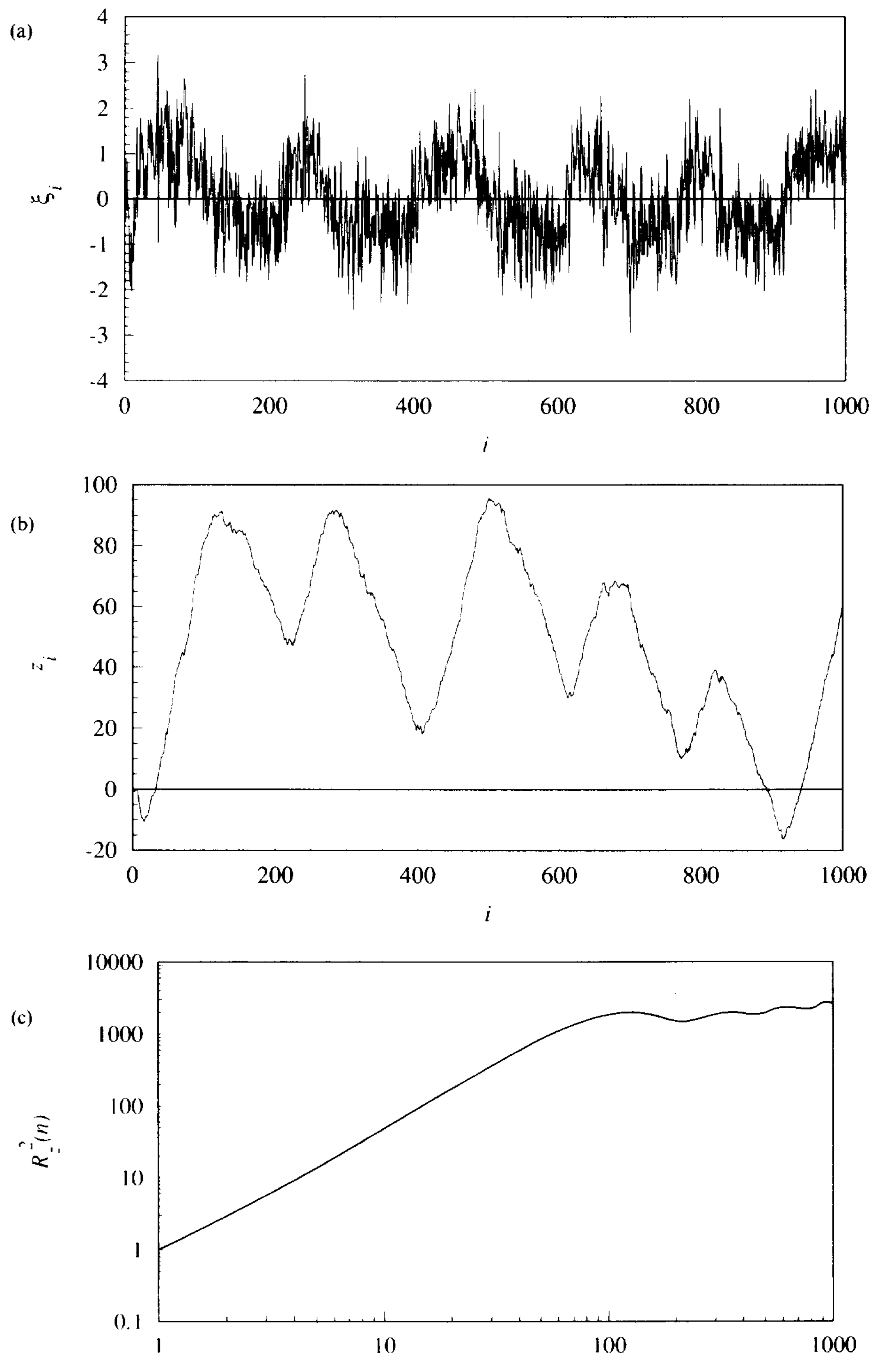

Figure 2. Representation of the fundamental quantities involved in the diffusional analysis. The time series refers to density fluctuations in intermittent regime, $j_L = 2.07$ m/s, $j_G = 2.58$ m/s recorded by the γ-densitometer. (a) Snapshot of the density time-series ξ_i vs i. $\Delta t = 10^{-3}$ s; (b) z_i vs i; (c) $R_z^2(n)$ vs n.

than R/S. The reason for this difference is to be sought in the cumulative nature of the main quantity involved in R/S analysis, the ratio between the maximum cumulative variation of the time series up to time n and the square root of the variance at time n, which is less sensitive than $R_z^2(n)$

to the composite fluctuation structure of mixed signals. All these aspects have been discussed in detail by Giona *et al.* (1994b) with regard both to model signals and to experimental traces.

3.2. *Identification of slug flow subregimes*

Figure 3 shows the behavior of the scaling exponents β_l in the intermittent regime as a function of the Froude number of the mixture for different values of the superficial liquid velocity. The following conclusions can be drawn.

The exponent β_l is monotonically decreasing with the superficial liquid velocity j_L. This behavior can be explained by considering that for low values of j_L the flow is more regular and consequently the exponent β_l approaches the value $\beta_l = 2$. This corresponds to almost pure deterministic oscillations. For high liquid velocity and low gas velocity, bubble/slug transition is observed. With the increase of j_L the flow becomes more complex, thus determining lower values of β_l.

At high liquid velocity and low gas velocity, bubble/slug transition is observed. Bubble flow corresponds to values of β_l in the range (0.9, 1.2). The transition region from bubble to intermittent region and from stratified to intermittent region obtained from the analysis of the mean square displacement $R_=^2(n)$ has been discussed by Giona *et al.* (1994a) and by Paglianti & Andreussi (1995).

The most interesting result that clearly emerges from figure 3 is the non-monotonic behavior of β_l with the Froude mixture number in the intermittent regime. For each j_L there exists a critical value of mixture velocity (or, more exactly, a small critical region) in which β_l attains its maximum value.

Physically, high values of $\beta_l \gg 1$ (and close to 2) correspond to highly coherent fluctuations. Indeed, a periodic signal is characterized by a scaling of $R_=^2(n)$ with $\beta_l = 2$.

The above observations point to the presence of a subregion within the intermittent flow region in which the slug motion appears to be highly coherent. Correspondingly, it can be hypothesized that the intermittent regime can be subdivided into two different subregimes separated by a transition zone located, as shown in figure 3, at a Froude number close to 7.5.

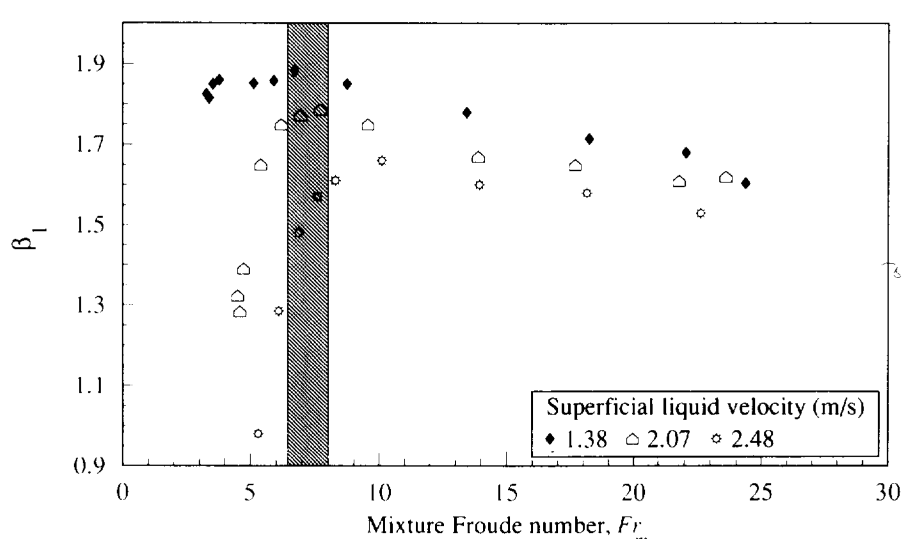

Figure 3. Behavior of the scaling exponent β_l, see [6], in slug regime vs Froude number for different values of the liquid velocity j_L. The local maximum in β_l is an indicator of high coherent fluctuations.

The results obtained by examining the behavior of β_1 are confirmed by relative diffusion analysis. The mean square displacement in relative diffusion $R_r^2(n)$ is defined as

$$R_r^2(n) = \frac{1}{\mathcal{N}(\epsilon)} \sum_{i=1}^{N} \sum_{j=i+1}^{N} (\xi_{i+n} - \xi_{j+n})^2 \eta(\epsilon - |\xi_i - \xi_j|)$$

$$\mathcal{N}(\epsilon) = \sum_{i=1}^{N} \sum_{j=i+1}^{N} \eta(\epsilon - |\xi_i - \xi_j|), \qquad [7]$$

where $\eta(\epsilon)$ is the step function, $\eta(x) = 1$ if $x \geqslant 0$, and $\eta(x) = 0$ if $x < 0$. Physically, the quantity $R_r^2(n)$ represents the mean square deviation in time of two points of the time series initially lying ϵ-close to each other. It can be shown that the initial value of the mean square displacement, $\alpha = R_r^2(n)|_{n=1}$, is related to the fraction f_n^2 of the power spectrum of the signal $\{\xi_i\}$ associated with random fluctuation (Giona *et al.* 1995b).

The parameter α is a monotonically increasing function of f_n^2. Figure 4 shows the value of α vs Froude mixture number in intermittent flow. The analysis of the behavior of α vs f_n^2 should be limited to ratios between the intensity of deterministic oscillations and of the stochastic fluctuations (conventionally called signal-to-noise ratio) equal to 0 dB (which corresponds to $\alpha \simeq 2.0$). For lower values of the signal-to-noise ratio this analysis does not provide an accurate estimate of f_n^2 (Giona *et al.* 1995b). This is the reason why only the data corresponding to lower liquid velocities ($j_L = 1.38$, 2.07 m/s) are given in this figure, since for higher j_L the intensity of stochastic contributions (below 0 dB) is such that it is not possible to infer any quantitative measure of f_n^2.

As in the case of figure 3, the parameter α shows a local minimum (i.e. the amount of stochastic fluctuation is minimum) for a value of the Froude number of the mixture which, within the range of experimental error, coincides with the value of the local maximum of β_1. A minimum in α means that the relative fraction of stochastic fluctuation f_n^2 also attains a local minimum. This result further supports the previous thesis on the existence of a region characterized by highly coherent fluctuations within the intermittent flow region.

4. CHARACTERIZATION OF SLUG FLOW SUBREGIMES

The division of slug flow regime into two different subregimes accounts for some previous observations (Nicholson *et al.* 1978; Kokal & Stanislav 1989) and makes it possible to give a satisfactory description of experimental trends of slug length, void fraction in the liquid slug and translational velocity.

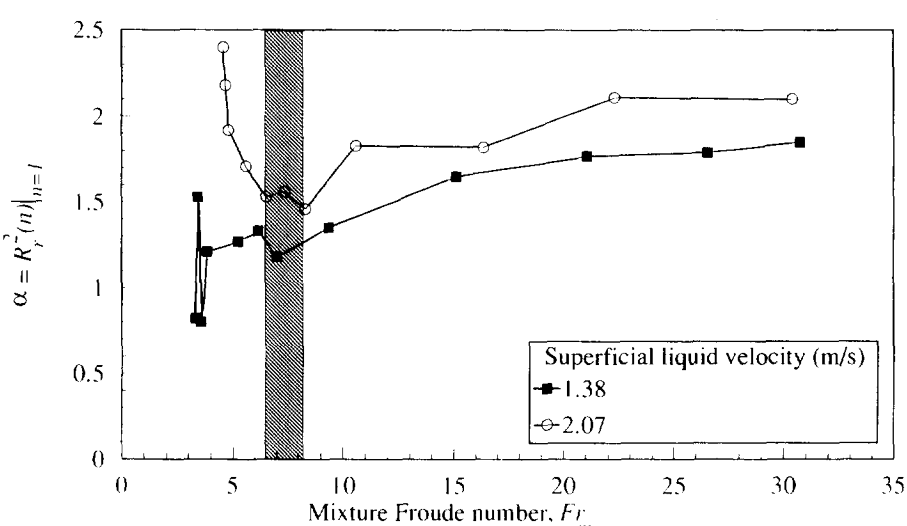

Figure 4. $\alpha = R_r^2(1)$ vs Froude number in intermittent flow. The local minimum in α indicates a lower intensity of stochastic fluctuations.

The previous section shows how the features of the EDB and slug flow subregimes can be highlighted by diffusional analysis. This section presents an appropriate derivation of a set of correlation for both EDB and slug regime.

In the slug flow model proposed by Andreussi et al. (1993), the main closure relations introduced are relative to the translational velocity of the slug, to the void fraction in the slug body, and to the slug length. In the following paragraphs, these relations are analysed in the light of the transition proposed.

4.1. Translational velocity

The translational velocity, V_t, is generally expressed as a function of the liquid velocity in the slug body in the following form:

$$V_t = C_0 V_{Ls} + V_0, \quad [8]$$

where V_{ls} is the average velocity of the liquid slug body, C_0 is a parameter, and V_0 depends on the pipe diameter. Different authors have used different values for C_0, ranging from 1 to 1.35 in a horizontal pipe. It may be observed that both C_0 and V_0 vary as the flow regime changes from EDB to slug regime. Bendiksen (1984) found a value of $Fr_{crit} \simeq 3$ for air–water systems. Following his approach, it is possible to write:

$$Fr_m > Fr_{crit} \rightarrow C_0 = 1.20; \quad V_0 = 0 \quad [9]$$

$$Fr_m < Fr_{crit} \rightarrow C_0 = 1.05; \quad V_0 = 0.54\sqrt{gD}. \quad [10]$$

Bendiksen (1984) suggested that the displacement of the nose of the gas bubble from the top of the channel towards the center could be responsible for this behavior. In figure 5, the effect of the Froude number of the mixture on C_0 is presented. The values for C_0 were determined by fitting the present experimental data with [9] and [10]. The behavior of C_0 may be separated into two regions: above $Fr_m = 6$, C_0 is fairly constant around the value $C_0 = 1.2$ and below $Fr_m = 6$, C_0 is fairly constant around 1.1. The present experiments show a threshold value between the two subregions of $Fr_m = 6$, which differs from the one proposed by Bendiksen (1984) ($Fr_m = 3$). This effect is caused by the use of different working fluids.

4.2. Slug length

Slug length (Maron et al. 1982; Dukler et al. 1985) or, equivalently, slug frequency (Tronconi 1990) is used as a second closure relationship. In the present case, slug length is chosen. Generally, in order to simplify the model, a constant slug length is assumed even if this assumption holds only

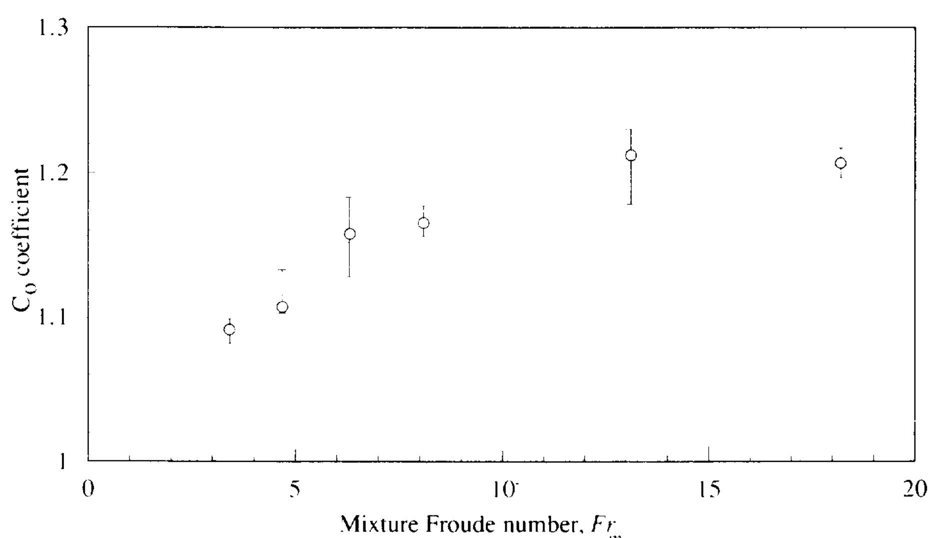

Figure 5. Measured bubble velocity and C_0 vs Froude number. Present experiments.

for high values of the gas velocity (Ferrè 1979). For lower values, slug length depends upon gas velocity. This effect is shown in figure 6, where data from Dukler & Hubbard (1975) relative to air and water are reported. This figure shows the existence of two different zones characterized by different values of slug length. In both zones, divided by a critical value of the Froude number of the mixture, slug length may be expressed as $L = k \cdot D$. For $Fr < Fr_{crit}$, $k = 15$, while for Froude numbers larger than Fr_{crit}, $k = 25$. It is important at this point to underline that the shorter slug length is a feature of the subregime itself and cannot be attributed to developing flow conditions (Nydal *et al.* 1992). This behavior deserves particular attention since the critical value of the Froude number is the same as that identified by Bendiksen in the analysis of translational velocity. This indicates that the threshold number identifies two zones characterized by different behavior of slug length and translational velocity. This observation can be useful also to improve the published models developed to compute slug length.

A model to calculate the slug length was first proposed by Maron *et al.* (1982). Later, Dukler *et al.* (1985) introduced a correction to account for viscous wall effects. Basically, the minimum stable slug length is the length at which the boundary layer in the liquid occupies the whole pipe section. Here, a further modification to that model is proposed to cover the whole region of slug and EDB flow. In the model by Dukler *et al.* (1985) the minimum stable slug length may be expressed as:

$$\left[(1-\Delta)+\frac{n}{n+2}(1-\xi_0)\left(1-2\Delta+\frac{n\Delta}{n+1}\right)-\frac{n}{n+1}(2-\xi_0)\right.$$
$$\left.\left(1-2\Delta+\frac{2n\Delta}{2n+1}\right)\right](1-\xi_0)\frac{d\Delta}{dX}+\left[\frac{n}{n+1}(2-\xi_0)\left(1-\Delta+\frac{n}{2n+1}\Delta\right)\right.$$
$$\left.-\frac{2n}{n+2}(1-\xi_0)\left(1-\Delta+\frac{n}{2(n+1)}\Delta\right)\right]\Delta\frac{d\xi_0}{dX}=\frac{2\tau_w}{\rho V_t^2}-\frac{\Delta(2-\Delta)}{2\rho V_t^2}\frac{dP}{dX} \quad [11]$$

where Δ is the dimensionless boundary layer thickness, n is the exponent in the general power law velocity profile, ξ_0 the dimensionless velocity of the inviscid core, dP/dX the pressure drop, τ_w the wall shear stress, and V_t the translational velocity of the slug. In the original analysis Dukler *et al.* (1985) overlooked the existence of EDB and, in horizontal pipes, computed the translational velocity as:

$$V_t = 1.225 V_m. \quad [12]$$

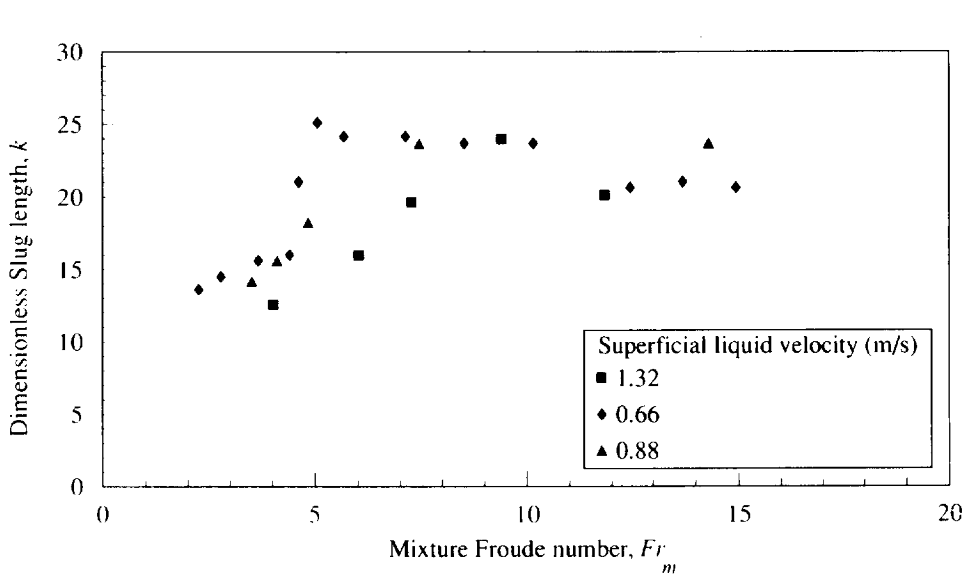

Figure 6. Average slug length vs Froude number. Data of Dukler & Hubbard (1975).

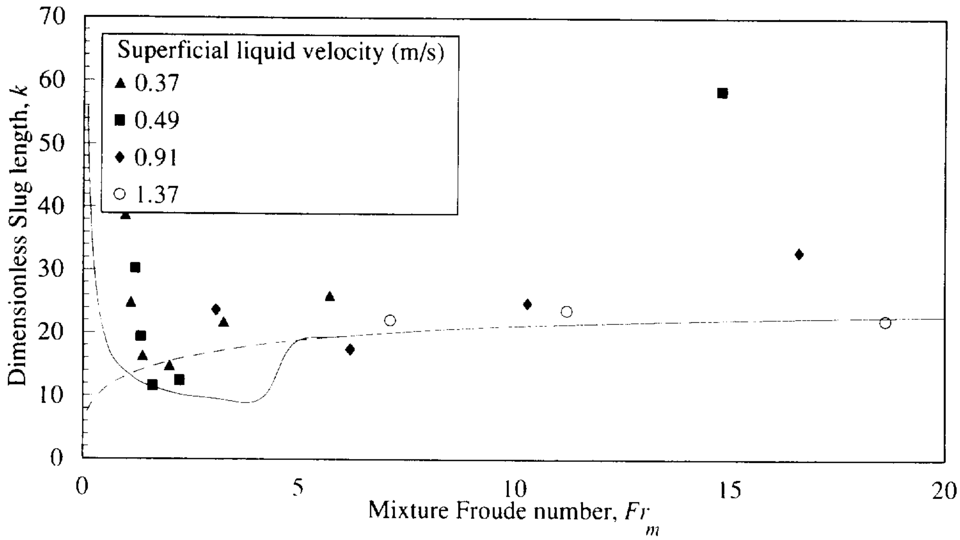

Figure 7. Average slug length vs Froude number. Comparison of the model suggested by Dukler *et al.* (1985) (dashed line), the present model (continuous line), and the experimental data of Nicholson *et al.* (1978).

Considering the two different subregimes, the two formulations of translational velocity may be adopted as presented in [10]. For $Fr > Fr_{crit}$, the relation proposed by Bendiksen (1984) is equivalent to the one used by Dukler *et al.* (1985). However, if $Fr < Fr_{crit}$, for low mixture velocity, a drift velocity caused by the difference in density appears also in horizontal pipes. This observation substantially modifies the computation of the minimum stable slug length in the region identified as EDB. Furthermore, with the model by Dukler *et al.* (1985) for mixture velocity approaching zero, the dimensionless length is zero. This result obviously clashes with visual observations. In figure 7 we plot the original model by Dukler *et al.* (1985), the model modified as just shown, and the experimental data obtained by Nicholson *et al.* (1978). Dukler *et al.* (1985) suggest that slug length should be calculated as $L_s = KL_{min}$ with $K = 2$ for water–air systems. However, since the data of Nicholson *et al.* (1978) are relative to an oil–air system, $K = 4$ was used for these data. The two models collapse into one another at high values of the Froude number. At low Froude numbers, the improved behavior of the modified model is noticeable. Figure 8 plots a comparison of the experimental data obtained in this work, the model by Dukler, and the modified model proposed in this work. The modified model furnishes better agreement with the data. This result

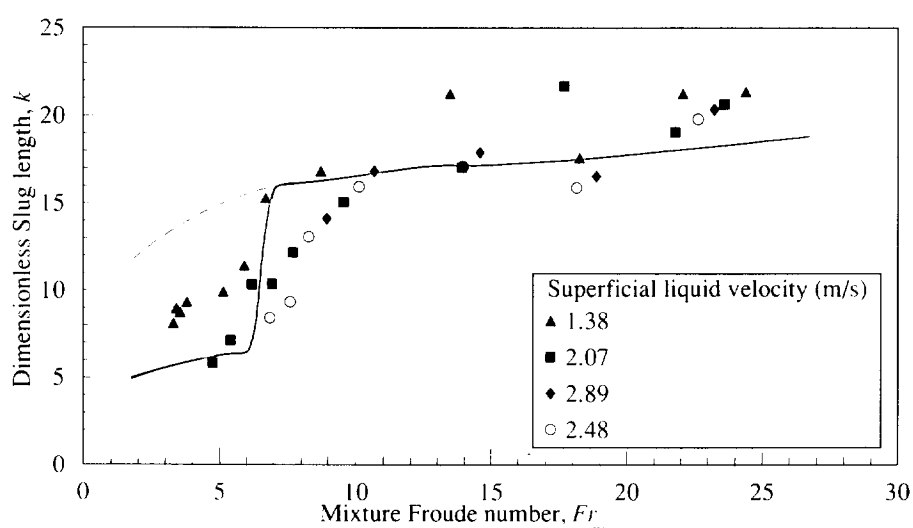

Figure 8. Average slug length vs Froude number. Comparison of the model suggested by Dukler *et al.* (1985) (dashed line), the present model (continuous line), and our experimental data.

is extremely important with regard to designing gas–liquid separators, which are usually present at the end of a two-phase flow pipeline. Neglecting the existence of EDB may lead to errors when computing the slug length and, consequently, to an unsuitable design of the gas–liquid separator.

4.3. *Void fraction*

The literature provides several relationships for calculation of the void fraction in the slug body (Hubbard 1965; Gregory *et al.* 1978; and Andreussi & Bendiksen 1989, among others). However, all of them are based on experiments in small-diameter piping. As shown by Jepson & Taylor (1993), such correlations underpredict the experimental data when applied to larger-diameter pipelines. Most experimental facilities employ small-diameter piping, but in industrial applications the pipe size is large. At larger diameters, therefore, for usual mixture velocities, the Froude number attains lower values and the flow regime is likely to be EDB. An adequate modeling of the void fraction of the slug body for the whole region would be advisable.

Andreussi & Bendiksen (1989) proposed a correlation to model the void fraction in the slug body. Their correlation is based on a material balance for the slug body and has been developed for the whole slug and EDB flow region. The correlation is as follows:

$$\alpha_s = \frac{V_{ls} - V_{Mf}}{\beta V_{ls} + V_{M0}}, \qquad [13]$$

where the functions β, V_{Mf} and V_{M0} are defined as:

$$\beta = \left[\left(1 + \frac{1}{C_1}\right) + \frac{1 - S_D}{C_1(C_0 - 1)}\right] \qquad [14]$$

$$V_{Mf} = \frac{(V'_{Mf} - V_0)}{C_0 - 1} \qquad [15]$$

$$V_{M0} = C_2 \frac{V_{G0}}{C_1(C_0 - 1)} + \frac{V_0}{C_0 - 1}\left(1 + \frac{1}{C_1}\right). \qquad [16]$$

In these equations S_D is a distribution slip ratio, V'_{Mf} represents the mixture velocity below which there is no production of small bubbles whereas V_{Mf} gives the real lower limit below which no bubbles can be present in the slug body. This limit has been identified as the transition between plug and slug regimes. C_1 and C_2 are two adjustable parameters, while C_0 and V_0 are the coefficients that make it possible to compute the translational velocity using [8]. It is interesting to observe that a discontinuity of the void fraction appears if the parameters C_1 and C_2 are defined neglecting the presence of the EDB region. This is shown in figure 9, where the complete relation by Andreussi & Bendiksen (1989) is plotted. In their work, Andreussi & Bendiksen (1989) suggested simplifying the complete relation by assuming $V_0 = 0$ and $C_0 = 1.2$, for the whole range. This is equivalent to neglecting the existence of the EDB subregime, which may be feasible for small pipelines but induces errors if the pipe diameter is large. The analysis of the [16] shows that also for correlations based on material balances, it is necessary to define some adjustable parameters (C_1 and C_2). If these parameters are optimized using experimental data obtained on small pipelines and neglecting the presence of EDB, a systematic error in the computation of the void fraction may be introduced in larger pipelines. This type of error, experimentally shown by Jepson & Taylor (1993), can arise because two pipelines with different diameters working at the same mixture velocity necessarily operate at different Froude numbers. This difference can induce a change of subregime. The different behavior of the void fraction in the two subregions can also be seen from the analysis of the experimental data obtained in this work, as plotted in figure 10. It is extremely important to underline that the Froude number at which the void fraction shows a discontinuity is the same as that at which translational slug velocity and slug length also show a discontinuity (see figures 5 and 8).

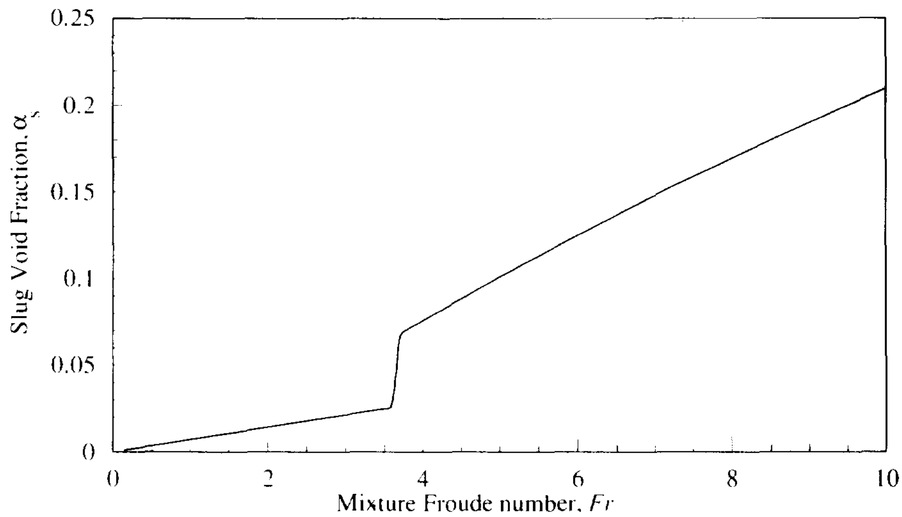

Figure 9. Average volumetric gas fraction in the liquid slug vs Froude number. Relation suggested by Andreussi & Bendiksen (1989)—air–water system $d = 5$ cm, horizontal pipe.

5. SUMMARY AND CONCLUSIONS

In two-phase flow, the experimental time series recording different flow variables may be analysed in several ways to clarify the intrinsic features of the flow regime. Diffusional analysis has been shown to supply information of higher quality if compared with standard statistical techniques or even R/S techniques. In particular, diffusional analysis allows detailed characterization of the short and long-term behavior of the signal, which vary with flow variables. In this work, diffusional analysis is employed to analyse time series from capacitance probes and γ-densitometer and identifies two different flow behaviors in the slug flow region.

The slug flow regime may be divided into two different subregimes, SL and EDB, characterized by liquid slugs which differ in length, void fraction and translational velocity.

A critical Froude number of the mixture (which appears to depend on the physical properties of the working fluids) at which transition occurs has been identified. With air and light oil, used in this paper as working fluids, this transition can be localized at a critical Froude number of 6–7.

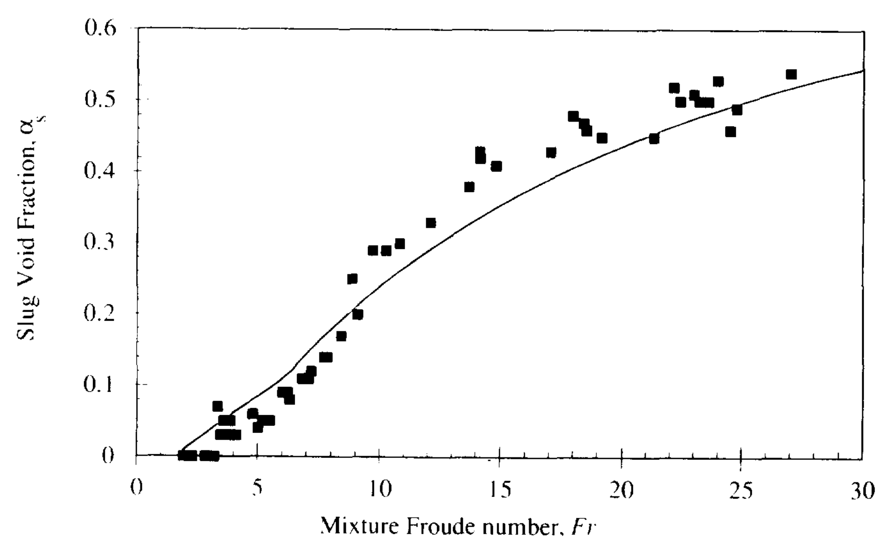

Figure 10. Average volumetric gas fraction in the liquid slug vs Froude number. Experimental data obtained in this work. Theoretical prediction obtained using $C_1 = 13.33$ and $C_2 = 114.5$. For the region $Fr_m > 6$, the values $S_D = 1$, $C_0 = 1.2$ and $V_0 = 0.0$ m/s were used. For the region $Fr_m < 6$, the values $S_D = C_0 = 1.109$, $V_0 = 0.298$ m/s were used.

Laboratory experimental data are usually obtained at Froude numbers at which SL regime occurs. However, these results are generally extrapolated to design pipelines of much larger diameter, which, at the usual operational velocities, are characterized by smaller Froude numbers. Therefore, the extrapolation from laboratory-assessed models to actual plants may be one source of error both for designing pipelines, as shown by Jepson & Taylor (1993), and for designing gas–liquid separators, because of inaccuracies and errors in predicting slug length.

On the basis of the subdivision of the slug flow region into SL and EDB flow, a modification to the original model proposed by Dukler *et al.* (1985) has been proposed and assessed against present and literature data. The modified model allows prediction of slug length in plug flow, EDB flow and slug flow regimes.

If we consider the whole region of intermittent flow, it is possible to conclude that three different subregimes coexist within its boundaries: plug flow, elongated bubbles with dispersed bubbles flow and slug flow, all of which are characterized by the presence of liquid slugs followed by gas bubbles. Plug flow occurs at low Froude numbers, and the liquid slug is not aerated. EDB flow occurs at intermediate Froude numbers and slug flow occurs at higher Froude numbers. They both have aerated liquid slugs, but differ substantially in the values of void fraction, slug length and translational velocity.

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