Validation of a physically-based model for slug initiation and evolution in hydrodynamic slug flow

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1 ABSTRACT

A mechanistic model has been developed for the rate of initiation of hydrodynamic slugs and has been coupled with improvements in the closure models for slug flow. The resulting Slug Tracking simulator is capable of predicting the slug frequency and slug length distribution, and their evolution along a long pipeline. The simulations are validated against published laboratory data, against data from the large scale Tiller loop, and against field data. For field cases, computed slug lengths and frequencies are typically within a factor of two of measured values; the frequencies compare favourably with the best available correlations.

2 INTRODUCTION

Slug flow is a commonly occurring phenomenon in hydrocarbon production pipelines and many other process applications. Slugs can form for a variety of reasons, including operational slugging, terrain and severe slugging, and hydrodynamic slugging. Dynamic multiphase flow simulators for long flowlines typically operate with a coarse grid (spacing of order 100 times the pipe diameter or more) and correspondingly large time steps. Nevertheless, they can generally capture phenomena associated with operational, terrain, and severe slugging, since the associated time and length scales are large. In contrast, hydrodynamic slugs arise from short length-scale phenomena, developing from large waves with steep gradients over length scales of the order of the pipe diameter.

Even though hydrodynamic slugs are initially quite short, the distribution of slug lengths can evolve substantially as the slugs propagate through long, undulating pipelines, sometimes leading to the formation of very long slugs, with associated problems at the receiving facilities. Furthermore hydrodynamic slugging can interact with terrain slugging in complex ways, leading to difficulties in predicting the onset and amplitude of large-scale flow instabilities. Additionally, all slugs, short or long, lead to unsteady loads on pipes and equipment, which can contribute to fatigue failure. For these reasons, it is very important to have accurate predictions of slug length and frequency.

Some progress has been made with “Slug Capturing” approaches, which attempt to resolve the two-fluid equations on a fine grid (1, 2, 3), 4, 5, 6). However, the underlying mathematical model is only conditionally well-posed, so that a mathematical solution may not exist, and the simulation results may not converge as the grid is refined. The model can be made well-posed by adding interfacial pressure or diffusion terms, but
these modify the short-lengthscale features of the flow in a way that may not be physically realistic. Furthermore, the application of these simulations is severely limited by the very large computational cost for simulation of full-scale pipeline systems over operational timescales.

The best approach for simulating real pipeline systems remains the Slug Tracking approach pioneered and developed by Bendiksen et al. (7), Straume et al. (8), Barnea and Taitel (9), Nydal and Bannerjee (10), and Larsen et al. (11), among others. Slug Tracking simulations can produce remarkably good results for cases of operational, terrain, and severe slugs, in which slug initiation is driven by large-scale variations of the flow. But methods for initiation of hydrodynamic slugs have been unsatisfactory.

The current status of slug initiation in Slug Tracking is essentially the same as reported by Shea et al. (12):

“In the Slug Tracking model, the slugs are initiated by programming logic rather than mechanistic methods. To allow the user to tune the Slug Tracking model, a dimensionless parameter known as the delay constant is included.”

In the present paper, we present a mechanistic model for the initiation of hydrodynamic slugs, and their subsequent evolution in Slug Tracking simulations. This is the outcome of a thorough evaluation and renewal of the Slug Tracking module in the OLGA” dynamic multiphase flow simulator.

A few results obtained using an early form of the model have been presented before (13), but this is the first time the model has been presented in detail. Since the model is new and prediction of the slug length is notoriously difficult, we set a modest target of predicting the slug length and/or slug frequency within a factor of two. At this level of accuracy, a model can provide significant value in design and operation of multiphase pipelines. The performance of the model is assessed by comparison with data from laboratory experiments, as well as data from the large-scale Tiller flow loop and several field cases. Although the overall performance of the new model still leaves room for improvement, it represents a considerable step forward over existing techniques, and computed slug frequencies compare favourably with the best available correlations: Shea et al. (12) for field data and Schukes (14) for laboratory data.

3 ONE-DIMENSIONAL SIMULATORS AND SLUG TRACKING

One-dimensional multi-fluid models are based on conservation laws for mass and momentum (15). The flow is represented in terms of mass fields for the continuous and dispersed phases: the fields used as a basis for the momentum equations may be different from those used for the mass equations. Typically the number of mass equations is greater than the number of momentum equations and the difference is made up by introducing drift flux models for some of the fields.

Most one-dimensional models, including the widely used commercial simulators, represent the conservation laws in discrete form on a fixed grid. For practical simulations, the grid size is typically quite coarse, with section lengths of order 100 times the pipe diameter or more. The coarse grid means that the properties of the flow are averaged over a relatively large volume, so the physics of the flow must be represented in terms of flow patterns, with a set of closure relationships specific to each flow pattern.

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The common gas-liquid flow patterns represent separated flow (stratified or annular), fully dispersed flow (bubbly flow), and intermittent flow (slug flow). In three-phase (gas-oil-water) flow, the flow patterns are subdivided to represent the degree of dispersion of the two liquids.

Separated flows are characterised by distinct layers in each of which one of the phases is continuous. The main closure relations are for the values of wall and interfacial friction. Each continuous layer may have one or more of the other phases dispersed in it and additional closures are typically required to characterise these (partial) dispersions. The key closures control the degree of dispersion, the drop or bubble sizes and drift velocities, and the apparent mixture viscosity.

Slug flows are composed of alternating regions of separated and dispersed flow, and so draw on most of the closure relations for these flow regimes. Additional closures are required to characterise the three-dimensional physics of the slug fronts and tails. The slug tail (or bubble nose) velocity is typically specified by a semi-mechanistic model based on physical arguments and tuned to experimental data (16). The intense mixing at the breaking slug front is modelled through a correlation for the rate of gas entrainment across the slug front (17, 18) or for the mean void in slug (19).

In standard simulations of slug flow on a coarse grid, individual slugs are not represented. Instead, the model represents a typical slug “unit cell” consisting of a slug zone with dispersed flow and a long bubble zone with separated flow. The flow properties are averaged over the unit cell and these average properties are represented in the simulator.

In contrast, a very fine grid is used in Slug Capturing, with grid lengths of order 1 to 10 times the pipe diameter, or even smaller, so that individual slugs and long bubbles can be resolved. The slug fronts and tails are detected using threshold values of the holdup, and the respective closure relations are applied for control volumes within the slug body or the long bubble zone. The closures for the slug tail velocity and the gas entrainment at the slug front are incorporated in an ad hoc manner, if at all, for example by modifying the interfacial friction (5). At any given time step, only a small fraction of the control volumes contain slug fronts or tails, so the majority of the fine grid is effectively unused. This inefficiency can be offset to some extent by automatic local grid refinement (6). Nevertheless, the very fine grid size requires a correspondingly small time step, so that Slug Capturing simulations are very computationally expensive.

In the Slug Tracking approach, a fixed, coarse grid is supplemented by a moving grid that tracks the position of each slug front and tail, which are modelled as discontinuities in the mass and velocity fields (1). This allows an efficient representation of the holdup distribution with a relatively small number of grid points. The resulting simulations are somewhat slower than standard coarse grid simulations, but orders of magnitude faster than Slug Capturing simulations on a fine grid.

Including moving grid points for each slug front and tail makes it straightforward to directly incorporate the closure relations for the slug tail velocity and for the gas entrainment across the slug front. In this respect, Slug Tracking represents the physics of slug flow more accurately than Slug Capturing.

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1 The mass flow rates are of course continuous across these discontinuities.
Thus, in principle, Slug Tracking is much more efficient than Slug Capturing, allowing for much faster simulations. It is also much better suited to inclusion of the specific closures for slug flow, which are imposed at the slug front and tail. However, as the name suggests, Slug Tracking is good for following slugs, once they are introduced, but gives no information on when or where to introduce slugs. In the present work, this deficiency is overcome by introducing a physical model for the “birth rate” of slugs, in terms of the probability that a slug will be generated in a given control volume of the fixed grid in a given time step of the simulation.

A less significant problem with slug tracking is that the characteristic tail profile behind each slug cannot be resolved on a coarse grid. This can lead to a loss of accuracy when bubbles and/or slugs are much shorter than the fixed grid. In the present work, this problem is reduced by accounting for the tail profile in the conservation laws and closures of the model. This is possible because the time scale over which the tail profile varies is much shorter than the time scale of a typical flow transient. Thus, the tail profile quickly adopts a quasi-steady form, propagating behind the slug without change of shape (13). It is relatively straightforward to allow for this steady-state shape in the model.

In comparing the relative merits of different modelling approaches, it should be borne in mind that no slug model can be better than the closures it is based on. Apart from the model for slug initiation, the same closures are required in Slug Tracking and Slug Capturing. In two-phase flow, these include: the wall and interfacial friction values, the slug tail velocity, the rate of gas entrainment in slugs, and the slip between gas and liquid in the slug body. In three phase flow, we need additional closures to characterize the dispersion of oil and water. In general, the accuracy of the results is determined by the quality of the closure relations, and a more detailed representation of the solution (as in Slug Capturing) cannot compensate for this.

3.1 Characteristic velocities in multiphase flow

In designing a simulator for transient multiphase flow, it is very useful to bear in mind the different characteristic velocities of the system. In petroleum applications, gas-liquid flows should be treated as compressible, but the flow speed is generally much less than the speed of sound. (Important exceptions occur in rapid transients, such as blowdown and pipe rupture scenarios.)

In most multiphase flow simulations, there are three important families of waves, each with its characteristic velocities: pressure waves, gravity waves and kinematic waves. Pressure waves are the fastest, moving at the effective speed of sound for the multiphase system. In typical flow transients, the pressure waves propagate very quickly, and are damped out before very much flow has occurred. Gravity waves typically propagate much more slowly than pressure waves. They include relatively short range features such as hydrodynamically unstable waves and the slug tail profile. Kinematic waves transport liquid through the pipe, with velocities which are typically slightly larger than the velocity of the liquid phase. They may be slower or faster than gravity waves (respectively subcritical or supercritical flow).

In slug flow, the slug front is a kinematic wave, which moves faster than the liquid phase. Gravity waves cannot propagate for long distances; they are rapidly overtaken by the slug front, which propagates much faster.

Many simulations of flow transients are concerned with prediction of liquid surges and associated variations in pressure drop along a pipeline. In such simulations, the pressure and mixture velocity vary only gradually along the pipeline, so these can be very well
resolved on a coarse grid. The local liquid holdup may vary over much shorter
lengthscales. Generally, we are only concerned with the average properties of the flow,
but if we want to resolve each and every wave in a wavy stratified flow, then a fine grid
is needed to capture the gravity waves: an example is the scenario of using Slug
Capturing to simulate the initiation of slugs.

In slug flow, the significant variation of holdup occurs across each slug front and tail. In
the Slug Tracking approach, this variation is represented with high precision by the use
of moving grid points. So, when Slug Tracking is supplemented with a physical model
for slug initiation, the fine grid is no longer needed.

4 MODEL FOR SLUG INITIATION

The mechanistic model for slug initiation (20) derives from work carried out in the
HORIZON II JIP, which was summarized in a previous publication (13). The model is
based on the conservation equation for the number of slugs

\[
\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}(NU_A) = B - D
\]

[1]

In equation [1], \( N \) represents the density of slugs in the pipeline (1/m) and \( U_A \)
represents the advection velocity (average velocity with which slugs move through the
pipeline); the term \( B \) is the birth rate of short slugs (1/m/sec), which is assumed to
depend on the degree of instability in the system and the spatial density of slug
precursors \( N_p \) (1/m), while \( D \) is the rate of slug death, which does not need to be
modelled for slug tracking, since slugs die when their length approaches zero.

The slug precursor density \( N_p \) is obtained by simulating the unit cell length of
successive short slugs of lengths 5 to 10 diameters. To this end, a two-phase tail profile
model (13) is applied to compute the holdup distribution in the elongated bubble zone.

The introduction of slugs is governed by the slug growth criterion, also known as the
minimum slip criterion. This criterion can be expressed in terms of the front \( V^F \) and
tail \( V^T \) velocities of a candidate slug. If the flow is locally separated, we consider the
introduction of a candidate slug and calculate its front and tail velocity. If
\( V^F < V^T \), the slug will quickly die, so a new slug should not be introduced. On the other hand, if
\( V^F > V^T \), the slug will grow, so a slug may be introduced. In the latter case, the decision
to introduce a slug or not is based on an estimate of the probability of slug formation.

The birth rate \( B \) is modelled in the form

\[
B = k_B (N_p - N) \frac{V^F - V^T}{10D}
\]

[2]

where \( k_B \) is a constant. The final factor represents the (inverse) time for a slug to grow
to a length of 10 times the pipe diameter \( D \).

Then for a control volume of length \( \Delta z \) and a time interval \( \Delta t \), the probability of a new
slug being formed is \( P = B \Delta z \Delta t \). In most cases, the time step is small, so that \( P << 1 \).
5 IMPROVED CLOSURES FOR SLUG TRACKING

The Slug Tracking model has been carefully reviewed and revised in several ways to improve the physical basis of the model. In essence, the Slug Tracking model solves equations for the motion of each slug front and tail. Thus, the key components of the physical model are the closures that affect the slug front and tail velocity.

5.1 Slug tail velocity

The slug tail velocity is specified by a correlation based on that of Bendiksen (16), which has been thoroughly tested against a wide range of experimental data and found to be very accurate. In the present work, the dependence of the slug tail velocity on the slug length has been re-assessed.

![Figure 1. Variation of the slug tail velocity with slug length](for details see Ujang et al. (22)).

The flow in the front region of each slug is dominated by a recirculation zone or wake driven by the shear layer between the fast-moving liquid in the slug front and the relatively slow-moving liquid layer which it overtakes. If a slug is shorter than the length of the wake zone (which is of order 5 to 10 times the pipe diameter), the tail of the slug senses the velocity field in the wake. This leads to an increase in the tail velocity for short slugs, as first reported by Fagundes Netto et al. (21). Figure 1 shows a plot of slug tail velocity against the slug length; the tail velocity $V_T$ is normalised with the value $V^\infty$ corresponding to an infinitely long slug, and the slug length $L_S$ is normalised with the pipe diameter $D$. The plot comes from a CFD study by Ujang et al. (22) and includes comparison with experimental data (21) and literature correlations (23, 24).

In the present work, we have re-analysed a large number of datasets from the large-scale flow loop at Tiller in Norway. The measured data have been processed to determine slug length and velocity at several positions along the test section for many different combinations of superficial fluid velocities, test section inclinations and working fluids. The data are confidential, so only the trend can be shown; an example is shown in Figure 2.
5.2 Slug front velocity

The slug front velocity $V^F$ is not determined directly by a correlation. Rather it is determined by a mass balance across the slug front:

$$
(V^F - U_{GS})\alpha_{GS} = (V^F - U_{GB})\alpha_{GB} = q_{GE}
$$

where $\alpha$ refers to the phase volume fraction in the pipe cross section (holdup) and $U$ refers to the mean velocity of the phase in the cross section. Subscript $GB$ stands for Gas in the long Bubble zone and $GS$ stands for Gas in the Slug zone. The final term $q_{GE}$ is the rate of Gas Entrainment into the slug, expressed as a volumetric flux (m/s).

A closure model is used to specify either the volume fraction of gas in the slug front $\alpha_{GS}$ or the gas entrainment rate $q_{GE}$. In either case, it is straightforward to solve equation [3] for the slug front velocity in terms of the other quantities.

The rate of gas entrainment into the slug front depends on the local conditions ahead of the slug, particularly, the relative velocity of the slug front and the liquid layer ahead of it (17, 18). If the slug tail profile is resolved on a fine grid, the variation of the liquid layer velocity is also resolved. For simulations on a coarse grid, this variation must be included explicitly in the model, and that is the approach taken here.

As the length of the long bubble between slugs increases, the liquid level and velocity immediately ahead of the next slug gradually fall towards equilibrium conditions, and the gas entrainment rate increases. Thus, slugs that follow relatively short bubbles have a lower gas entrainment rate, and consequently a lower slug front velocity.

Figure 3 shows a sketch of how the gas volume fraction in the slug front is expected to vary with the length of the preceding long bubble. For a very long bubble, the liquid layer reaches equilibrium conditions, and the gas entrainment is constant. As the bubble gets shorter, there is less time for the liquid layer to reach equilibrium. Consequently, the liquid velocity ahead of the slug is larger, and the driving force for gas entrainment is reduced. When the gas bubble is very short, there is insufficient time for the entrained
gas leaving the back of one slug to escape from the liquid layer before the next slug arrives. This bypass effect leads to a sharp increase in the gas fraction in the front of the next slug.

![Figure 3. Sketch of the variation of void in slug with the length of the preceding long bubble.](image)

The variation of the slug front velocity with the length of the preceding bubble is qualitatively the same as the sketch in Figure 3. In contrast to the slug tail velocity shown in Figure 1, the minimum of the curve in Figure 3 does not represent a stable length for the long bubble. It is an unstable point; shorter bubbles will decrease in length and quickly disappear, whereas longer bubbles will gradually increase in length.

6 VALIDATION AGAINST LABORATORY EXPERIMENTS

The first test of the new Slug Tracking model is to compare the predicted slug frequency with data from laboratory experiments. Figure 4 shows a comparison of predicted and measured frequency from four experimental studies, two from the WASP loop at Imperial College London (25, 26) and two from the University of Illinois (27, 28). The test sections are horizontal, about 3-inch diameter and 20 to 40m in length, with air and water as the working fluids. These data represent a subset of those collected and correlated by Schulkes (14), where more details of the experiments are conveniently tabulated. It can be seen that, with the exception of a few points from Manolis (25) the remainder of the predictions (about 95%) lie well within a factor of two of the measurements.

Figure 4 also shows the predictions of the Schulkes correlation (14) for the same cases. It can be seen that the accuracy of the correlation is quite similar to that of the Slug Tracking simulation for these cases, which were used in making the correlation.

Some data were excluded from the comparison on one of two grounds: 1) If the number of slugs counted in a given experiment is small, then the relative error in the reported slug frequency is large. We estimate the relative statistical error as ±2n^{-1/2}, where n is the number of slugs counted. We set a relatively modest constraint that the statistical error should be less than 30%, so that n should be at least 45. 2) Some of the experiments are not truly hydrodynamic slug flow, in that there is never more than a single slug in the test pipe. We exclude these experiments by requiring that the average number of slugs in the pipe is greater than unity, \( n_p = L_p f_S / V_T \) > 1, where \( L_p \) is the pipe length, \( f_S \) is the reported slug frequency, and \( V_T \) is the tail velocity, estimated from a correlation (16).
Figure 4. Comparison of the predicted and measured slug frequency for laboratory experiments (25, 26, 27, 28).

Figure 5. Comparison of the predicted and measured values for the data of Khaledi et al. (29, 30). (a) Slug frequency. (b) Mean slug length. Cases with oil viscosity 35 Pa.s, 100 Pa.s, and pressure 4 bar, 8 bar.
Khaledi et al. (29) reported slugging experiments with SF$_6$ gas and a range of viscous oils. Data were captured near the midpoint of a 51 m long test section of diameter 0.069 m. Hovden et al. (30) further analysed these data and made comparisons with an early version of the present model. For these data, which are not part of the basis of the Schulkes correlation (14), the accuracy of the correlation is not quite as good as that of the Slug Tracking simulation, which predicts the frequency to within a factor of two in all but two cases, as shown in Figure 5 (a).

Figure 5(b) shows a comparison of the mean slug lengths predicted by the model with those derived from the experimental data. Apart from one point (which is outside the frame of the figure), all of the predictions lie well within a factor of two of the measurements.

Figure 6 shows the predicted and measured slug length distributions for one of the cases from Figure 5. The agreement is very satisfactory, both qualitatively and quantitatively. The prediction of the shape of the slug length distribution represents a significant step forward from previous slug tracking simulations.

7 VALIDATION AGAINST DATA FROM THE TILLER LOOP

The large-scale flow loop at Tiller in Norway has a test section of 19 cm diameter and approximately 1 km length. Besides the larger diameter, which is more representative of field conditions, this gives a much larger length-to-diameter ratio than is commonly found in laboratory experiments. In the present work, a large number of experiments have been re-analysed to determine the slug statistics at several positions along the pipeline. The working fluids for these experiments were pressurised nitrogen and diesel, lube oil, or naphtha; the test section was horizontal or had a slight upwards inclination.

Figure 7 shows a typical case, in which the mean slug length gradually increases along the test section, while the slug frequency decreases. This evolution of the slug population is very gradual, and is not generally apparent in laboratory data, for which the pipe length-to-diameter ratio is typically less than 1000. Nevertheless, the overall change is quite large and will obviously be very significant for the long pipelines encountered in field applications. The evolution results from small differences in the front and tail velocity of individual slugs, which leads to some of the shorter slugs dying off. As can be seen, the model for slug initiation gives a reasonable prediction of the length and
frequency of the slugs at the first measurement point, whereas the revised Slug Tracking model reproduces the gradual evolution of these parameters.

![Graph showing variation of mean slug length and slug frequency with position](image)

**Figure 7. Variation of (a) the mean slug length and (b) the slug frequency with position in one of the Tiller experiments.**

8 VALIDATION AGAINST FIELD DATA

Figure 8 shows comparisons of the predicted and measured slug lengths and frequencies for several cases from five fields (Heidrun, Magnus, Prudhoe Bay, Wythe Farm, and SE Forties); six cases from the Tiller loop are also included. These cases form a subset of those used as a basis of the Shea correlation for slug frequency (12); they correspond to hydrodynamic slugging in approximately horizontal pipelines of a few kilometres length.

Some of the pipelines have a riser at the end; in these cases, comparisons are made with the predicted properties at the riser base. When slugs enter the riser, the Taylor bubbles may become unstable, resulting in churn flow in the slug bubble region. Furthermore, there is typically a dramatic increase in gas entrainment at the slug front, which leads to void fronts within the slugs, and sometimes completely consumes the long bubble zone (31). Though a slug bubble may disappear as it travels up in the riser, the pattern of high-void and low-void zones persists. For these situations, the OLGA slug tracking scheme cannot always maintain the slug identity; this disturbs the statistics of slugs in the simulation compared with the measurements, where slugs are identified from changes in the void fraction.
The slug lengths are predicted quite well, with 75% of predictions within a factor of two of the measurements. There are more data for the slug frequency, since lengths were not reported in one of the datasets. The slug frequencies are predicted not quite so well, with only 50% of predictions within a factor of two. In pipeline flow applications, it is useful to be able to predict both the slug length and the slug frequency. However, the slug length is by far the more important of these, since it determines the magnitude of unsteady loading, and is a key factor in slug catcher design. With this in mind, the performance of the new model in comparison with the field data seems to be promising.

Figure 8b also includes the predictions of the Shea correlation for the same cases. It can be seen that the performance of the correlation is similar to that of the Slug Tracking simulations for these cases, which were used in making the correlation.
9 DISCUSSION AND CONCLUSIONS

A new mechanistic model has been developed for the rate of slug initiation in time and space, and has been coupled with an updated and improved Slug Tracking simulator. The number of slugs initiated is generally relatively high. The initiation model performs well in comparison to laboratory data with relatively short pipelines. The slug length and slug frequency are typically predicted well within a factor of two; this is as good as or better than the best available correlation, which is that of Schulkes (14).

In all cases, the stochastic initiation method, coupled with a physically sound model for evolution, leads to a realistic slug length distribution. When the mean slug length is predicted correctly, the whole slug length distribution is generally in good agreement with measurements.

The improvements in the Slug Tracking simulator mostly address the way in which the front and tail velocities of slugs respond to local variables such as the length of individual slugs and bubbles. The velocity differences are quite small (typically in the 1% range), but lead to significant changes in the mean slug length and frequency over long pipelines. In comparison with the Tiller data, we see that the improved Slug Tracking model is able to capture the evolution of slug length and frequency along the length of the pipeline both qualitatively and quantitatively.

Comparison with field data also shows quite reasonable results. The mean slug lengths are predicted within a factor of two in most cases, whereas the slug frequencies are predicted within a factor of three. Again this is as good as or better than the best available correlation [Shea et al. (12)].

The new model is still far from perfect and there is significant room for improvement. It should be emphasised that the Slug Tracking simulator is very complex, and results depend on all of the closure relations used. Over the years, most of the activity to improve the closure relations has focused on the prediction of overall pressure drop and holdup. We are now actively working to improve the closures in regard to predictions of slug length and frequency. The most significant closure in this regard is probably that for gas entrainment into slug fronts, but the closures for the wall and interfacial friction in the separated zone are also important. We are also working to improve the models used for steeply inclined and vertical flow.

Despite the reservations expressed above, the present results allow us for the first time to predict slug length distributions and slug frequencies based directly on a physical model without the need for tuning. These results provide a very promising basis for further development.

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