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SIMULATION OF INTERMITTENT FLOW IN MULTIPHASE OIL AND GAS PIPELINES

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ABSTRACT

This paper reviews recent advances made in the computational simulation of intermittent flow, and in particular the slug flow regime in pipes carrying multiphase fluids. The methodology is based on the transient, one-dimensional two-fluid model equations that are solved numerically using fine grids and small time steps to capture the hydrodynamic instabilities that initiate waves and slugs. The capture of slugs is achieved in a completely automatic manner and leads to remarkably accurate predictions of average slug characteristics when compared to data from laboratory experiments. More astonishing is the ability of the one-dimensional model to capture stochastic nature of slug flow. In industrial applications involving pipelines extending several kilometres, special numerical procedures must be adopted to speed up the computations to keep them within practical time constraints.

NOMENCLATURE

A pipe cross-sectional area (m^2)
D pipe diameter (m)
D_g gas hydraulic diameter (m)
F frictional force per unit volume (Nm^{-3})
f friction factor (-)
g gravitational acceleration (ms^{-2})
h height of liquid layer (m)
p pressure (Nm^{-2})
Re Reynolds number (-)
S contact perimeter (m)
U superficial velocity (ms^{-1})
u velocity (ms^{-1})
t time (s)
x distance along the flow (m)
α Phase fraction (-)
β angle of inclination of pipe to the horizontal (^{o})
ν kinematic viscosity (m^{2}s^{-1})
ρ density (kgm^{-3})
τ shear stress (Nm^{-2})

Subsripts

g gas
i gas-liquid interface
l liquid

INTRODUCTION

Intermittent flow, especially the slug flow regime, occurs in many engineering applications, particularly in the transport of hydrocarbon fluids in pipelines in the oil and gas industry. The slug flow regime, in which large gas bubbles flow alternately with liquid slugs at randomly fluctuating frequency, is usually undesirable since the intermittency of slugs causes severe adverse conditions. Firstly, the flow rates of the gas and oil arriving at the receiving equipment (separators and slug-catchers) can fluctuate widely thereby undermining the efficacy of the equipment (e.g. separator flooding); to cater for this situation, processing facilities are usually designed with generous "safety margins" at the expense of cost, weight and size. Secondly, the flow intermittency results in highly-unsteady loading on the piping system and processing equipment, which can result in catastrophic failure due to metal fatigue. It is therefore important to be able to predict the onset and subsequent development of slug flow; it would be even more beneficial if slug characteristics, such as slug length and frequency could be calculated as well.

In horizontal and nearly horizontal pipes, slug flow can be generated from stratified flow by two main mechanisms: (i) liquid accumulation due to instantaneous imbalance between pressure and gravitational forces caused by pipe undulations, and (ii) natural growth of hydrodynamic instabilities. In the first, slugs may form at pipe dips due to the retardation and subsequent accumulation of liquid in the dips leading to the filling up of the cross-section with liquid. An extreme example of this terrain induced slug flow is called ''severe slugging'' and occurs when a slightly inclined pipeline meets a vertical riser (Schmidt et. al., 1985). This phenomenon is fairly well understood and methods for calculating its development exist. In the case of hydrodynamic instabilities, small random perturbations of short wavelengths arising naturally may grow into larger and longer waves on the surface of the liquid. The mechanism behind this growth is the classical Kelvin–Helmholtz instability (Lin and Hanratty, 1986). Such waves may continue to grow picking up liquid flowing ahead of them, until they bridge the pipe cross-section, thereby forming slugs. These slugs may grow if the slug fronts travel faster than the tails; conversely they would collapse. Stable slug flow is obtained if the slug front and tail travel at the same speed. In real flow, all these events take place at different times, hence some slugs grow, others collapse; also slugs may travel at different speeds, thereby leading to the merging of some slugs with others (Taitel and Barnea, 1990).

Slug flow may also arise from both of the aforementioned mechanisms simultaneously in long pipelines transporting hydrocarbons. There, slight terrain undulations may lead to the generation of slugs in addition to those generated by inherent flow instabilities. In such cases, the slugs generated from one mechanism interact with those arising from the other leading to a complex pattern of slugs, which may overtake and combine.

Oil and gas pipelines are typically several, if not tens of, kilometres long. The methodology described herein shows that in order to capture inherent hydrodynamic instabilities, streamwise mesh sizes of the order of centimetres and time steps of the order of milliseconds are needed. To simulate the transient dynamics of the flow in real pipelines in three dimensions would simply be infeasible on even the most powerful of current computer systems; this explains why no work on such simulation has been attempted in the past apart from short pipe sections, which is of little use in real pipeline calculations. One-dimensional, transient models of multiphase flow are therefore the only practicable means for calculations in real pipelines. The model utilised for is called the "multi-fluid" model in which transport equations for mass, momentum and energy are formulated for each phase.

Dynamic multiphase flow computations in industrial pipelines are normally based on the two-fluid model, and some are embodied in well established commercial codes like OLGA, PROFES and TACITE. All use coarse grids (pipe segments) of several tens or hundreds of metres in length; such calculations do not resolve fast transients nor are able to capture hydrodynamic instabilities. Instead, two types of approaches are followed to simulate the effects of intermittent/slug flow, one in which the presence of slugs is merely represented on an average basis by empirical closure relations (mainly for shear forces) pertaining to slug flow. The other approach is based on the Lagrangian tracking of individual slugs within the framework of the two-fluid model. Commonly, slugs of pre-determined length and frequency are assumed to generate using crude empirical relations. Subsequently, the position of each slug tail and front is monitored along the pipe in a Lagrangian manner with time. Neither of the above approaches can capture the initiation of slug flow naturally and both rely on empirical slug initiation relations to start a slug regime calculation. Moreover, neither is capable of accounting for the effects of interactions between slug flow and terrain undulations.

The one-dimensional two-fluid model has been the subject of extensive analyses of the Kelvin-Helmholtz type to investigate its ability to simulate wave growth (e.g. Barnea and Taitel, 1994). Results of these analyses show clearly that for certain flow conditions, perturbations occurring in stratified flow are amplified in time resulting in the formation of waves that may eventually grow to form slugs. More recently, Issa and Woodburn (1998), and Issa and Kempf (2003) have shown that by solving numerically the transient, one-dimensional, two-fluid model equations it is possible to capture the growth of disturbances leading to the generation and subsequent development of slugs in an automatic manner. That work constitutes a breakthrough in providing a capability (*slug-capturing*) for predicting the onset of slug flow caused by hydrodynamic instabilities. It has been demonstrated that the resulting predictions for the main characteristics of slug flow compare astonishingly well with experimental data. Moreover, a remarkable finding in the above cited works was the generation of slugs of randomly variable length at different instants in time. Such prediction indeed tallies with what happens in reality.

Despite the fact that the model used is only one-dimensional, computations still require an inordinately long time for real pipelines, since mesh sizes of the order of few centimetres and time steps of the order of milliseconds have to be used to capture the instabilities responsible for slug initiation. It is therefore important to look at means of accelerating the calculations to render them of practical use. This paper reviews the situation with regard to making such applications practical and presents the results of calculations for a real pipeline.

MODEL EQUATIONS

The basis of the two-fluid model is the formulation of two sets of conservation equations for the balance of mass, momentum and energy for each of the phases. The one-dimensional form of the model is obtained by integrating (area averaging) the flow properties over the cross-sectional area of the flow (see Fig. 1).
Transfer of momentum and energy between the walls and the fluids and between the phases themselves across the interface is accounted for via source terms in the equations; they are formulated using empirical correlations (Ishii and Mishima, 1984).

The present work is focused on the transport equations for an isothermal flow. Hence the equations solved are for the conservation of mass and momentum for the gas and liquid phases. For one-dimensional stratified and slug flow they are:

Gas Continuity

$$\frac{\partial(\rho_g \alpha_g)}{\partial t} + \frac{\partial(\rho_g u_g \alpha_g)}{\partial x} = 0 \qquad (1)$$

Liquid Continuity

$$\frac{\partial(\rho_l \alpha_l)}{\partial t} + \frac{\partial(\rho_l u_l \alpha_l)}{\partial x} = 0 \qquad (2)$$

Gas Momentum

$$\frac{\partial(\rho_g \alpha_g u_g)}{\partial t} + \frac{\partial(\rho_g \alpha_g u_g^2)}{\partial x} = -\alpha_g \frac{\partial p}{\partial x} + \rho_g \alpha_g g \sin\beta + F_g + F_i \qquad (3)$$

Liquid Momentum

$$\frac{\partial(\rho_l \alpha_l u_l)}{\partial t} + \frac{\partial(\rho_l \alpha_l u_l^2)}{\partial x} = -\alpha_l \frac{\partial p}{\partial x} - (\rho_l - \rho_g)\alpha_l g \frac{\partial h}{\partial x}\cos\beta + \rho_l \alpha_l g \sin\beta + F_l - F_i \qquad (4)$$

In these equations, α represents the volume fraction with the condition that: $\alpha_l+\alpha_g=1$.

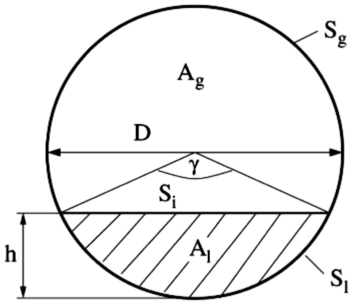

Figure 1: Pipe cross section**.**

Terms F_g, F_l and F_i in the above equations represent the frictional forces per unit volume between each phase and the wall and between the phases at the interface respectively. They are prescribed by the following closure relations:

$$
\begin{aligned}
F_g &= \tfrac{1}{2} f_g \rho_g |u_g| u_g S_g / A \\
F_l &= \tfrac{1}{2} f_l \rho_L |u_l| u_l S_l / A \\
F_i &= \tfrac{1}{2} f_i \rho_g |u_g - u_l| (u_g - u_l) S_i / A
\end{aligned}
\tag{5}
$$

These friction factors are specified from empirical correlations. In the present work, the gas-wall factor is based on the widely used correlation of Taitel & Dukler (1976):

$$f_g = C_g \, \mathrm{Re}_g^{-n_g} \tag{6}$$

where the Reynolds number is based on the gas hydraulic diameter D_g and defined as:

$$\mathrm{Re}_g = \frac{D_g u_g}{\nu_g} \tag{7}$$

The coefficients C_g and n_g take the values of 0.046 and 0.25 respectively if the flow is turbulent (Re_g>2100), or 16 and 1 if the flow is laminar ($\mathrm{Re}_g \leq 2100$).

The best correlation for calculating the liquid-wall friction factor f_l, was found to be that of Spedding & Hand (1997). Thus, for laminar flow:

$$f_l = \frac{24}{\mathrm{Re}_l^s} \tag{8}$$

and for turbulent flow:

$$f_l = 0.0262 \left(\alpha_l \, \mathrm{Re}_l^s \right)^{-0.139} \tag{9}$$

In equations (8) and (9), the Reynolds number Re_l^s is based on the liquid superficial velocity and the pipe diameter as:

$$\mathrm{Re}_l^s = \frac{D U_l}{\nu_l} \tag{10}$$

The interfacial friction factor f_i is based on the same correlation of Taitel and Dukler (1976) as for gas-wall shear. Hence:

$$f_i = C_i \, \mathrm{Re}_i^{-n_i} \tag{11}$$

where Re_i is defined as:

$$\mathrm{Re}_i = \frac{D_g (u_g - u_l)}{\nu_g} \tag{12}$$

In equation (11) the coefficients C_i and n_i take the same values as those for the gas friction factor.

SLUG CAPTURING

In the work of Issa and Woodburn (1998), and Issa and Kempf (2003), the initiation and generation of slug flow were also shown to be captured as an outcome of the growth of instabilities in stratified flow in an automatic manner. The prerequisite for such capability is accurate numerical resolution in both space and time so that any small numerical perturbations (due to round-off and other numerical errors) are captured and allowed to grow naturally as the governing equations dictate. Figure 2 depicts the outcome of such calculation. In the figure, the liquid hold-up is plotted along the pipe at several instants in time starting from stratified flow. The first disturbance that can barely be discerned in the second inset generates automatically and then grows to bridge the pipe thereby generating a slug. Subsequent disturbances generate periodically to lead to more slugs and eventually resulting in a continuous train of slugs. What is remarkable is the fact that the predicted flow is stochastic in nature, in that no slug is identical to the others, a result that mimics nature closely.

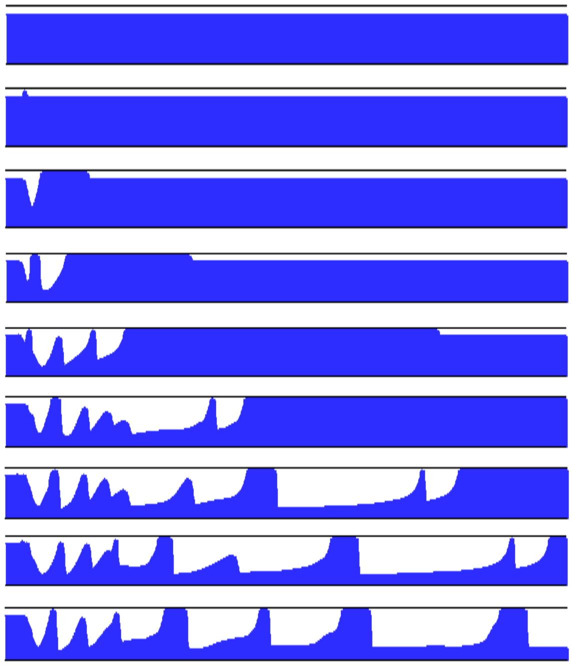

Figure 2: Predicted liquid hold-up distributions along a pipe at different instants in time in slug flow.

The results of numerous slug capturing computations have been compared with experimental data in an extensive validation programme which has proved that the methodology gives remarkably realistic predictions of slug flow characteristics (such as slug frequency and length). An example of that study is presented in figures 3 and 4 (taken from Issa & Kempf, 2003) where the predicted average slug frequency and average liquid hold-up are compared with measurements for horizontal and slightly downward inclined pipes.

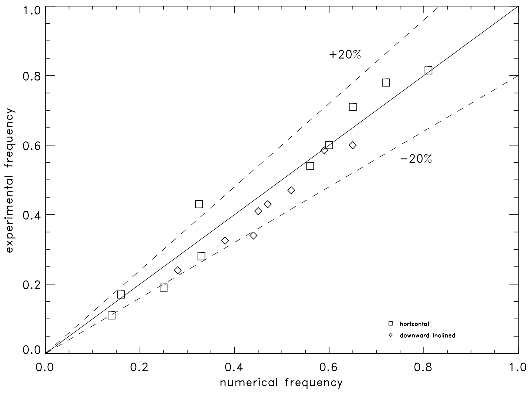

Figure 3: Slug frequency in horizontal and slightly inclined pipes.

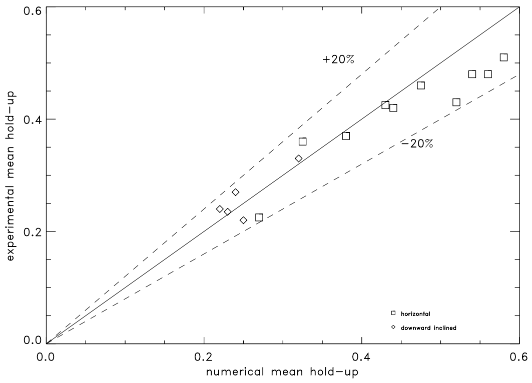

Figure 4: Mean hold-up in horizontal and inclined pipes.

It can be seen from the figures that the agreement between computations and experiment is excellent bearing in mind that the predictions are entirely mechanistic without the need to impose any external perturbation to generate slugs or any special treatment to simulate their subsequent movement.

A remarkable feature of the computations is that the predicted slugs exhibit a similar trend to those in real slug flow in that they are not all of the same length or frequency. Indeed there is an element of statistical randomness in their characteristics as is the case in actual flow. A typical histogram of the slug lengths produced is shown in Figure 5 (also taken from Issa and Kempf, 2003) as an example. Such a histogram is obtained from the computations by monitoring the liquid hold-up at two points along the pipe (near the outlet) in time. From these hold-up values the times of arrival and departure of slugs are established and from these, the slug velocity can be determined. The length of each slug that passes can thus be calculated from the passage time and the slug velocity (in much the same way as is done in actual experiments). The computed values shown in the figure relate to a case with gas and liquid superficial velocities of 4 and 0.4 m/s, respectively. The experimental evidence for this case indicates that the slug lengths are typically in the range of 12–30 times the pipe diameter. Also as in real slug flow, the variations in slug characteristics occur around a statistical mean, which is what is used to compare the calculations against the data.

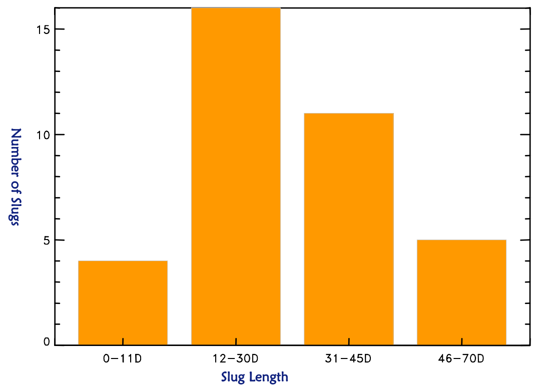

Figure 5: Predicted slug length histogram.

INDUSTRIAL APPLICATION

The methodology is applied here to a real pipeline 15 km long and 20 inch diameter carrying oil and gas; the outlet pressure is 96 bar. The topology of the line is depicted in Figure 6 where the first section shows the initial 50m, where the pipe dips after a short horizontal section. The second section shows the major portion of the pipe (around 15 km) which is more or less horizontal with few undulations. The third section depicts the final 50m section where it rises at an incline and then levels off to the outlet. A mesh of 400,000 cells was found to give mesh-independent results.

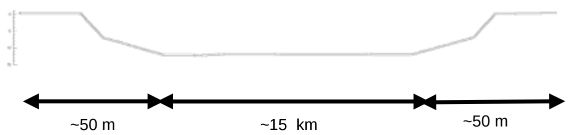

Figure 6: Topology of pipeline.

Simulations were carried out over nearly two hours of real flow time starting from arbitrarily assumed initial conditions; this is the integration time required for the flow to reach statistically steady state. Time steps of less than 1 ms were taken and the computations on a single processor machine require some 45 days to complete. This clearly is not a practical proposition for industrial purposes, hence means of accelerating the calculations are needed and the most effective measure to achieve that goal is by parallel processing which is being pursued at present.

Snap-shots of the phase fraction distributions in the three sections of the pipe are given in panels (a), (b) and (c) in Figure7. It can be seen that in the first section, the flow is stratified and is stable. In the middle section, flow instabilities likely to be induced by either hydrodynamic instabilities or pipe undulation (or both) develop and form successive roll waves that continue until the final section of the pipe where after encountering the bend and uphill section, form slugs that continue until pipe outlet.

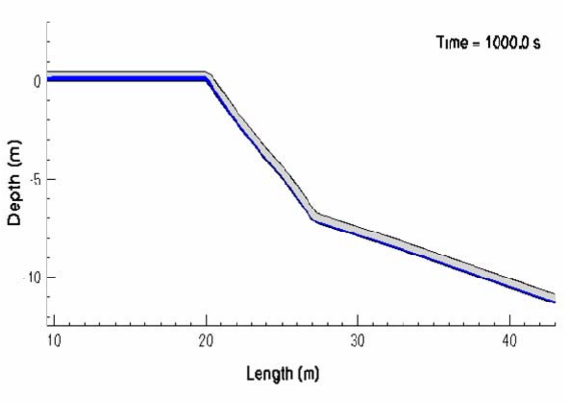

Figure 7-a: Liquid hold-up distribution in first section

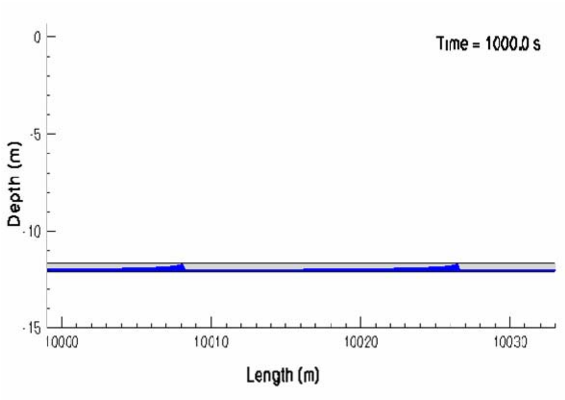

Figure 7-b: Liquid hold-up distribution in middle section

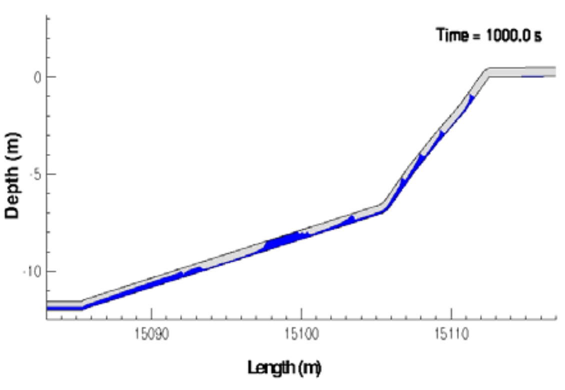

Figure 7-c: Liquid hold-up distribution in final section

PRACTICAL CONSIDERATIONS

As was mentioned earlier, in order to capture the fine details of the flow, leading to the growth of hydrodynamic instabilities that form either roll waves or develop into slugs, small mesh sizes (grid intervals of few cm) and short time steps of (of the order of milliseconds) have to be used. This obviously demands very high computing resources to perform calculations that commence from arbitrarily assumed flow conditions (normally stratified flow), then proceed to capture the initiation and subsequent development of waves/slugs automatically, and finally reach a statistically steady state.

It is clear that in an industrial application where pipelines are of the order of tens if not hundreds of kilometres in length, then millions of nodes and time steps may be necessary to perform the same kind of slug-capturing calculations shown above. Thus, seemingly simple one-dimensional calculations become a major effort requiring enormous computing effort. In order for the computations to be completed within practical times to be of use to industry (hours or days rather than weeks), means of accelerating the calculations must be found: speed-up of at least one order of magnitude is necessary to achieve this objective.
In what follows is a general discussion of options that have been considered for accelerating the calculations. It will be apparent that only one option (that of parallel computing) is able to achieve the required speed-up.

Adaptive meshing: The purpose of adaptive meshes is to minimise the total number of grid nodes in the domain by concentrating the mesh only in areas where high resolution is required (i.e. where steep gradients are present). Although this may appear as a particularly logical and attractive proposition, it does have its serious limitations in the context of slug simulation. To begin with, it is necessary to establish a priori where the relevant areas in the flow field are in order to concentrate the mesh in those areas. However, this is extremely difficult if not impossible in wavy/slug flows where regions of wave or slug initiation cannot be predicted in advance. The situation is made even more complicated by the unsteady nature of the flow where local mesh refinement must be dynamic in time. Furthermore, experience shows that the gains from this approach can seldom yield the order of magnitude improvements sought here.

High order differencing schemes: Several high order schemes for discretising the governing transport equations, both in space and time, exist. These would normally need less mesh nodes than lower order schemes to yield the same degree of numerical accuracy, hence resulting in less computing time. They are therefore becoming more widely used. However, here again, the resulting reduction in number of nodes is nothing like what is needed to reduce the computational effort involved in slug capturing. Moreover, in order to capture the growth of hydrodynamic instabilities, there is an upper limit on the mesh size to be able to resolve the small disturbances responsible for initiating the waves irrespective of the order of the differencing scheme used.

Efficient solution algorithms: Most existing solution techniques utilise an iterative process to arrive at the final result because of the strong non-linear coupling of the multiphase flow equations. In steady state flow, this is normally the only feasible method of reaching a solution. In the context of time-dependent calculations, iteration may be performed at each time step. With so many time steps needed to march to the final solution, the effort expended in obtaining the solution therefore may become enormous. To remedy this, two alternatives may be adopted. In the first, the *multigrid* technique can be utilised to speed up convergence of the iterative process. However, this comes at the expense of increase in memory requirement and algorithm complexity as intermediate solutions on the many grids employed need to be handled. Also, although reported speed-ups can be achieved on linear systems of equations, the same may not necessarily be realised on real non-linear systems. The second approach is by employing *non-iterative* techniques wherein the solution achieved at the end of each time step contains certain discretisation errors. Such errors (especially non-conservation of mass) can build up gradually to the detriment of accuracy of the solution and stability of the computations, thereby necessitating even smaller time steps, which defeats the object of the exercise.

Parallel computing: With the development of fast networking technology and multi-core computers, processors can now be utilised to share the effort in performing calculations simultaneously. In one approach, different portions of the problem (e.g. portions of the grid) are assigned to different processors or computers. In this way, the execution task is run in parallel on all processors thereby speeding up the solution process as though it is run on a much more powerful computer. It is because of this advantage that parallel computing is relied upon today in many of the industrial CFD analyses and why the commercial CFD codes now offer this capability as a main feature.

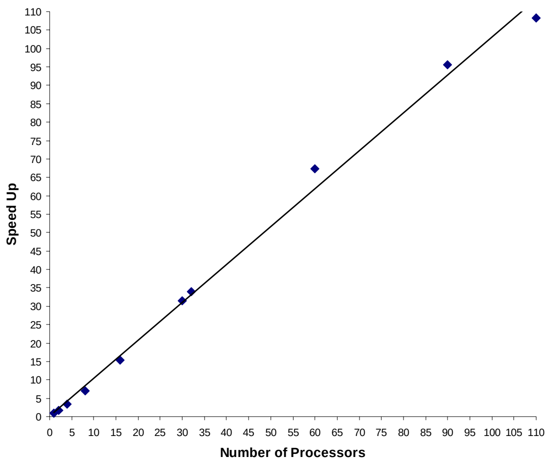

Figure 8: Example of parallel-computing performance.

Figure 8 shows an example of the speed-up obtained with parallel computing on several processors and it clearly illustrates that this is the most feasible way to achieving the acceleration in the calculations necessary to make the methodology a practical tool in the oil and gas industry.

CONCLUSION

The transient one-dimensional two-fluid model has been shown to be able to simulate wave growth in unstable stratified flow leading to the initiation and subsequent evolution of trains of roll waves and slugs. The methodology has been validated against a range of laboratory experimental data with excellent agreement being obtained. The predictions yield stochastic distribution of slug characteristics such as length and frequency similar to real slug flow. This ability is rather surprising, but explicable, in view of the simplicity of the model.

The method has also been applied to the computation of intermittent flow in real pipelines; an example of a 15 km long pipe was presented. Such computations necessarily involve hundreds of thousands, and sometimes millions of nodes as well as millions of time steps in order to capture and resolve inherent hydrodynamic instabilities. To this end sufficient computer resources must be made available for the calculations. It can be argued however that the magnitude of the problem in wave/slug capturing in a real pipeline in the oil industry is no bigger than three-dimensional cases encountered in other industries. Perhaps the main additional burden is the time dependent nature of the slug flow which necessitates the use of transient computations thereby making them time consuming. A brief review of the potential benefits and drawbacks of different techniques to speed up those calculations was then presented. It is suggested that perhaps the single most powerful route to reducing computing time is the use of parallel computing. Here, there are several strategies to implementing the parallelism, most of which lead to almost linear speed-up with the number of processors deployed. Use of such strategies would undoubtedly result in making slug-capturing simulations manageable as routine calculations

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