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The Evolution of Multiphase Flow Simulators

P. Andreussi

University of Pisa
TEA Sistemi spa
(paolo.andreussi@tea-group.com)

Acknowledgements

MAST Team

Marco Bonizzi
Andrea Fani
Simone Coltelli
Vittorio Faluomi
Alessandro Mariotti
Enrico Pitton
Daniele Picciaia
Sanjoy Banerjee

OLGA Team

Kjell Bendiksen
Ole Nydal
Chris Lawrence

Old Guys

Barry Azzopardi
Geoff Hewitt
Tom Hanratty
Abe Dukler

Introduction

✓The interest of the Oil Industry towards the exploitation of subsea reservoirs increased significantly over the last 30 years. This led to the development of transient flow simulators able to describe multiphase flow through long pipelines and process equipment.

✓Some of the challenges related with subsea hydrocarbon transportation systems are

- Low reservoir pressure
- Onset of unsteady flow conditions
- Formation of solid compounds
- Erosion and corrosion of pipe wall
- Formation of high viscosity emulsions

✓ Tools developed over the years are also used for the design of on-shore pipelines.

Multiphase Pipe Flow

In the beginning there was only chaos

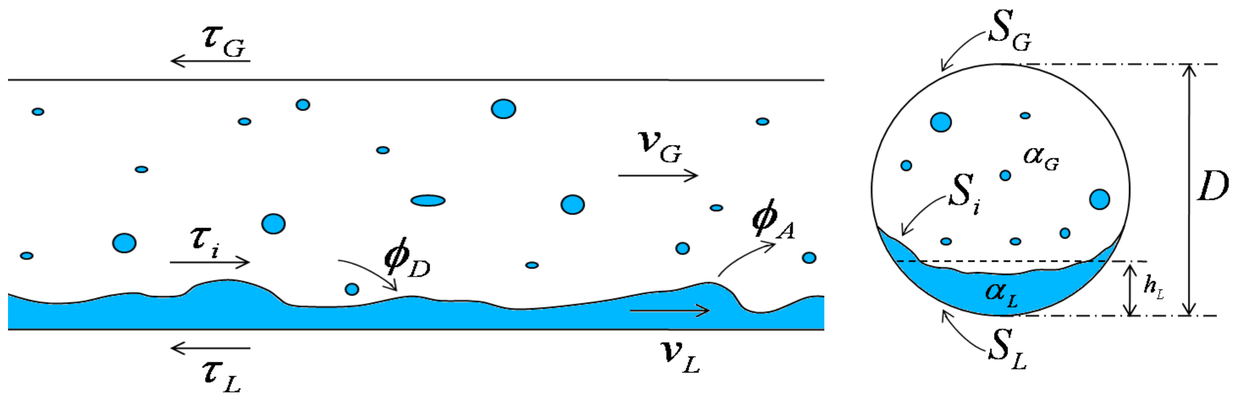
Up to the 1970’s, multiphase pipe flow was mainly perceived as chaotic motion of gas-liquid mixtures, too difficult to model. Design methods were based on empirical correlations. Among these, the correlation due to Lockhart and Martinelli (1949) has been the basis for the development of more advanced flow models.

Multiphase Pipe Flow

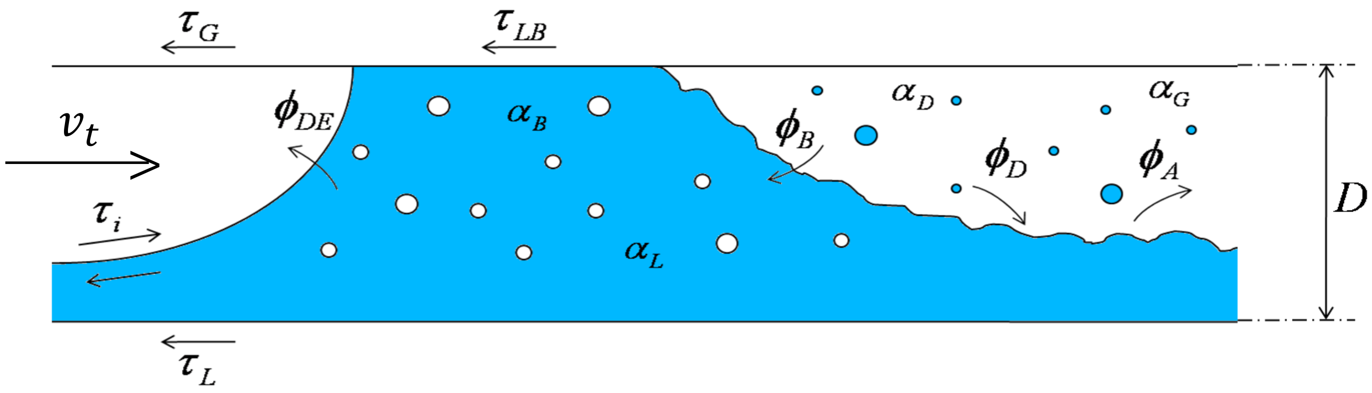
…then the light was made …

In the following years, experimental observations led to the development of simple, steady-state models, based on mass and momentum balances. The flow map by Taitel & Dukler (1976) and the slug flow model by Dukler&Hubbard (1975) represented a turning point in multiphase flow simulations.

Stratified/dispersed flow



Slug/bubbly flow



Flow Regime Transitions, Taitel & Dukler (1976)

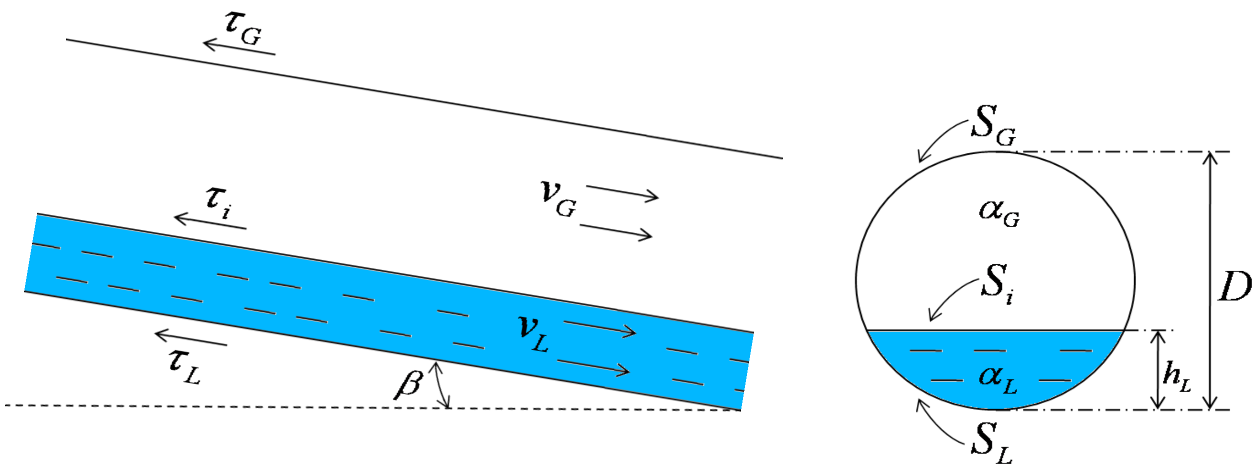
✓The T&D analysis of flow regime transitions starts from the condition of stratified flow. A momentum balance on each phase yields

Liquid

$$\frac{\partial}{\partial t}\left(\alpha_L \rho_L v_L\right)+\frac{\partial}{\partial x}\left(\alpha_L \rho_L v_L^2\right)=-\alpha_L \frac{\partial P}{\partial x}-\frac{\tau_L S_L}{A}+\frac{\tau_i S_i}{A}+g\alpha_L \rho_L \sin\beta$$

Gas

$$\frac{\partial}{\partial t}\left(\alpha_G \rho_G v_G\right)+\frac{\partial}{\partial x}\left(\alpha_G \rho_G v_G^2\right)=-\alpha_G \frac{\partial P}{\partial x}-\frac{\tau_G S_G}{A}-\frac{\tau_i S_i}{A}+g\alpha_G \rho_G \sin\beta$$



Flow Regime Transitions, Taitel & Dukler (1976)

- ✓ T&D expressed the shear stresses τ_{G}, τ_L and τ_i as

$$\tau_L = f_L \frac{\rho_L \upsilon_L^2}{2} \quad , \qquad \tau_G = f_G \frac{\rho_G \upsilon_G^2}{2} \quad , \quad \tau_i = f_i \frac{\rho_G (\upsilon_G - \upsilon_L)^2}{2}$$

They assumed $\tau_i = \tau_G$ and computed the friction factors f_L and f_G with the same functions of the liquid and gas Reynolds numbers as in single phase flow,

$$f_L \ \ or \ \ f_G = c \left(\frac{D_H \upsilon}{\nu} \right)^m$$

- ✓ Once the shear stresses are given, for steady flow, the gas and liquid momentum balances can easily be solved, providing the pressure gradient and the film height.

Growth of an interfacial disturbance, T&D (1976)

- ✓ An interfacial disturbance may grow due to the unbalance between the differential gas pressure due to gas acceleration over the disturbance and the force of gravity acting on the liquid. This happens when

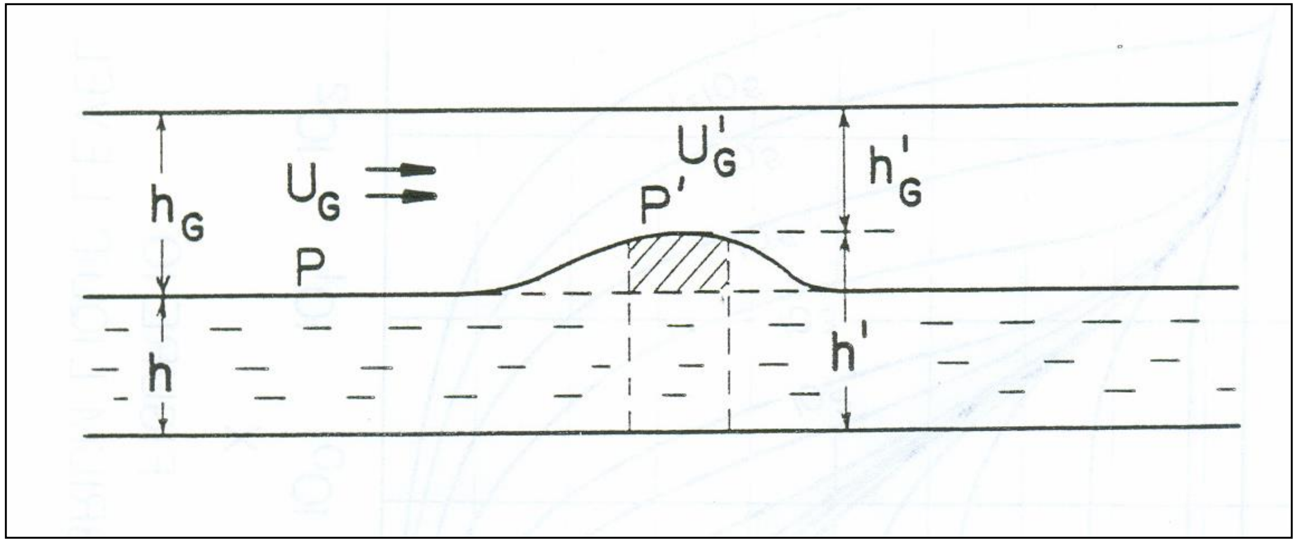
$$P - P^{'} = \frac{1}{2}\rho_G (U^{'}_G - U_G \geq (h_G - h^{'}_G) g (\rho_L - \rho_G)$$

- ✓ In dimensionless form, this equation has been expressed as

$$Fr^2 f\left(h_L / D\right) \leq 1$$

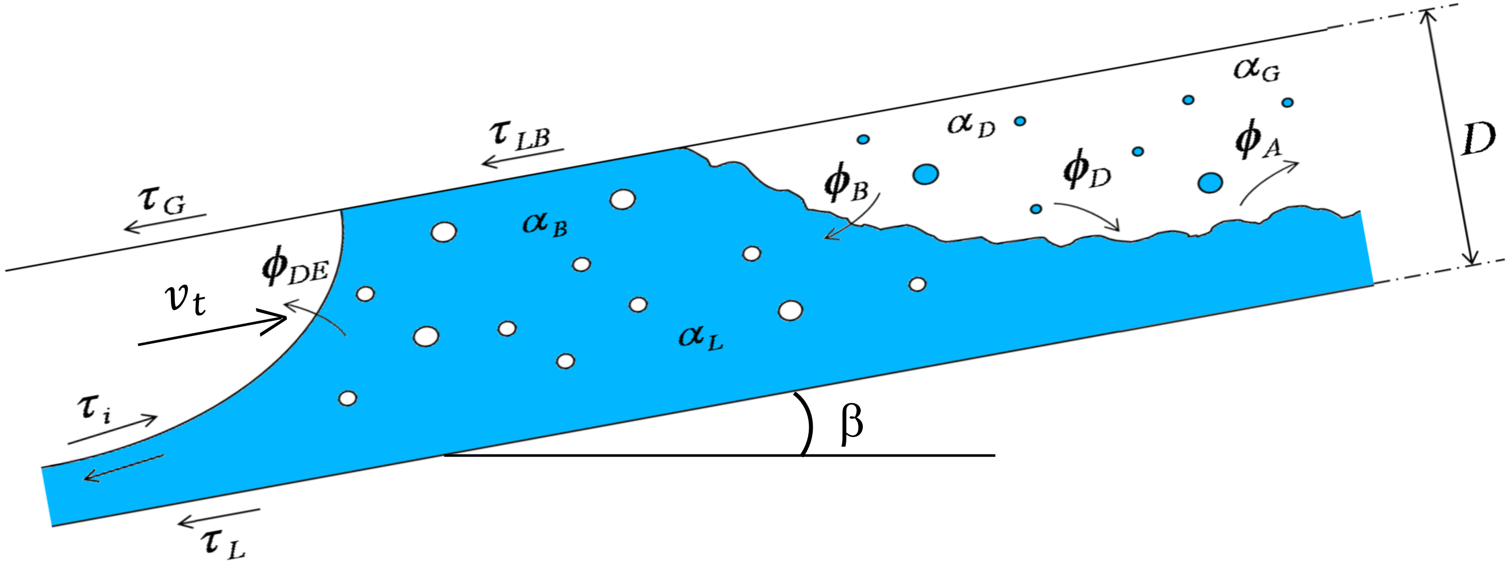
where

$$Fr = \sqrt{\frac{\rho_G}{\rho_L - \rho_G}} \frac{\upsilon_{GS}}{\sqrt{Dg \ \cos\beta}}$$



Slug Flow Model, Dukler & Hubbard (1975)

- Basic Assumption: Slug Flow is made of a sequence of identical slug units traveling at a constant translational velocity, v_t, which is predicted with an empirical correlation.
- D&H wrote a set of 15 equations (mass and momentum balances, closure equations), but ended up with 16 unknows. In order to close the problem, they assigned the measured slug frequency.



Multiphase Pipe Flow

- ✓ Starting from the early 1980's, the underlying work on physical models allowed the development of first transient flow simulators (OLGA, PLAC, TACITE) for applications of interest to the Oil Industry. Among these codes, OLGA became, over the years, the reference tool for Flow Assurance studies.
- ✓ The success of OLGA can be related to the following factors:
  - Good quality of transient simulations
  - Code validation with field/laboratory data
  - Strong support from the Oil Industry
  - Ability to deal with all Flow Assurance issues
  - Quality of the OLGA team

Multiphase Pipe Flow

- ✓ From a technical view-point, OLGA is getting old and even if the underlying physics is rather simple, the code requires expert users and the available documentation is poor.
- ✓ From a commercial view-point, the cost of an OLGA license is high and this may explain why in recent years other flow simulators have been developed. Among these, Ledaflow received a strong support by the Oil Industry.
- ✓ Ledaflow has been developed in the same technical environment as OLGA and the two codes appear to be similar, also in their cost.

Main Features of OLGA

- ✓ OLGA solves 1D mass, momentum and energy conservation equations relative to gas-liquid or gas-liquid-liquid flow in a pipe.
- ✓ Numerical solution is based on a coarse grid (100 D) and an implicit integration scheme. This implies that the sub-grid structure of the flow can only be caught by some type of averaging over the grid length.
- ✓ The sub-grid structure of Slug flow is described with a simplified version of the Dukler&Hubbard (1975) model, as a sequence of identical slug units of unknown length or frequency. The slug velocity is predicted with an empirical correlation.

Flow Regimes in OLGA

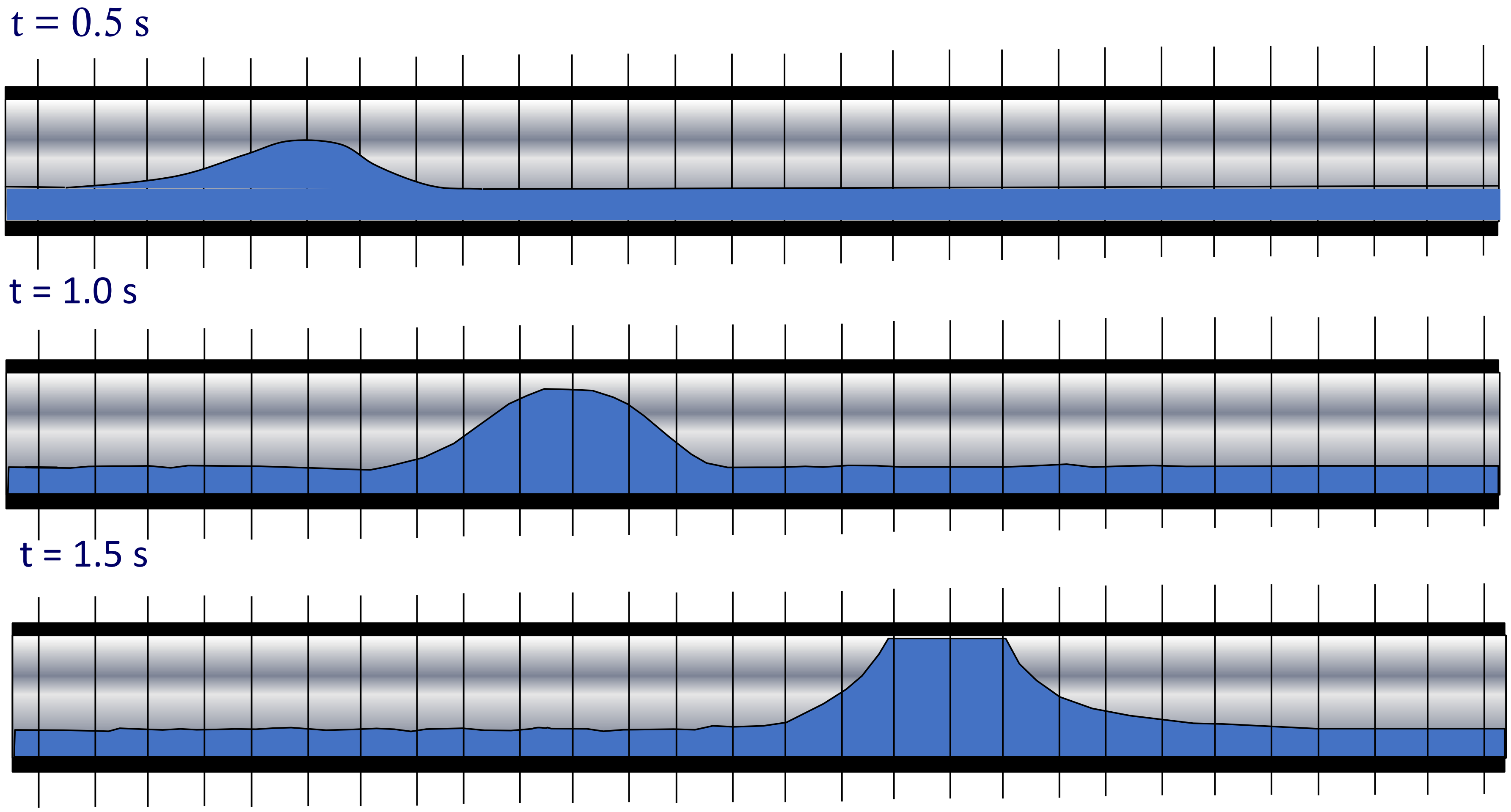
- ✓ In OLGA the following flow regimes are considered for all pipe inclinations:
  - Distributed Flow
    - Slug
    - Bubble
  - Separated Flow
    - Stratified
    - Annular/Mist
- ✓ At each time step conservation equations are solved two times and it is assumed that the stable flow pattern is the one providing the minimum gas velocity. In Distributed Flow, the stable flow pattern is bubble flow when the average gas void fraction in the slug unit is less than the void fraction in the slug body. In Separated Flow the stable flow pattern is annular flow when the wave height is such that the wave reaches the top of the tube.

Evolution of Multi-Field models

- ✓ Issa and Kempf (2003) showed that the transition between Stratified and Slug Flow can be predicted by the direct solution of a transient Two-Fluid model, when a fine grid is adopted (ΔZ = D). This method is called Slug Capturing.
- ✓ This result has been exploited by Bonizzi, Andreussi and Banerjee (2009) and led to the development of MAST, a flow simulator which solves conservation equations relative to 4-fields (continuous and dispersed gas, continuous and dispersed liquid) in a grid with typical size of 1-2 pipe diameters.

M. BONIZZI, P.ANDREUSSI, S.BANERJEE, “Flow Regime Independent, High Resolution Multi-Field Modelling of Near-Horizontal Gas-Liquid Flow in Pipelines”, Int. J. Multiphase Flow, 35, 34-46, 2009.

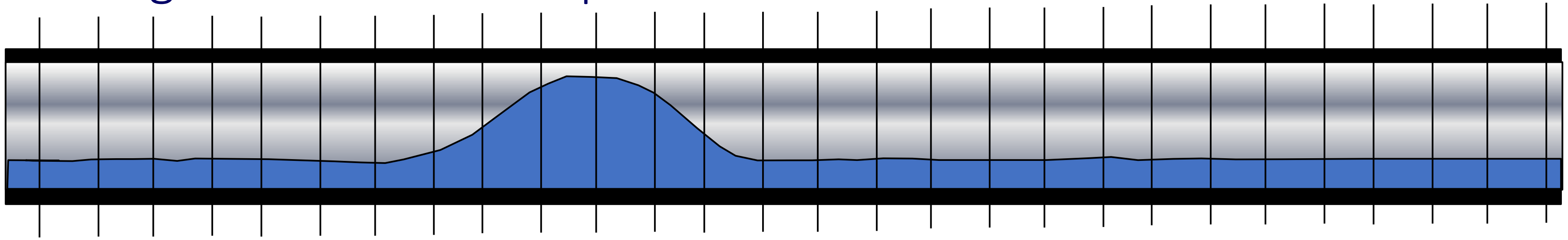
Growth of an interfacial disturbance, MAST (2009)



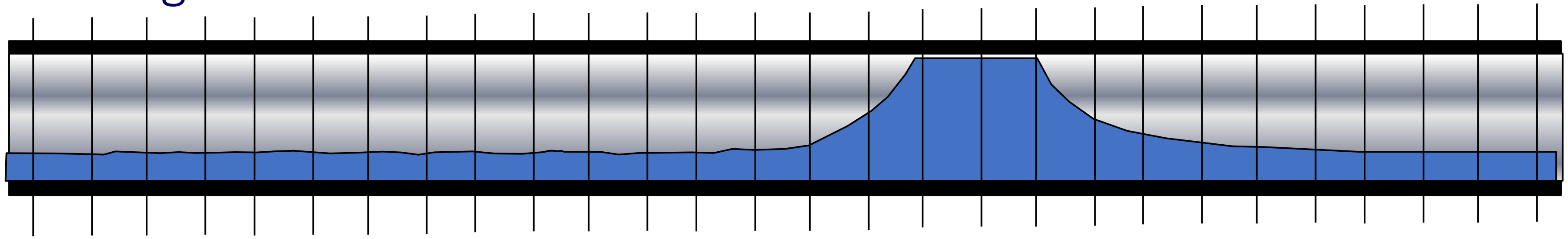
Transition to slug flow, MAST

- ✓ Slug Capturing models are based on a ***Slugging Criterion,*** which establishes when a growing wave touches the top of the pipe. When this happens, gas momentum equation is switched off and the nature of the system of PDEs suddenly changes.

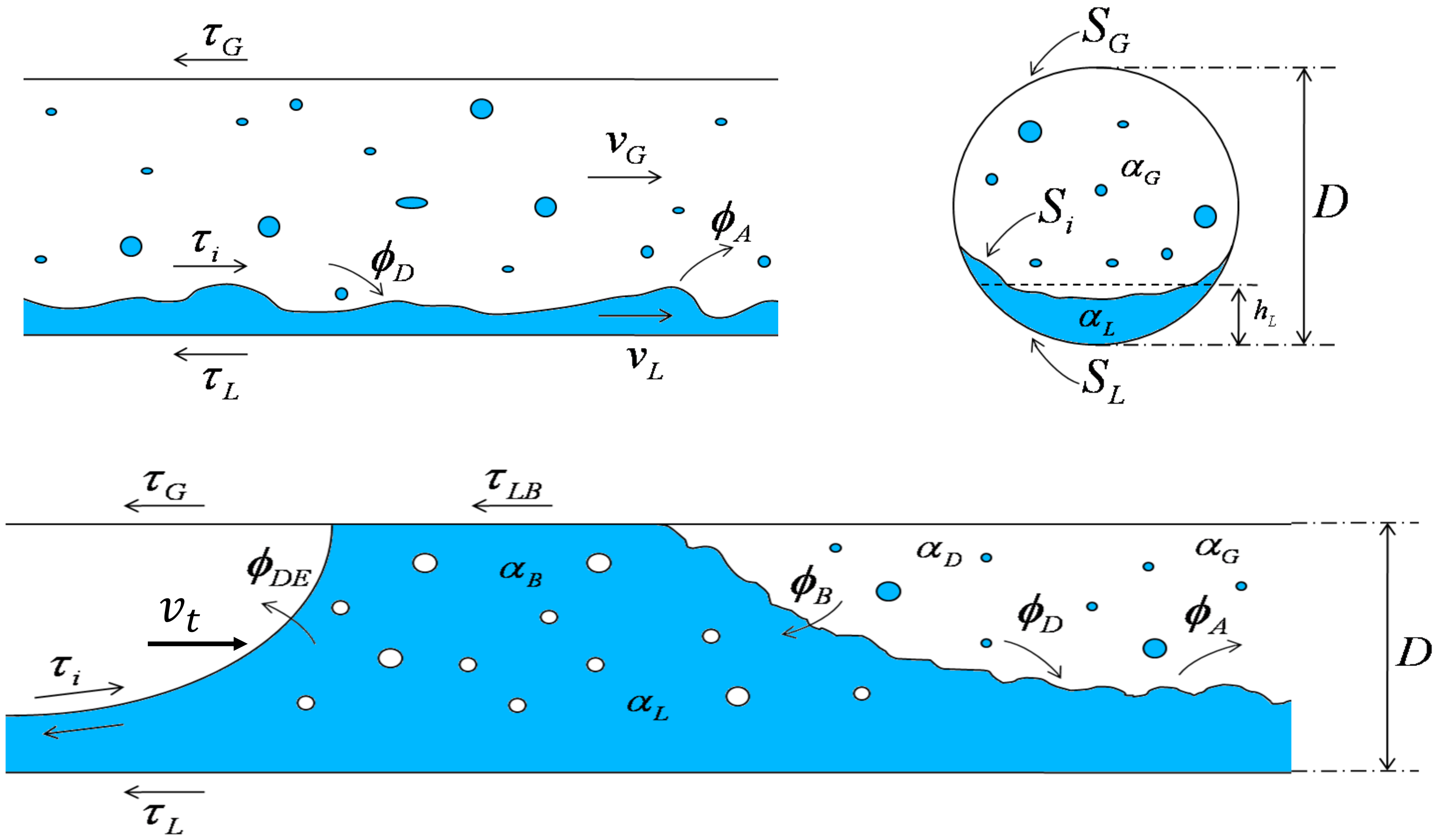
A   Large wave close to top wall



B   Slug is formed



Structure of gas-liquid pipe flow



Conservation of Mass

OLGA

- Gas

$$\frac{\partial}{\partial t}(\alpha_G \rho_G) + \frac{\partial}{\partial x}(\alpha_G \rho_G v_G) = \psi_G$$

- Continuous Liquid

$$\frac{\partial}{\partial t}(\alpha_F \rho_L) + \frac{\partial}{\partial x}(\alpha_F \rho_L v_F) = -\psi_G \frac{\alpha_F}{\alpha_F + \alpha_D} - \phi_A + \phi_D$$

- Dispersed Liquid

$$\frac{\partial}{\partial t}(\alpha_D \rho_L) + \frac{\partial}{\partial x}(\alpha_D \rho_L v_D) = -\psi_G \frac{\alpha_D}{\alpha_F + \alpha_D} + \phi_A - \phi_D$$

MAST

- Continuous Gas

$$\frac{\partial}{\partial t}(\alpha_G \rho_G) + \frac{\partial}{\partial x}(\alpha_G \rho_G v_G) = \psi_G \frac{\alpha_G}{\alpha_G + \alpha_B} - \phi_B + \phi_{DE}$$

- Dispersed Gas

$$\frac{\partial}{\partial t}(\alpha_B \rho_G) + \frac{\partial}{\partial x}(\alpha_B \rho_G v_B) = \psi_G \frac{\alpha_B}{\alpha_G + \alpha_B} + \phi_B - \phi_{DE}$$

- Continuous Liquid

$$\frac{\partial}{\partial t}(\alpha_F \rho_L) + \frac{\partial}{\partial x}(\alpha_F \rho_L v_F) = -\psi_G \frac{\alpha_F}{\alpha_F + \alpha_D} - \phi_A + \phi_D$$

- Dispersed Liquid

$$\frac{\partial}{\partial t}(\alpha_D \rho_L) + \frac{\partial}{\partial x}(\alpha_D \rho_L v_D) = -\psi_G \frac{\alpha_D}{\alpha_F + \alpha_D} + \phi_A - \phi_D$$

Conservation of Momentum (OLGA)

- Continuous Liquid

$$\frac{\partial}{\partial t}\left(\alpha_F \rho_F v_F\right)+\frac{\partial}{\partial x}\left(\alpha_F \rho_F v_F^2\right)=-\alpha_F \frac{\partial P}{\partial x}-\frac{\tau_L S_L}{A}+\frac{\tau_i S_i}{A}+g\alpha_F \rho_L \sin\beta-\psi_G \frac{\alpha_F}{\alpha_F+\alpha_D}v_A-\phi_A v_F+\phi_D v_D$$

- Gas+Dispersed Liquid

$$\frac{\partial}{\partial t}\left(\alpha_G \rho_G v_G+\alpha_D \rho_L v_D\right)+\frac{\partial}{\partial x}\left(\alpha_G \rho_G v_G^2+\alpha_D \rho_L v_D^2\right)=-\left(\alpha_G+\alpha_D\right)\frac{\partial P}{\partial x}-\frac{\tau_G S_G}{A}-\frac{\tau_i S_i}{A}$$

$$+g\left(\alpha_G \rho_G+\alpha_D \rho_D\right)\sin\beta+\psi_G \frac{\alpha_F}{\alpha_D+\alpha_F}v_A+\phi_A v_F-\phi_D v_D$$

Conservation of Momentum (MAST)

- Dispersed Liquid

$$\frac{\partial}{\partial t}\left(\alpha_D \rho_L v_D\right)+\frac{\partial}{\partial x}\left(\alpha_D \rho_L v_D^2\right)=-\alpha_D \frac{\partial P}{\partial x}+g\alpha_D \rho_L \sin\beta-\psi_G \frac{\alpha_D}{\alpha_F+\alpha_D}v_A+\phi_A v_F-\phi_D v_D+F_D$$

- Continuous Liquid+Dispersed Gas

$$\frac{\partial}{\partial t}\left(\alpha_L \rho_L v_L+\alpha_B \rho_G v_B\right)+\frac{\partial}{\partial x}\left(\alpha_B \rho_G v_B^2+\alpha_L \rho_L v_L^2\right)=-\left(\alpha_L+\alpha_B\right)\frac{\partial P}{\partial x}-\frac{\tau_L S_L}{A}+\frac{\tau_i S_i}{A}$$
$$+g\left(\alpha_L \rho_L+\alpha_B \rho_G\right)\sin\beta-\psi_G \frac{\alpha_F}{\alpha_D+\alpha_F}v_A-\phi_A v_F+\phi_D v_D+\phi_B v_G-\phi_{DE} v_B$$

- Continuous Gas+Dispersed Liquid

$$\frac{\partial}{\partial t}\left(\alpha_G \rho_G v_G+\alpha_D \rho_L v_D\right)+\frac{\partial}{\partial x}\left(\alpha_G \rho_G v_G^2+\alpha_D \rho_L v_D^2\right)=-\left(\alpha_G+\alpha_D\right)\frac{\partial P}{\partial x}-\frac{\tau_G S_G}{A}-\frac{\tau_i S_i}{A}$$
$$+g\left(\alpha_G \rho_G+\alpha_D \rho_D\right)\sin\beta+\psi_G \frac{\alpha_F}{\alpha_D+\alpha_F}v_A+\phi_A v_F-\phi_D v_D-\phi_B v_G+\phi_{DE} v_B$$

Conservation of Energy

$$\frac{\partial}{\partial t}\left(\rho_G v_G E_G + \rho_L v_F E_F + \rho_L v_D E_D\right) + \frac{\partial}{\partial x}\left(\rho_G v_G^2 E_G + \rho_L v_F^2 E_F + \rho_L v_D^2 E_D\right) = Q$$

$$E = e + \frac{1}{2}v^2 + gh$$

Main features of MAST

- ✓ Model equations are integrated in space using a first order upwind scheme and in time using an explicit Euler method. This allows easy parallelization of the code.
- ✓ Closure equations used to predict wall and interfacial friction factors are flow regime independent and can be chosen by the user from a set of available correlations.
- ✓ Most of the R&D work behind the development of MAST has been published in the open literature.
- ✓ MAST has been developed in cooperation with ENI and validated against data taken at the Multiphase Flow Laboratory of TEA Sistemi, the SINTEF Data bank and various sets of field data provided by ENI, Statoil, BP and Total.

Comparison among flow simulators, Pressure Gradient

	LP Data	SESAME	SINTEF	Overall
MAST	11.0	14.6	13.0	12.6
OLGA	32.6	15.6	14.5	20.0

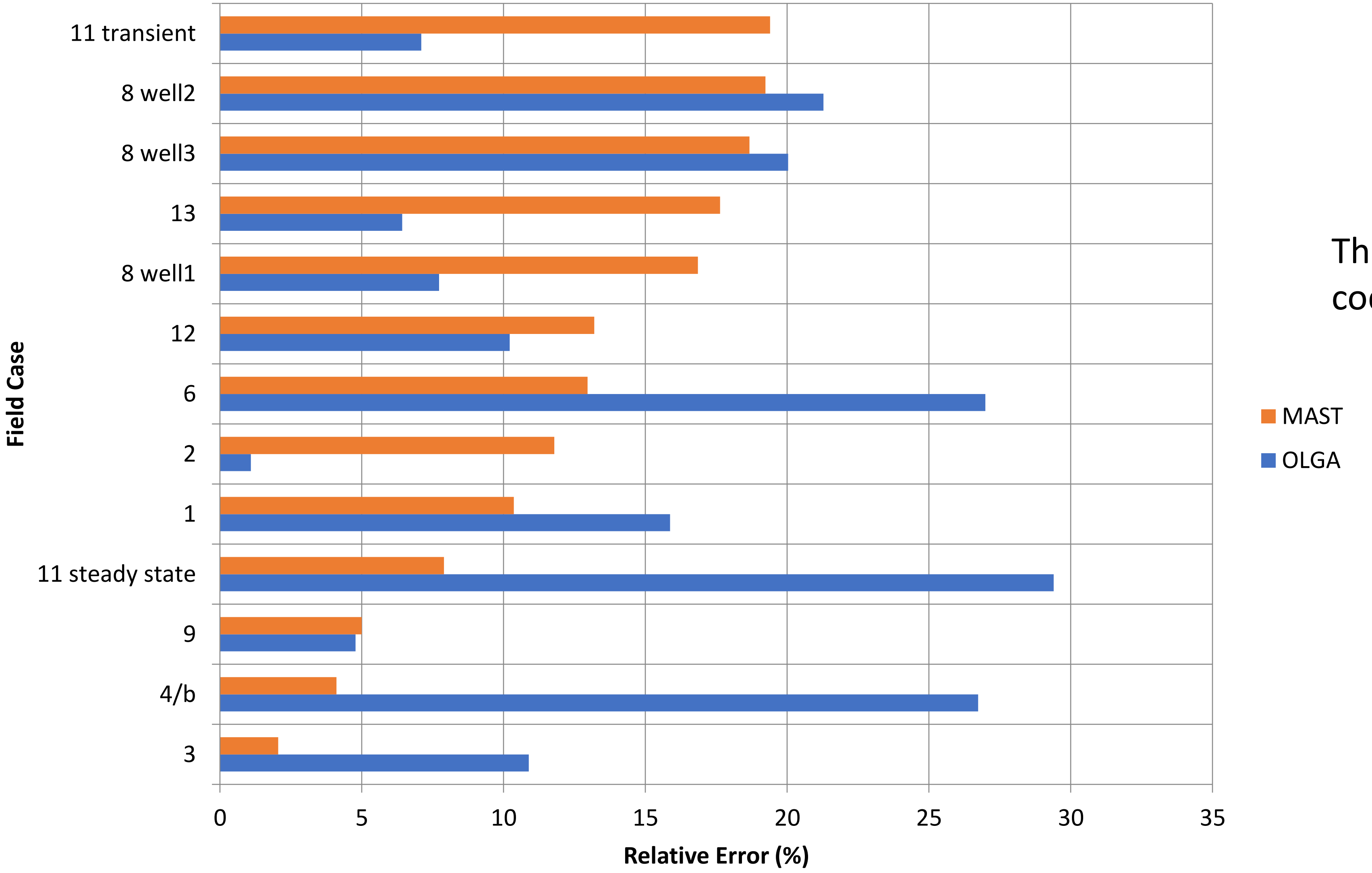
Comparison among flow simulators, Liquid Hold-up

	LP Data	SESAME	SINTEF	Overall
MAST	16.7	8.2	12.8	13.5
OLGA	24.9	15.3	15.6	18.7

Comparison among flow simulators, Investigated Scenarios

CASE	SYSTEM	FLUID	TYPE	TOTAL LENGTH	ARRIVAL PRESSURE
-	-	-	-	km	bara
1	Offshore Network	Gas	Steady state	Pipeline 1: 1+63 Pipeline 2 5+63 Pipeline 3: 22+63	100, 43.1, 41.5
2	Offshore Network	Gas Condensate	Steady state	20+45	59
3	Onshore Network	Gas Condensate	Steady state	Well1: 2+14.5 Well2: 1.2+14.5	72
4	Onshore Network	Gas Condensate	Steady state	34	66, 70
5	Offshore Line	Gas	Steady state	4.8	5.6 ÷ 8.8
6	Offshore Line	Oil	Steady state	Well1: 6.8 Well2: 7.7	8
7	Onshore Line	Oil	Steady state	15.7	39
8	Deepwater Well +line	Oil	Steady state	Well1: 6.5 Well2: 7.3 Well3: 6.5	22
9	Deepwater Well +line	Oil	Steady state	Well1: 5.8 Well2: 6.3	39 - 34
10	Deepwater Well + Network	Oil	Steady state/Transient	5.5	8.5
11	Offshore Line	Gas Condensate	Steady state/Transient	Steady state: 44.7 Transient: 150.8	Steady state: 71.8 Transient: 100 ÷ 125
12	Offshore Line	Gas	Steady state	20	21 ÷ 34
13	Onshore Line	Gas Condensate	Steady state	13+33	90

Pressure drops (MAST vs. OLGA)



The mean error for both codes is around 14 %

Transient slug flow models

- ✓ In OLGA, slug flow is described with a simplified, steady-state, slug-unit model. The evolution of a slug train generated at the inlet of a long pipe is predicted with the **Slug Tracking** module, which uses an empirical correlation to predict the slug inlet frequency.

- ✓ Fan et al. 2013 (British Petroleum) analysed a set of field data using this module and found that the results were strongly dependent on the value of this frequency. This limitation of the Slug Tracking module is well known in the Flow Assurance community.

Transient slug flow models

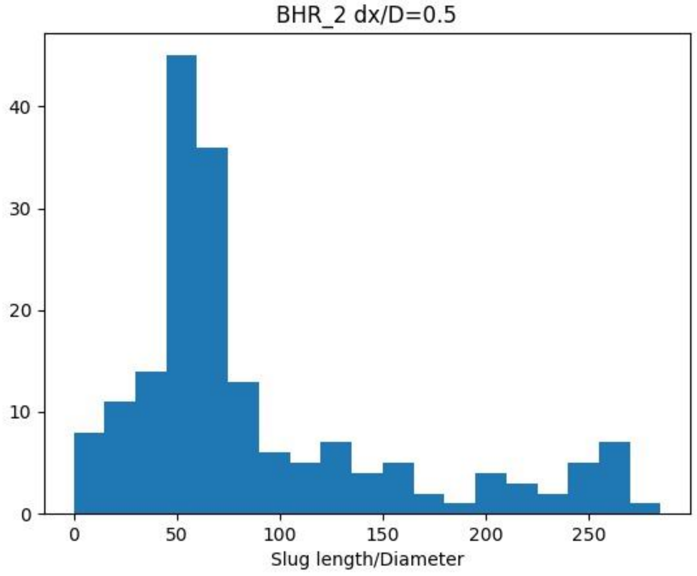
- ✓ **Slug Capturing** allows the formation of single slugs and their evolution along the pipe to be caught. To this purpose a fine grid and a long execution time are needed. Recently, Lockett et al. 2017 (British Petroleum) tested different simulators based on the Slug Capturing method (Prompt, Ledaflow, MAST) and found satisfactory results.

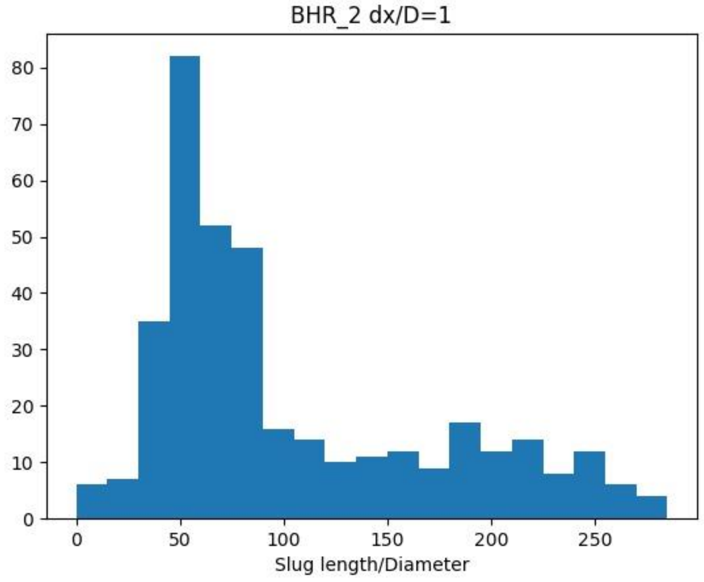
- ✓ With this approach, the effect of grid size should be carefully studied because in slug capturing the minimum slug length which can be observed is equal to the grid size. Then, the correct choice of grid size becomes a central issue. The question is how much coarse can be a “fine” grid, still providing good results and low computation time?

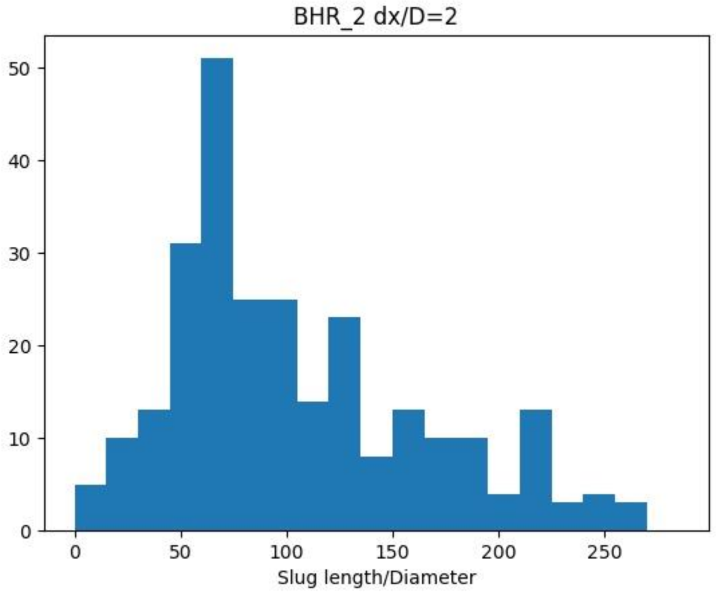
Analysis of slug data

- ✓ A set of data produced at BHR Laboratory (Dhulesia et al. 1991) can be used to analyse the effects of grid size on slug length distribution. Main flow parameters are: L=375 m, D=0.2 m, Usl=0.8 m/s, Usg from 1.26 to 7.52 m/s and Pout=1 bar

Effect of grid size on slug length distribution



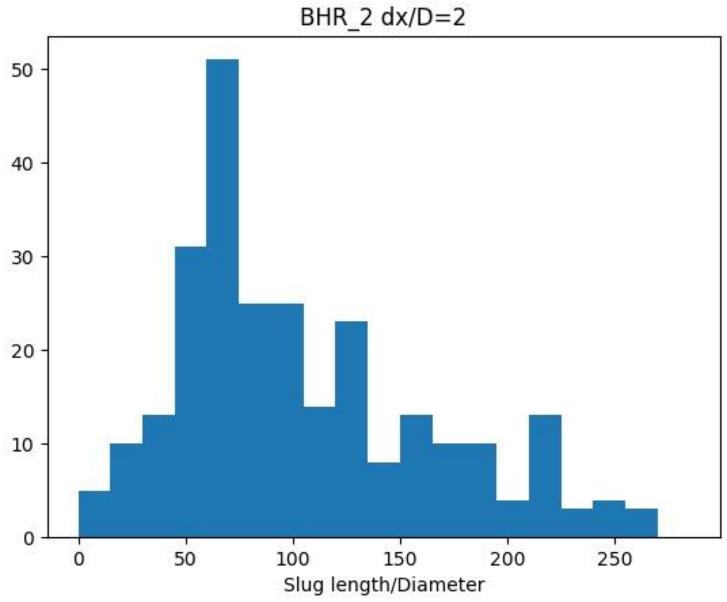


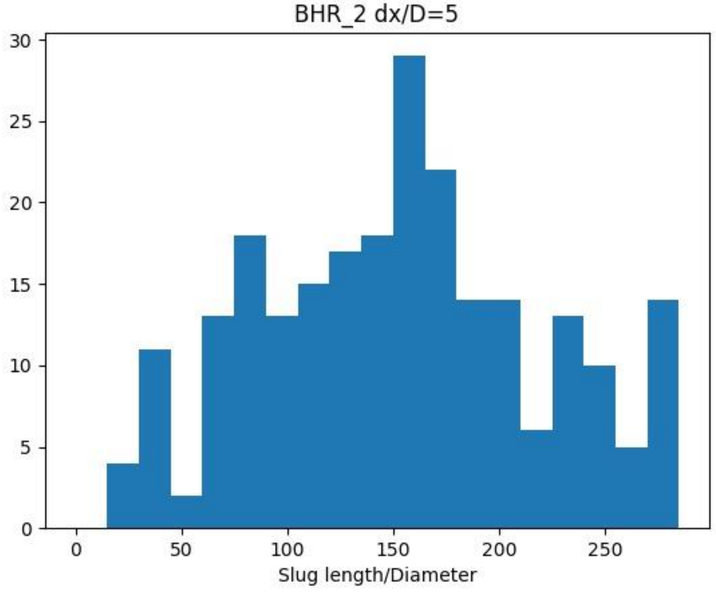


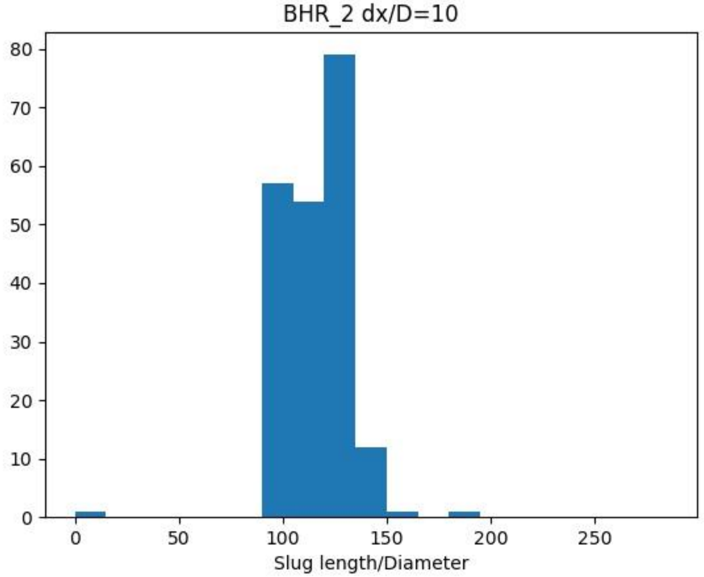
Analysis of slug data

- ✓ Predictions are fair up to a grid size equal to 2 D. For 5 D, the maximum slug length is caught. For 10 D small slugs are lost, but still the presence of very long slugs (200 D) is detected.

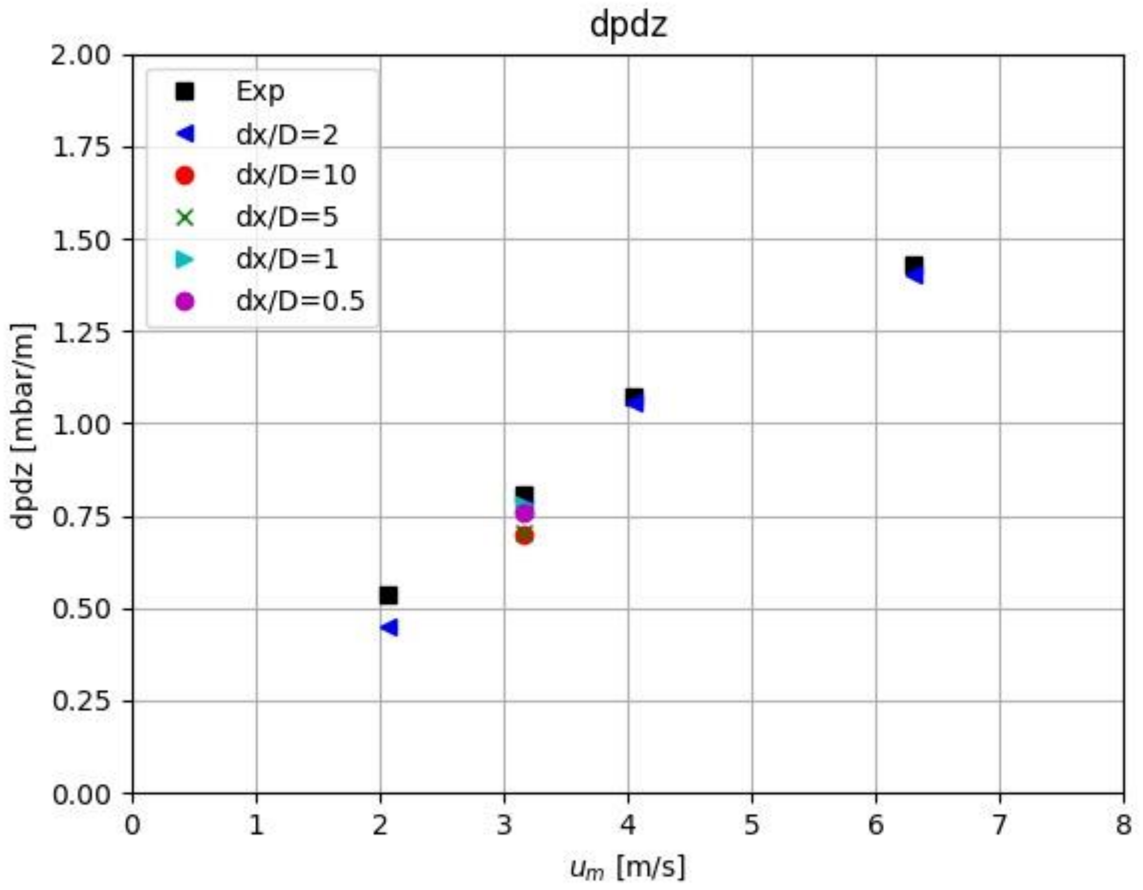
Effect of grid size on slug length distribution

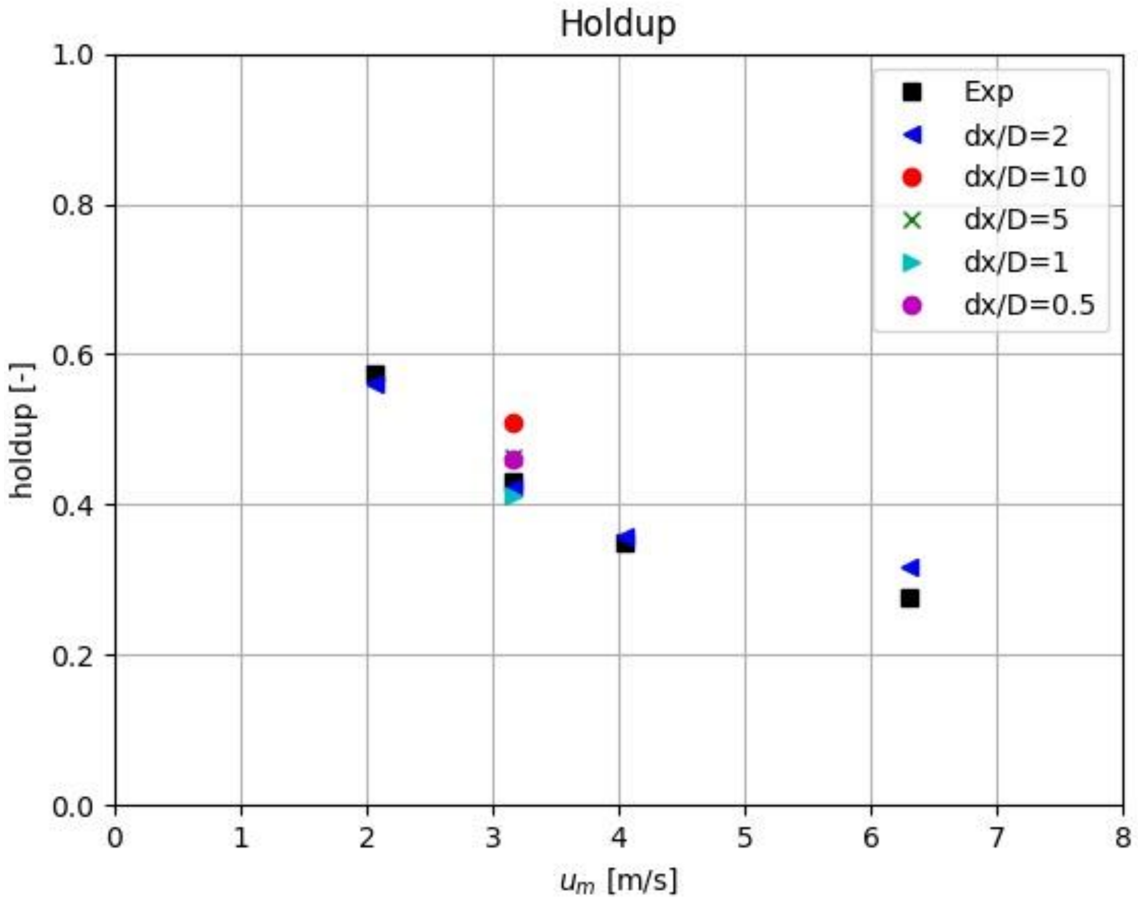




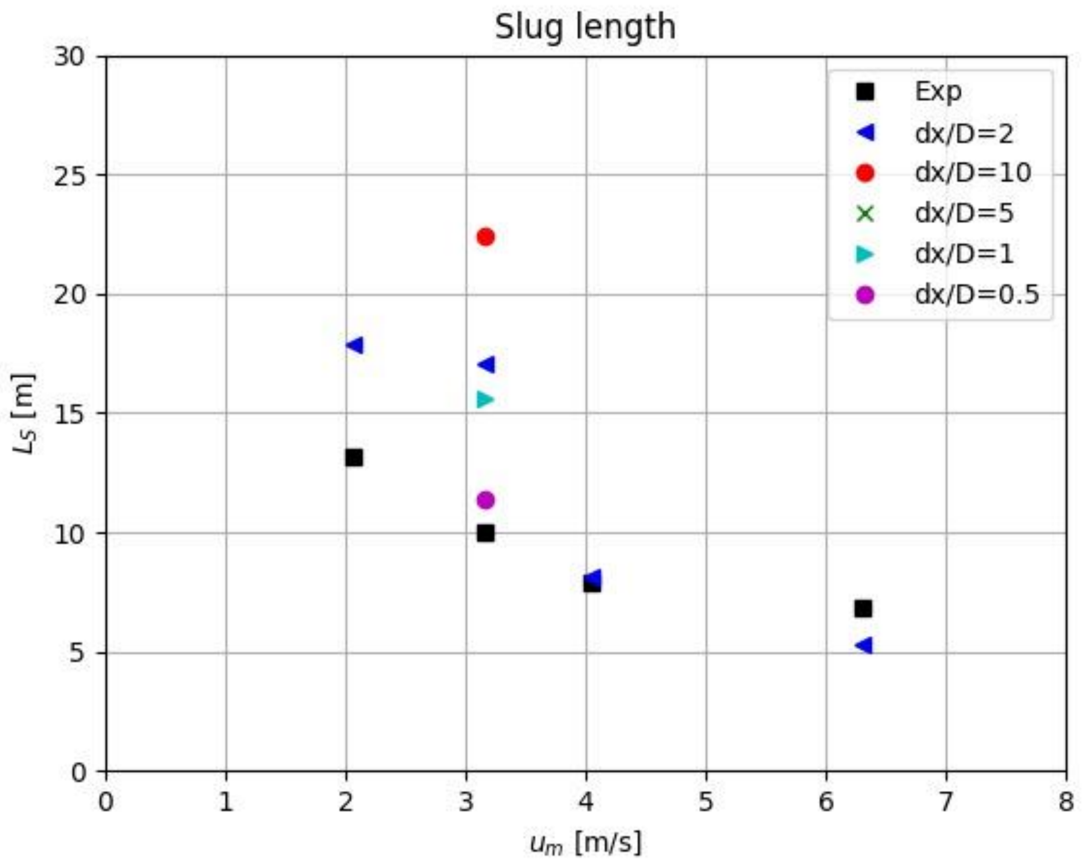


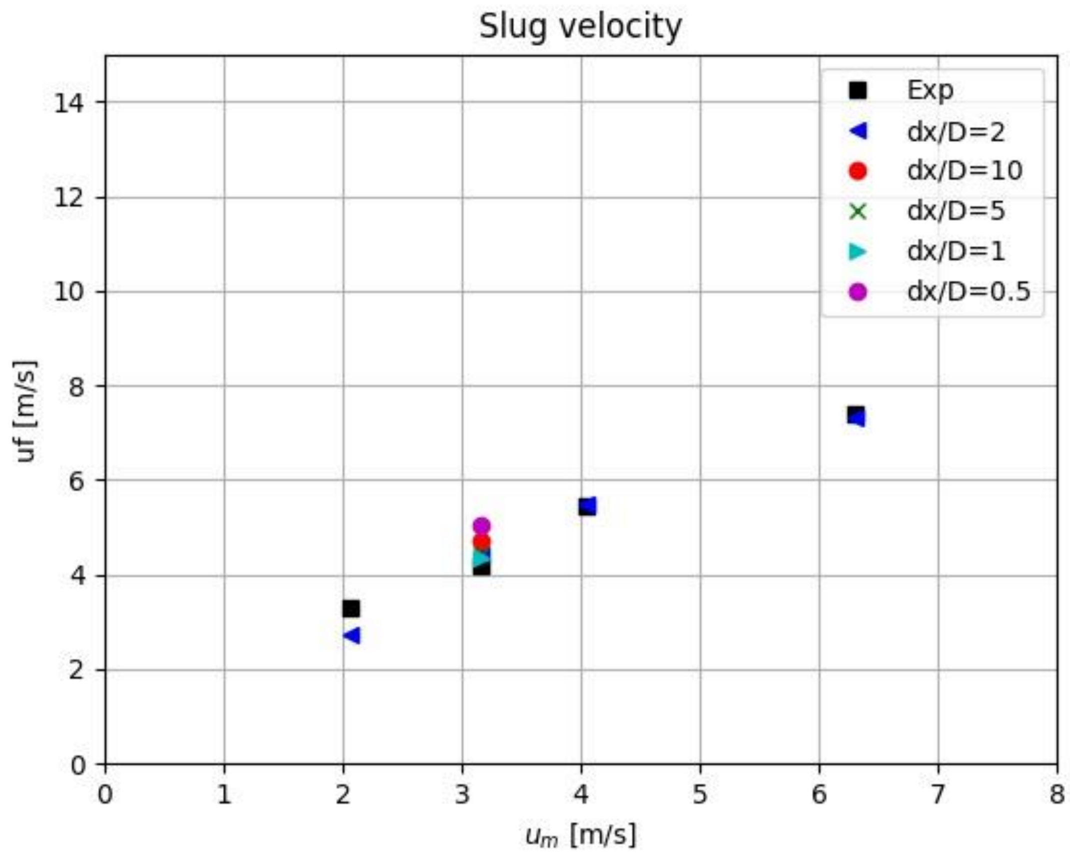
Effect of grid size on pressure gradient and liquid holdup



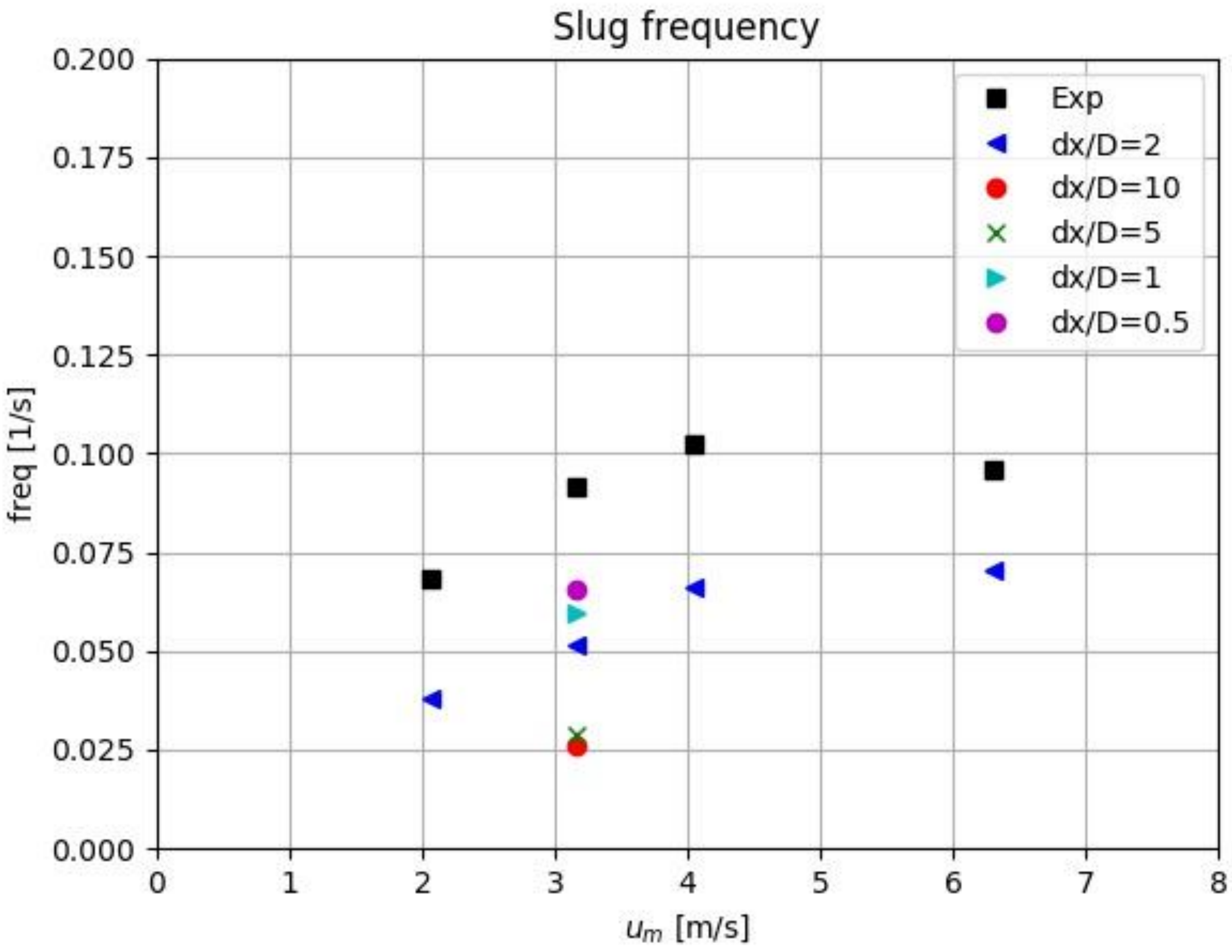


Effect of grid size on slug length and velocity





Slug frequency



Present and Future of OLGA (according to Chris Lawrence)

- ✓ At the last BHR Conference (Cannes, June 2017), Chris Lawrence (Schlumberger) presented his views on the future of multiphase flow simulators and pointed out that the computation time required by fine grid models puts them out of business.

Simulation options

Simple example

Long pipeline D ~ 1 m, L ~ 100 km, Velocity U ~ 10 m/s

Simulated time T ~ L/U ~ 10000 s (~ 3 hr)

1D simulation, coarse grid

$\Delta Z \sim 100\times D \sim 100$ m → 10^3 cvs

$\Delta T \sim \Delta Z/U \sim 10$ s → 10^3 time steps

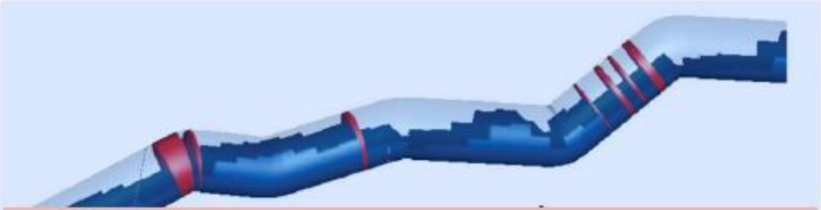
Operation count ~ $10^6 \times N_{1DC}$

1D simulation, "fine" grid

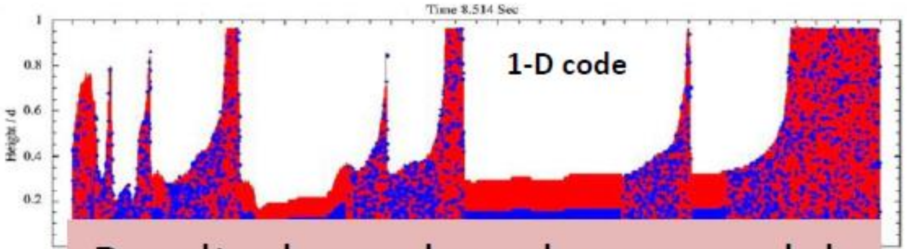
$\Delta Z \sim D \sim 1$ m → 10^5 cvs

$\Delta T \sim DZ/U \sim 0.1$ s → 10^5 time steps

Operation count ~ $10^{10} \times N_{1DF}$



Results depend on closure models
e.g. interfacial friction



Results depend on closure models
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Chris Lawrence, Schlumberger, Invited Lecture,
18° Int. Conference on Multiphase Technology, Cannes, 2017

Simulation options

Simple example

Long pipeline D ~ 1 m, L ~ 100 km, Velocity U ~ 10 m/s

Simulated time T ~ L/U ~ 10000 s (~ 3 hr)

1D simulation, coarse grid

$\Delta Z \sim 100 \times D \sim 100$ m → 10^3 cvs

$\Delta T \sim \Delta Z/U \sim 10$ s → 10^3 time steps

Operation count ~ $10^6 \times N_{1DC}$

Results depend on closure models
e.g. interfacial friction

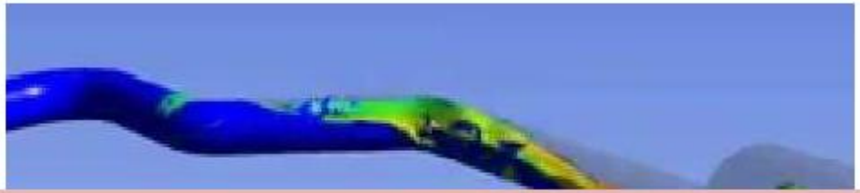
3D simulation, coarse grid

$\Delta X \sim \Delta Y \sim D/30 \sim 3$ cm

$\Delta Z \sim D/10 \sim 10$ cm → 10^9 cvs

$\Delta T \sim DZ/U \sim 0.01$ s → 10^6 time steps

Operation count ~ $10^{15} \times N_{3D}$

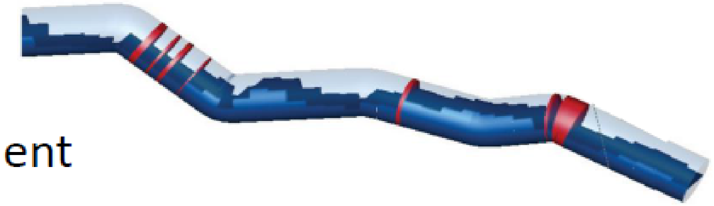


Results depend on closure models
e.g. turbulent transport across interfaces

Chris Lawrence, Schlumberger, Invited Lecture,
18° Int. Conference on Multiphase Technology, Cannes, 2017

Conclusion

- 1D simulations on a coarse grid are still a workhorse
  - The only reasonable option for very long pipelines and complex networks
  - Design, operation, optimisation
  - Underlying models are still in development
  - Moving to pre-integrated 3D models with 1D computation time



- CFD and 1D fine-grid simulations are complementary tools:
  - Detailed examination of local regions in space/time
  - Low aspect ratio equipment: separators, pumps, valves, …

Chris Lawrence, Schlumberger, Invited Lecture,
18° Int. Conference on Multiphase Technology, Cannes, 2017

Slug Capturing models

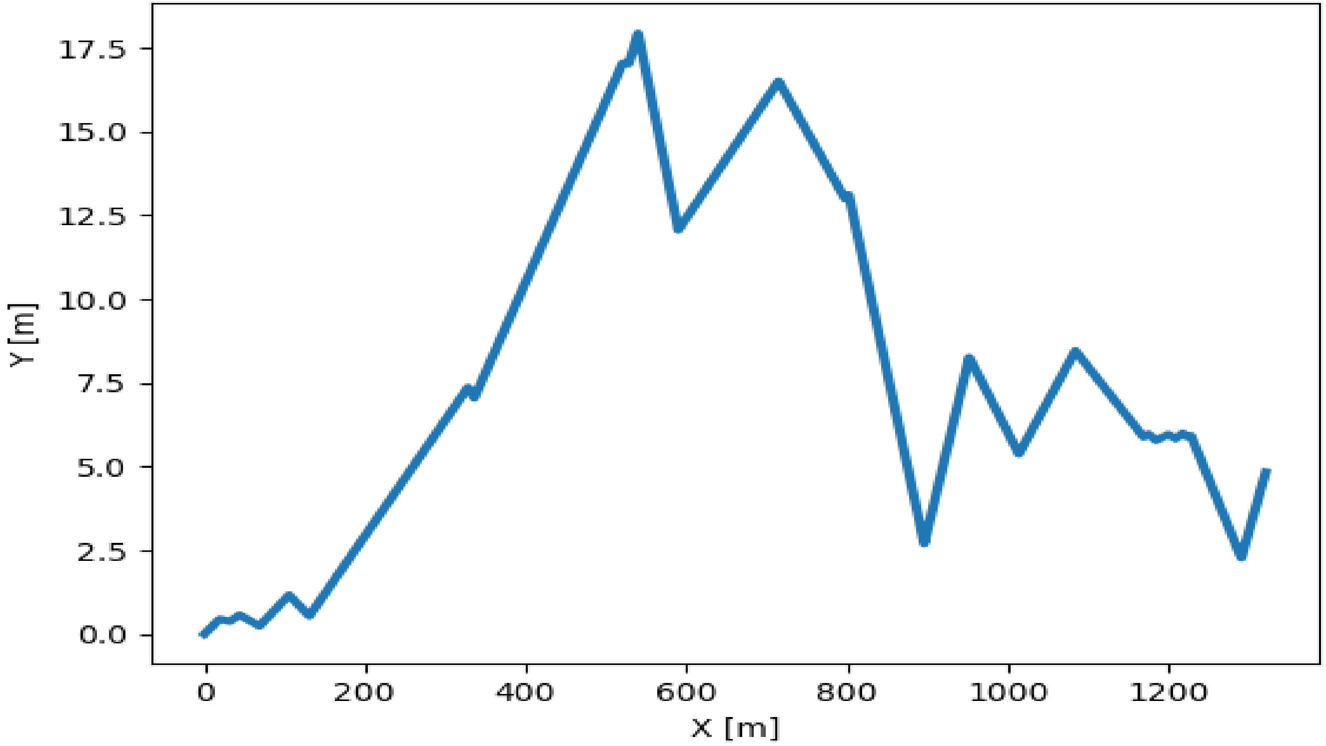
- ✓ The execution time is the main limitation of flow simulators like MAST, which require a fine grid to model flow regime transitions and complex flow patterns, such as slug flow.
- ✓ It is also clear that parallel computing provides a possible way out. At present, a parallel version of MAST permits a speed-up above 10x on a 16 core PC. Graphic boards may provide speed-ups greater than 500x.
- ✓ With speed-ups of this order, a simulator like MAST can be much faster than OLGA. How is it possible if the ratio between execution times is equal to 10^4?

Slug Capturing models

- ✓ The key point is that fine-grid simulators, when used with a coarse grid, still provide good results (and a reasonable execution time). The reverse is not true, i.e. a coarse-grid simulator like OLGA does not allow the simulation of slug flow or the detection of flow regime transitions when used with a fine grid.
- ✓ A set of simulations relative to a real pipeline on a hilly terrain can be used as a benchmark to clarify the differences between coarse and fine grid simulators, in terms of execution time and description of the flow structure.

Simulation of a pipeline in a desert south of Sicily

Line altimetry



Diameter: 0.387 m

L=1320 m

Q_{oil} =27.61 Kg/s

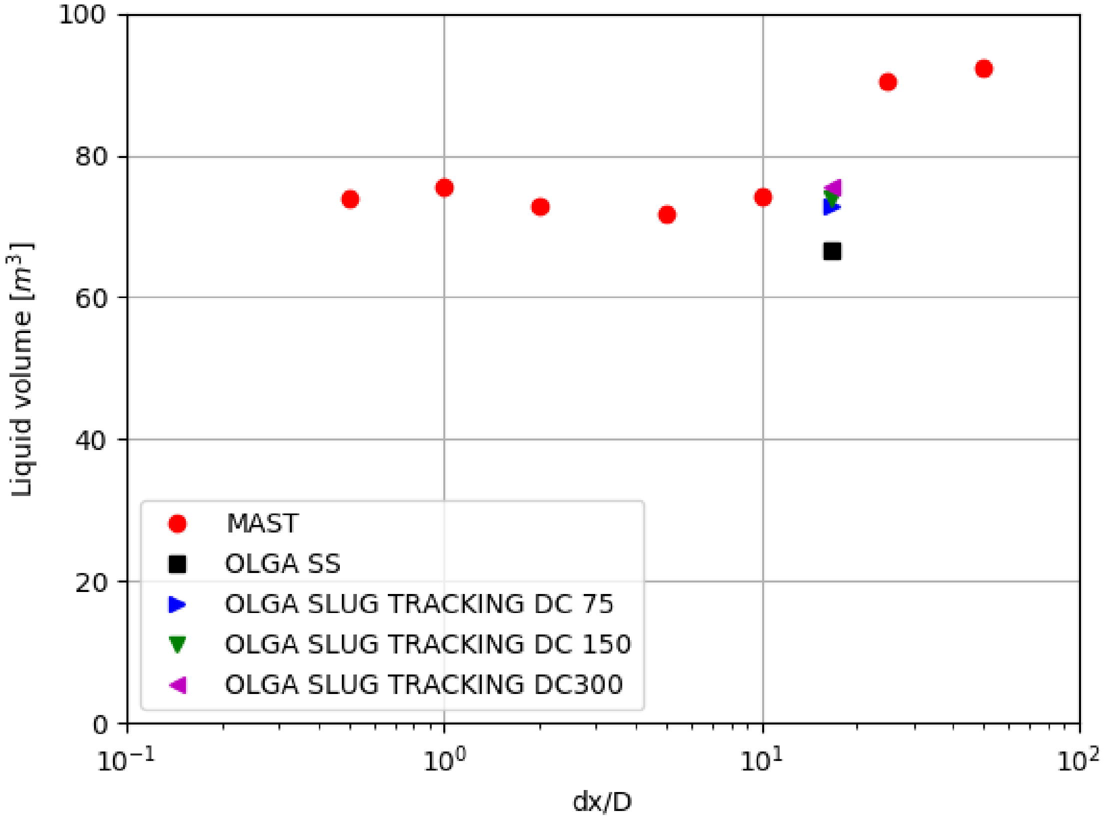
Q_{gas} =3.44 Kg/s

Q_{water} =1.8193 Kg/s

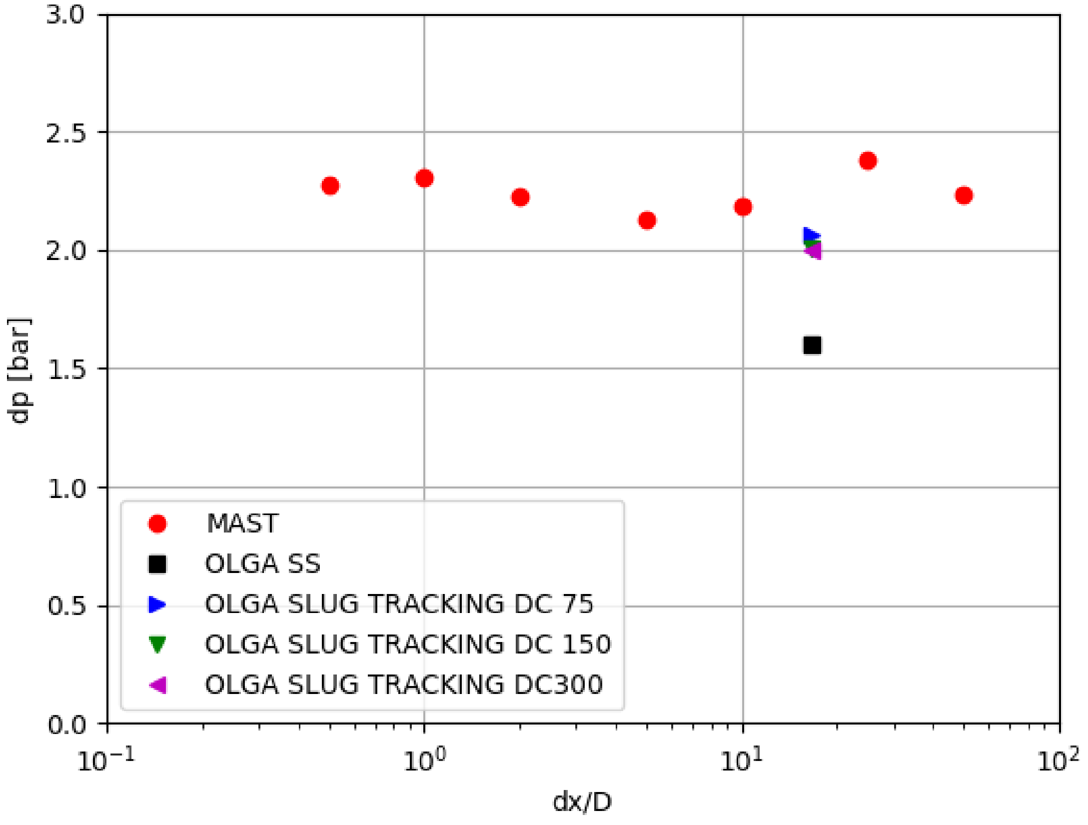
Pout=35 bar

Simulation of a pipeline in a desert south of Sicily

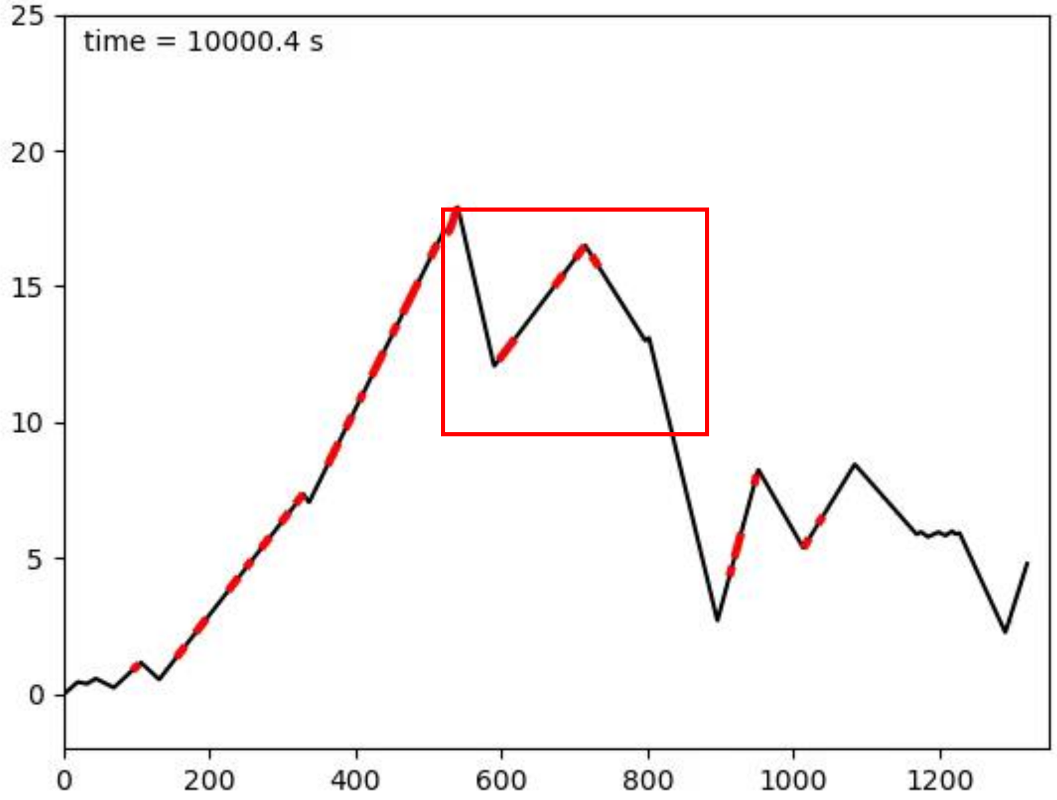
Liquid Volume



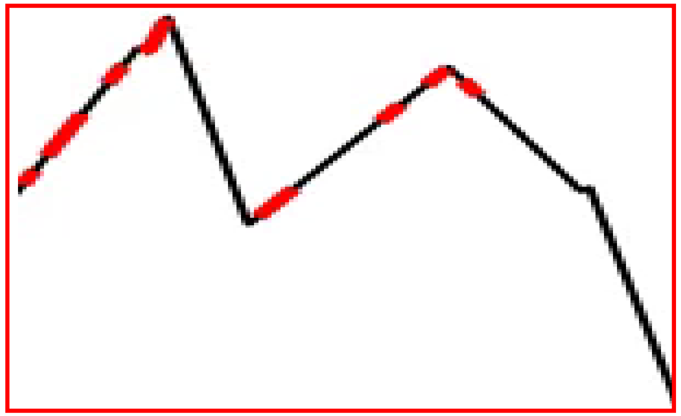
Pressure Drop

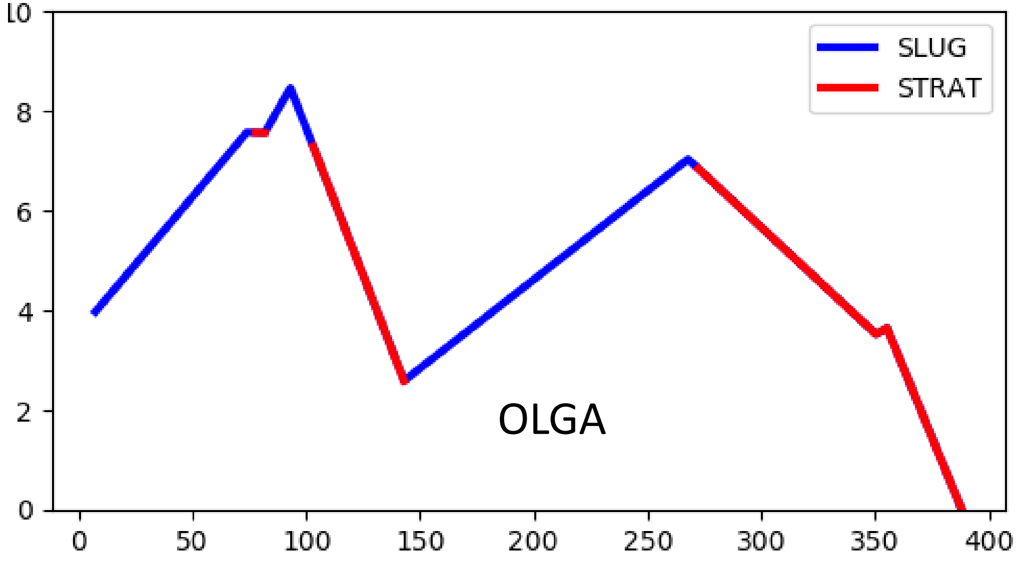


Simulation of a pipeline in a desert south of Sicily

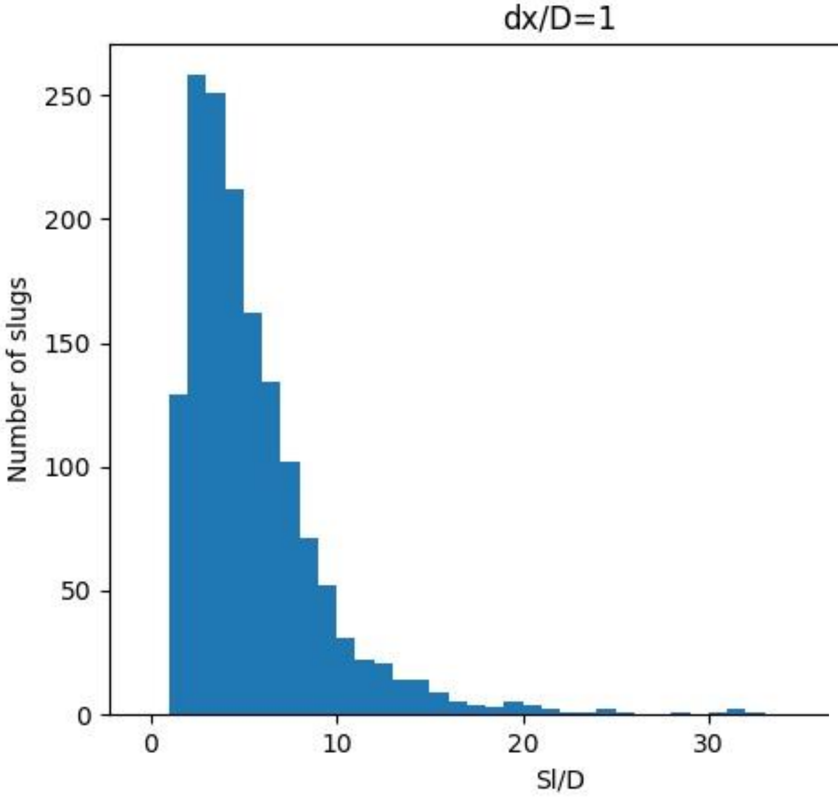


MAST

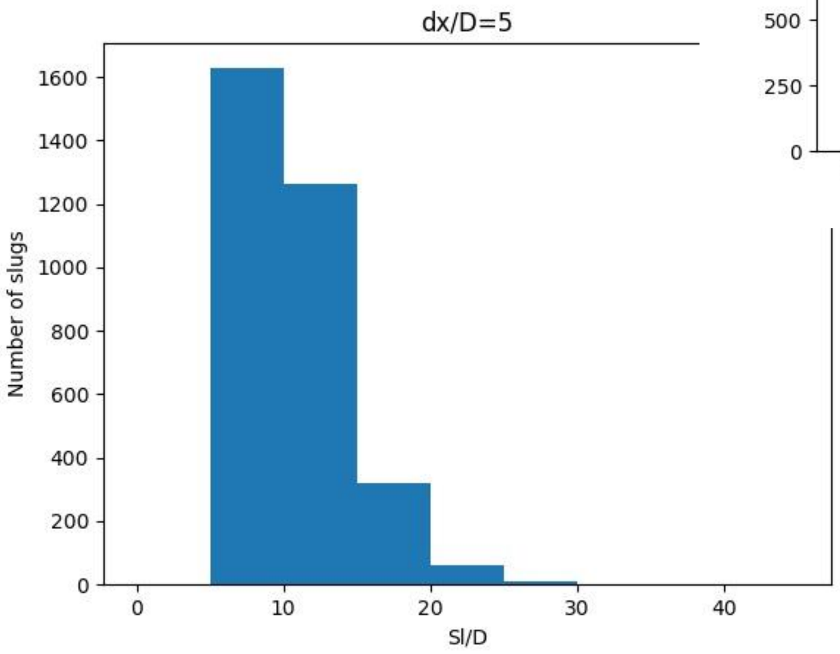


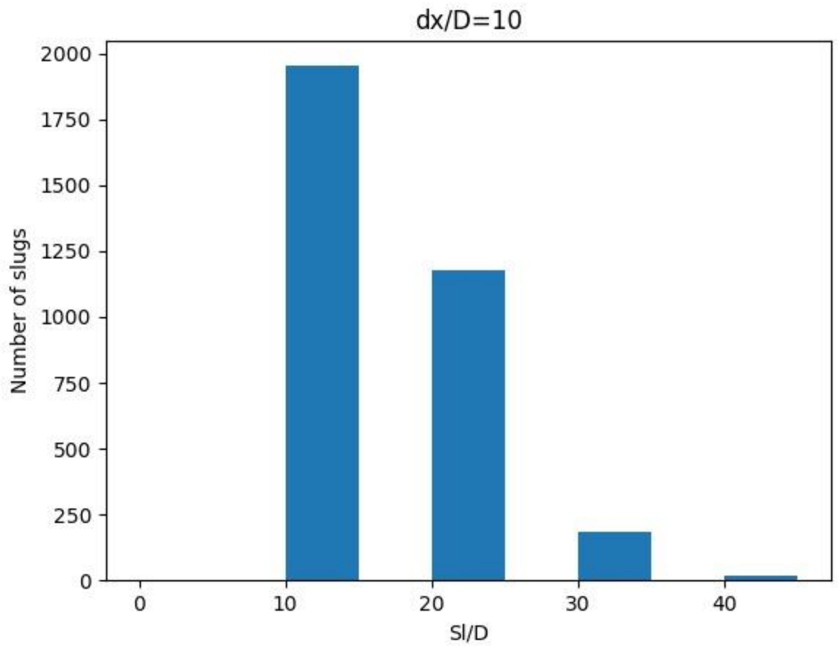


Slug statistics MAST



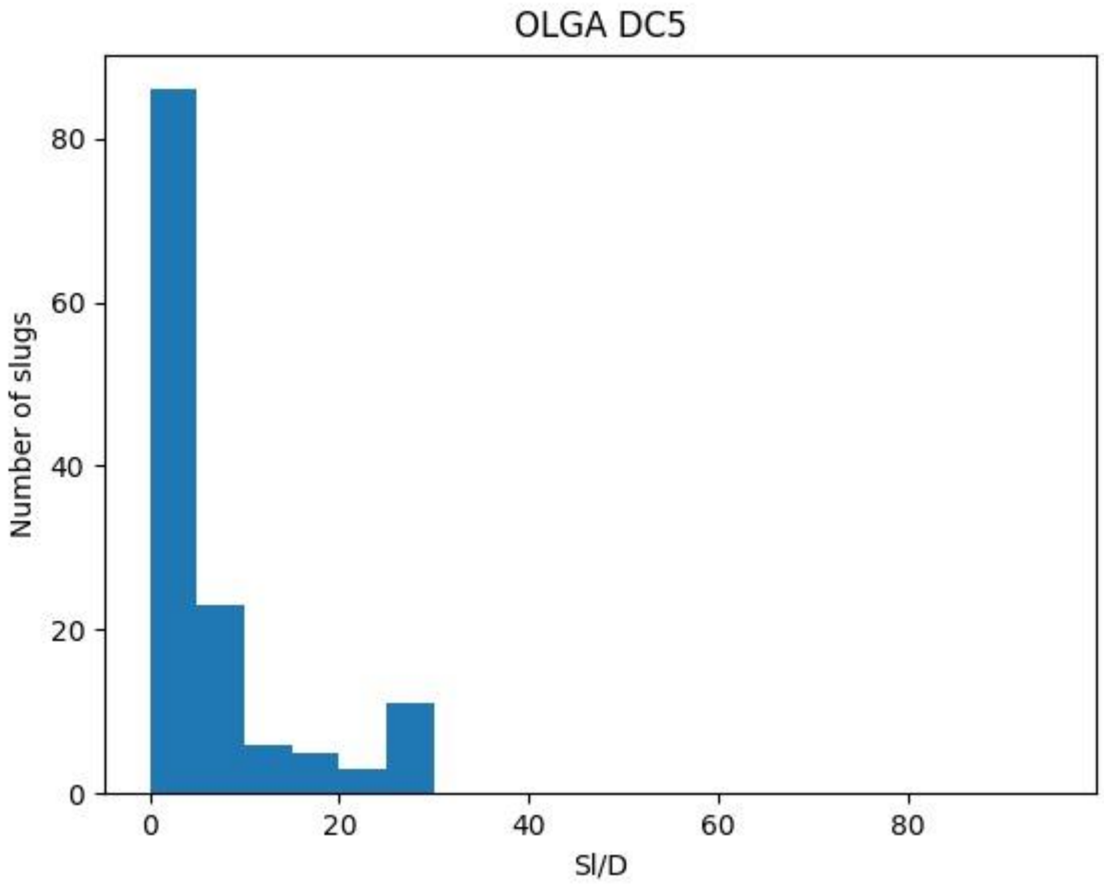
Freq=0.3 Hz



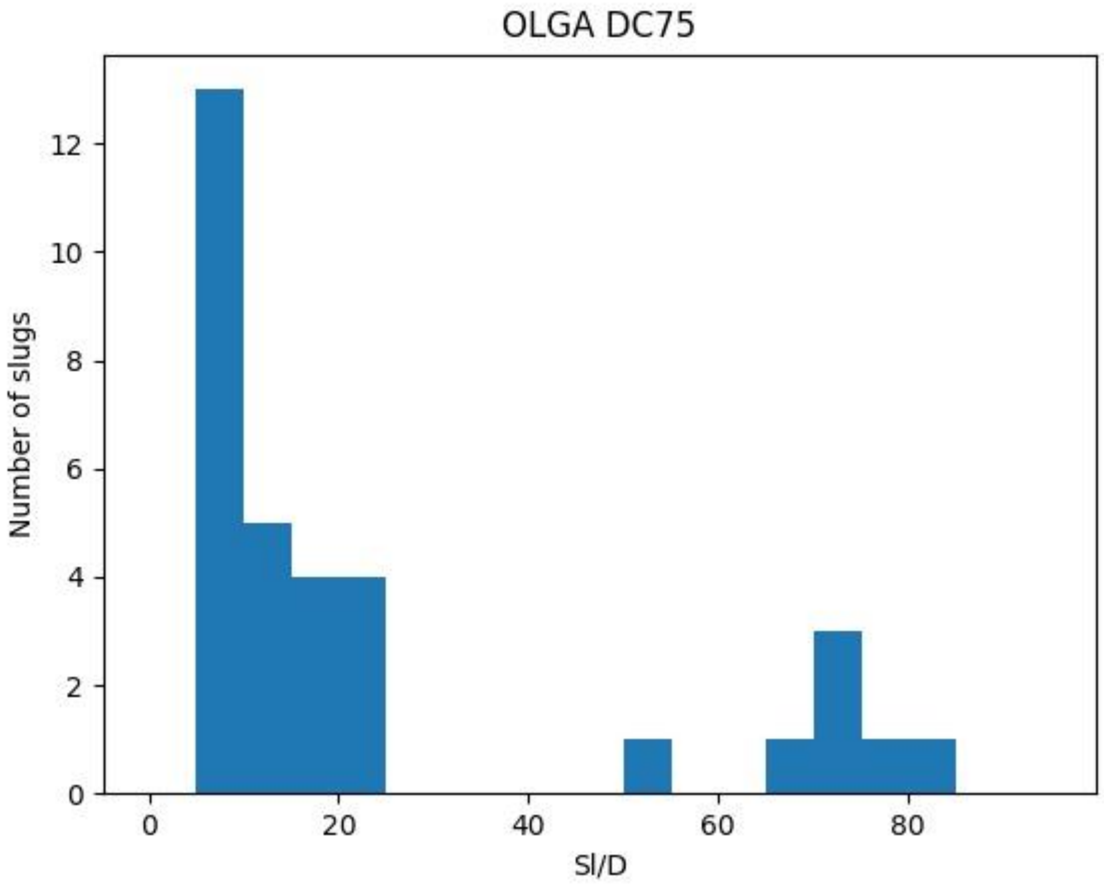


Slug statistics OLGA Slug Tracking module

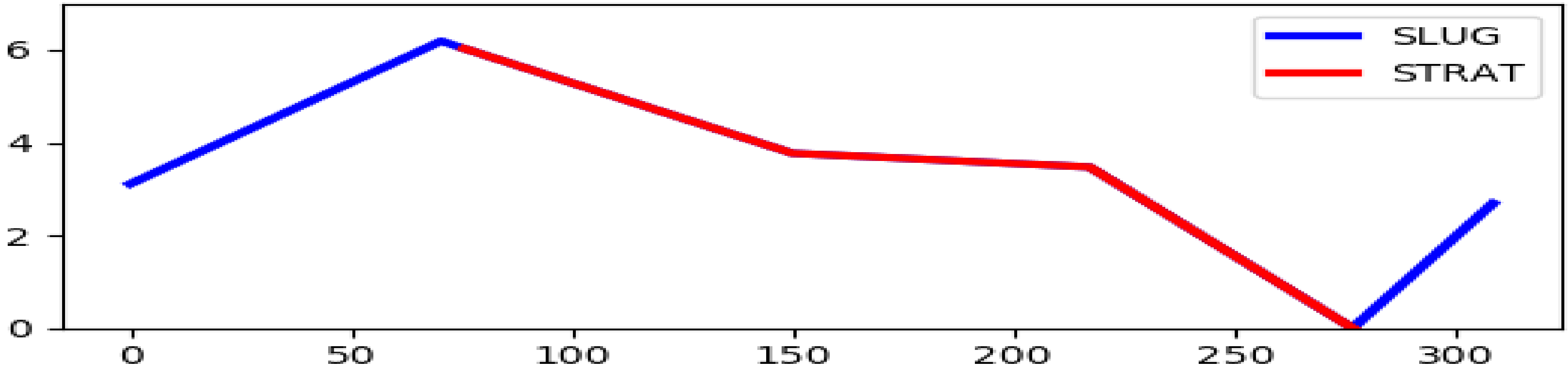
Freq=0.06 Hz
(Delay Costant=5)

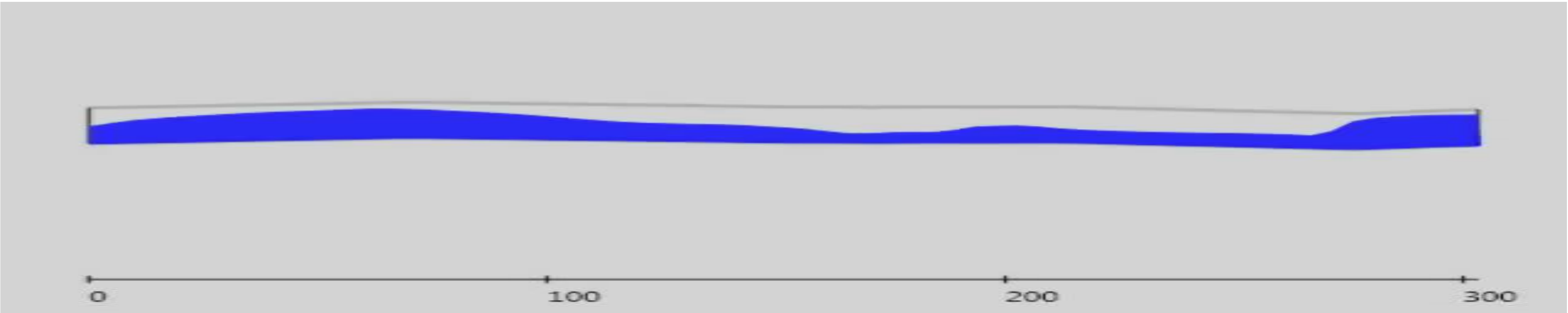


Freq=0.016 Hz
(Delay Costant=75)

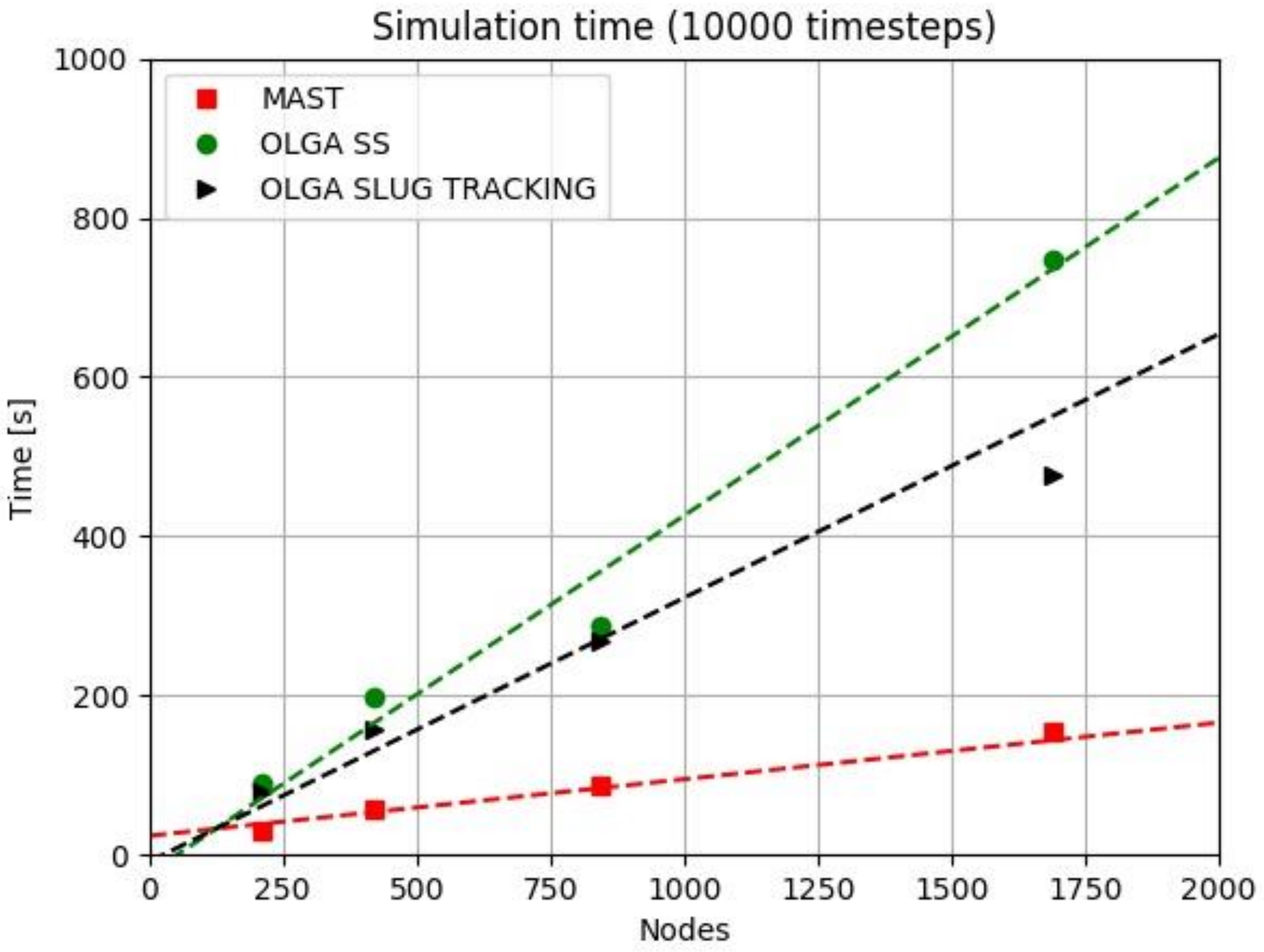


Simulation of a pipeline in a desert south of Sicily





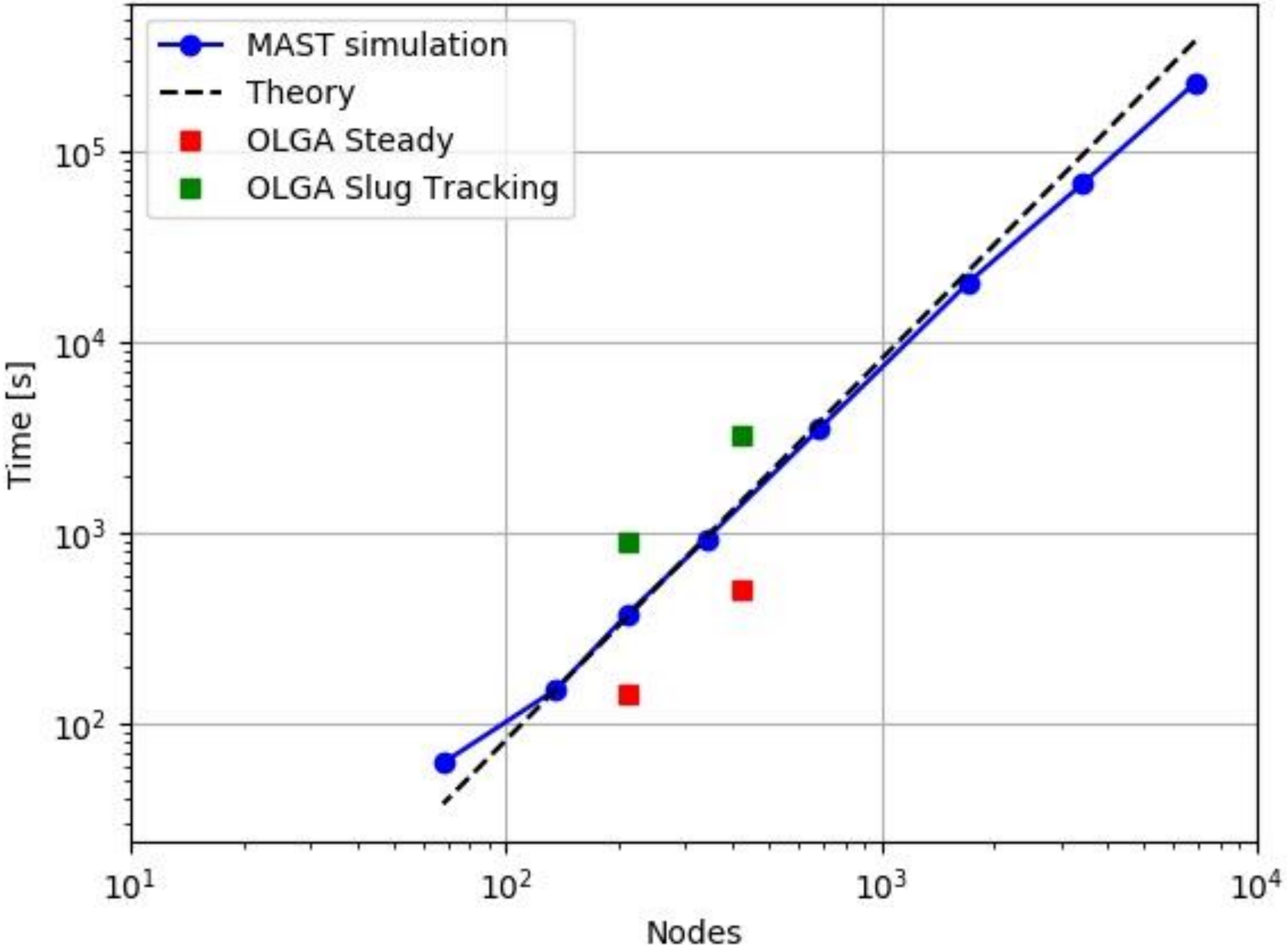
Computational cost



Computational cost

- ✓ The ratio between execution times equal to 10^4 becomes **100** when a 10 D grid is used, **20** considering the ratio between code efficiencies, **2** with a 10 core PC and **0.2** with a 100x GPU.
- ✓ However, the OLGA implicit solver typically operates with larger time steps and a parallel version is on the market.
- ✓ It can be concluded that the problem exists, but there are a few solutions ….

CPU time for 10000 s of simulation time



The future of Multiphase Flow Simulators

- ✓ Fine grid simulators running on a GPU of a standard PC already provide execution speeds which permit process control (e.g., control of severe slugging) and the analysis of complex pipeline networks.
- ✓ 2D-3D simulations can be used to develop pre-integrated models to be included into 1D flow simulators. This process is currently underway with OLGA.

“Pre-integrated” models

- Make a detailed analytical model of the subgrid phenomenon
- Integrate analytically over pipe control volume

Prototype is the friction model

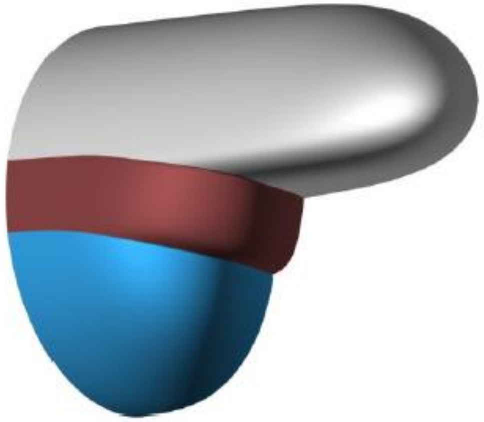
- In each layer, velocity profile = $fn\left(y, z, u_\varphi, \alpha_\varphi, \tau_\varphi, \tau_{i_\varphi}, \tau_{j_\varphi}\right)$
- Apply continuity of velocity and stress at the interfaces
- Integration gives relations between key quantities

$$fn\left(u_\varphi, \alpha_\varphi, \tau_\varphi, \tau_{i_\varphi}, \tau_{j_\varphi}\right) = 0$$

- Solve for stresses

$$\tau_\varphi = fn\left(\{u_\varphi\}, \{\alpha_\varphi\}\right)$$

- 3D model with 1D computation time



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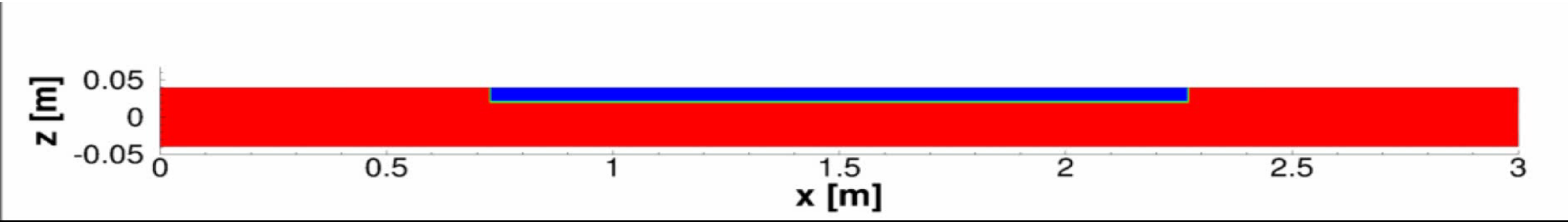

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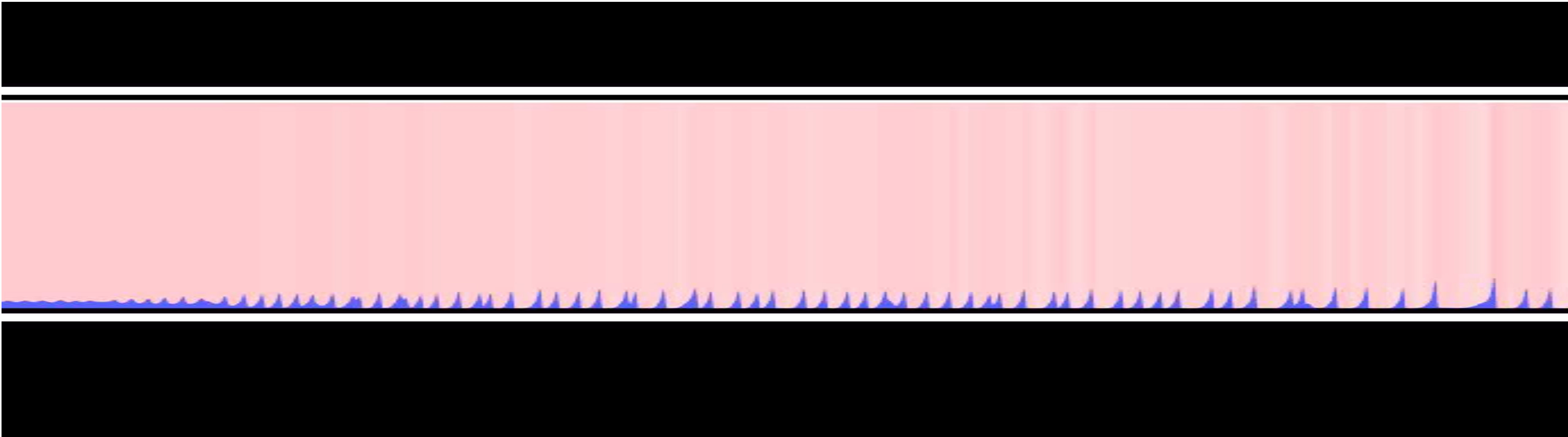
- ✓ 2D-3D simulations can be used to develop pre-integrated models to be included into 1D flow simulators. This process is currently underway with OLGA (OLGA HD) and with MAST (Slug flow of heavy oil).
- ✓ The case of **Stratified-Dispersed and Annular flow** in inclined pipes deserves a special attention because of the increasing interest towards production and transportation of wet gas and the poor description of this flow patterns in existing flow simulators. In this respect, the wave capturing approach can be interesting.

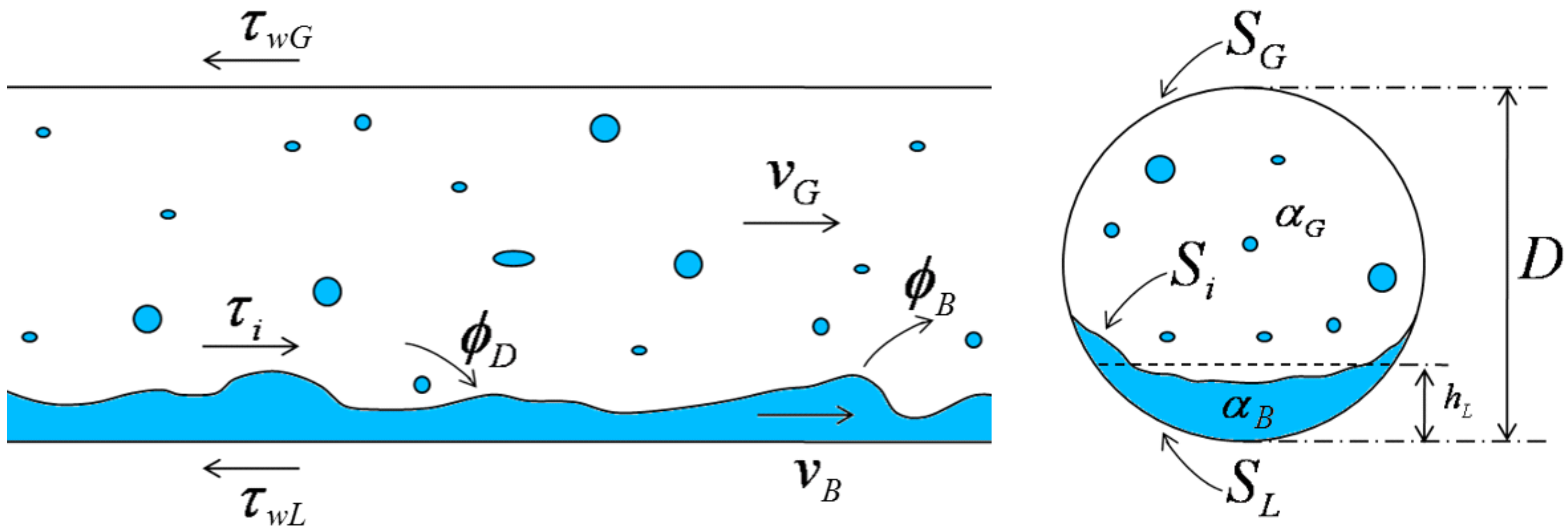
Wave capturing

- ✓ Extra-fine grids (0.1 D) allow prediction of long disturbance waves. As both the friction factor at the gas-liquid interface and the rate of droplet entrainment depend of the heigth of the liquid layer flowing at pipe bottom, a more fundamental description of the flow structure is possible.



Stratified-Dispersed Flow

- ✓ Models of stratified-dispersed flow usually consider the presence of three fields, gas, continuous liquid and dispersed liquid.
- ✓ A complex set of experiments conducted at the Multiphase Flow Laboratory of TEA Sistemi in the period 2010-2015 indicate that a forth field should be considered, i.e. a thin laminar film flowing at pipe wall. The importance of this field has recently be confirmed by Biberg et al. 2017.



Stratified-Dispersed Flow

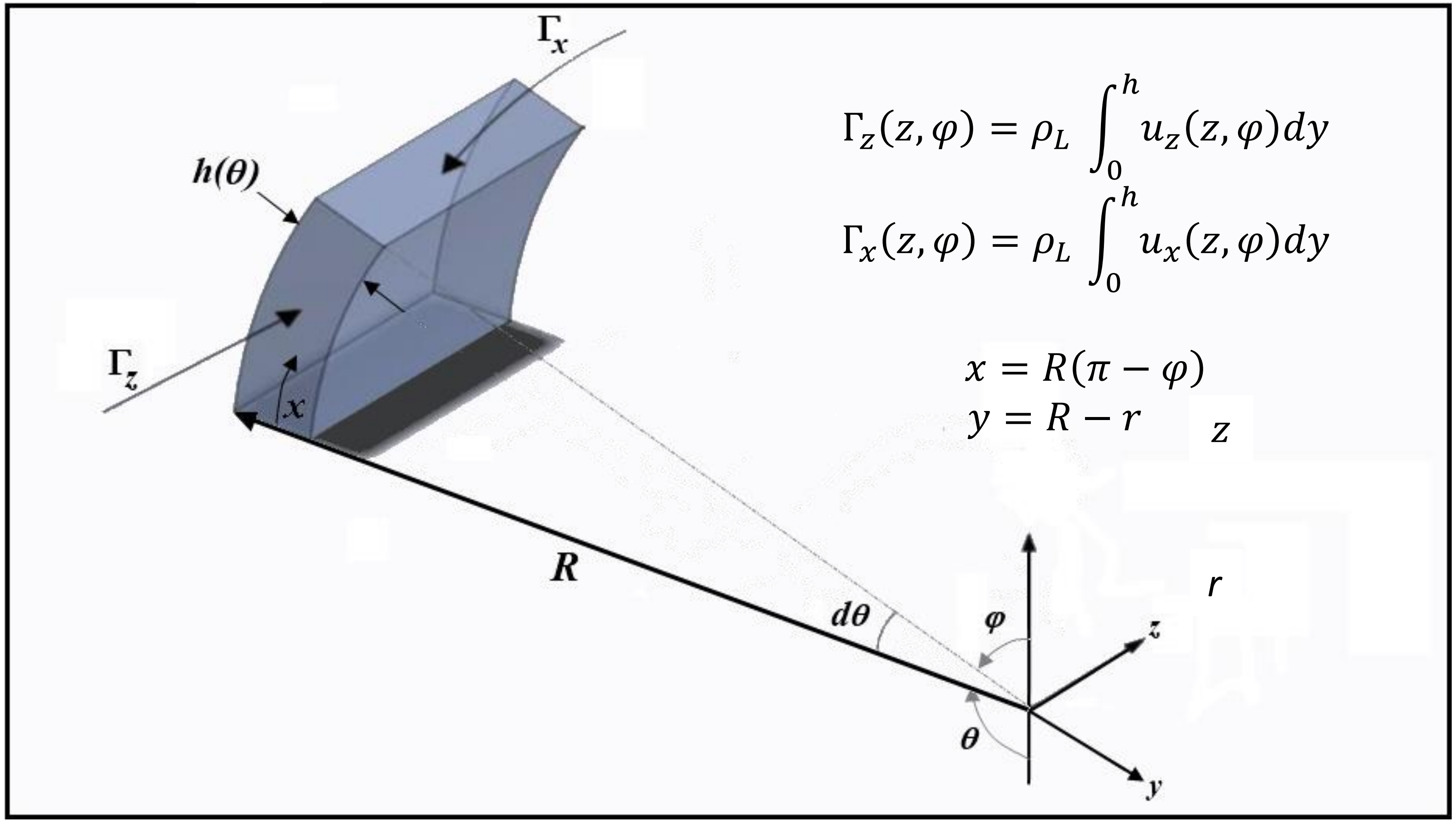
- E. PITTON, P. CIANDRI, M. MARGARONE, P. ANDREUSSI, 2014 "An experimental study of stratified-dispersed flow in horizontal pipes" Int. J. Multiphase Flow Vol. 67 pp. 92-103.

- P. ANDREUSSI, E. PITTON, P. CIANDRI, D. PICCIAIA, A.VIGNALI, M. MARGARONE, A. SCOZZARI, 2016 "Measurement of liquid film distribution in near-horizontal pipes with an array of wire probes" Flow Meas. Inst. Vol. 47 pp. 71-82.

- M. BONIZZI, P. ANDREUSSI, 2016 "Prediction of the liquid film distribution in stratified gas-liquid flow" Chem. Eng. Sci. Vol. 142 pp. 165-179.

2D Flow model

$h(z, x)$

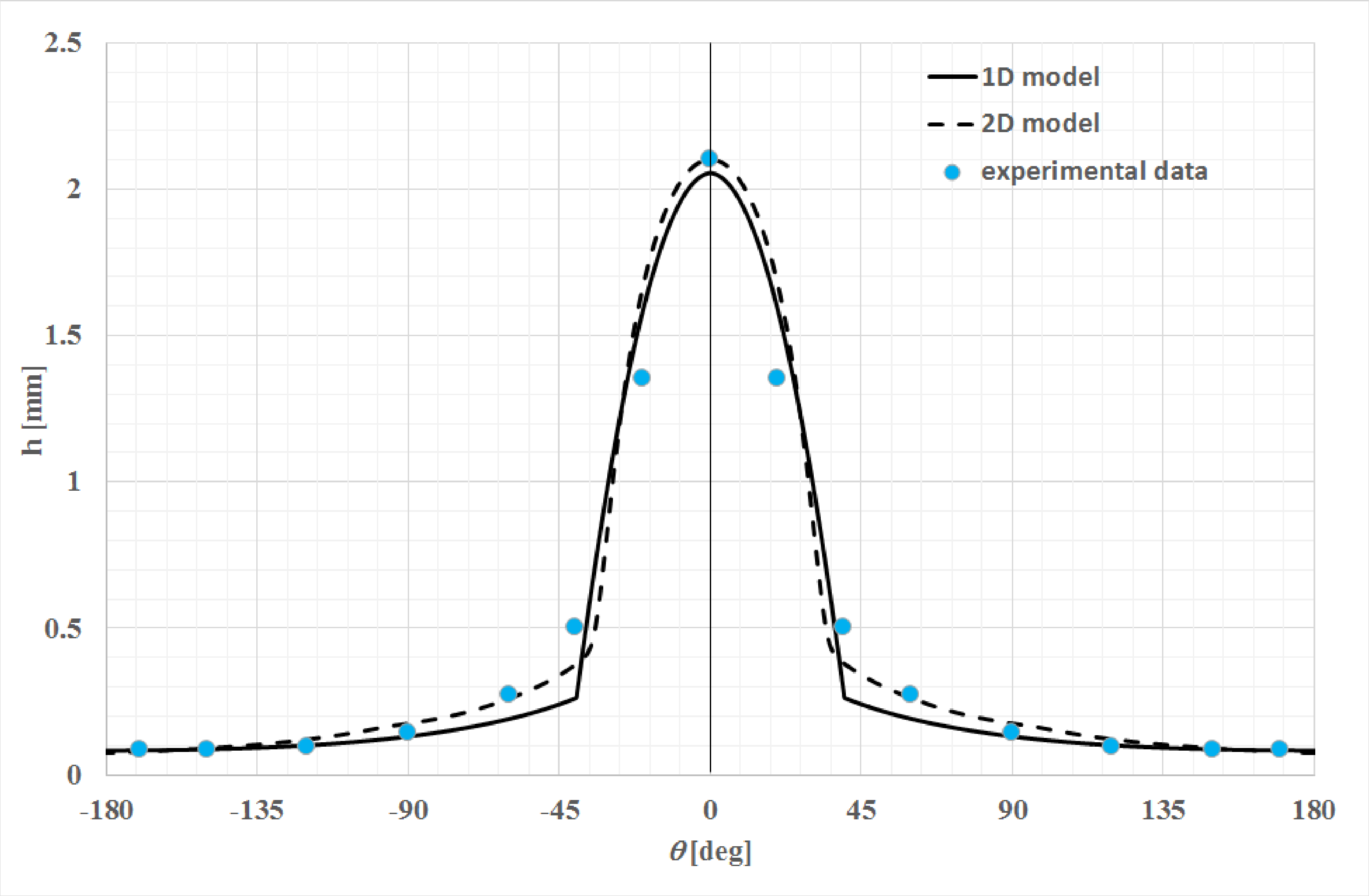


$$\Gamma_z(z, \varphi) = \rho_L \int_0^h u_z(z, \varphi) dy$$

$$\Gamma_x(z, \varphi) = \rho_L \int_0^h u_x(z, \varphi) dy$$

$$x = R(\pi - \varphi)$$
$$y = R - r$$

Circumferential film height distribution



2D Flow model

PARAMETER	MEASUREMENT	MAST Error (%)	REFERENCE MODEL
f_B (-)	0,57	0,55 (4%)	0,7
f_D (-)	0,24	0,24 (0%)	0,3
f_R (-)	0,19	0,21 (10%)	
α_B (-)	0,021	0,02 (4%)	0,024
ϕ_B $(kg/m^3 \cdot s)$	68	66 (3%)	1,25
ϕ_D $(kg/m^3 \cdot s)$	60	59 (2%)	1,25
ϕ_R $(kg/m^3 \cdot s)$	8	7 (12%)	
$(dp/dz)_{TP}$ (Pa/m)	940	920 (2%)	770
$(dp/dz)_G$ (Pa/m)	336	340 (1%)	339

Momentum balance

- The contribution of the different terms to the overall pressure gradient is reported below

$$-\frac{dP}{dz}=\frac{4}{\alpha_G D}\tau_{Gw}\left(\frac{\varphi_0}{\pi}\frac{f_{i,F}}{f_{Gw}}+\frac{(\pi-\varphi_0)}{\pi}\frac{f_{i,B}}{f_{Gw}}\right)+\frac{\phi_D}{\alpha_G}(\upsilon_D-\upsilon_W)+\frac{\phi_R}{\alpha_G}(\upsilon_R-\upsilon_W)$$

30% 32% 30% 8%

- In this computation υ_W is the disturbance wave velocity (computed by MAST) and the values of the interfacial friction factors are

$$f_{i,B}/f_{Gw}=2.5,\quad f_{i,F}/f_{Gw}=1.7$$

Conclusions

- ✓ The development of multiphase flow simulators and their use in the design of subsea pipelines represented a turning point for the O&G Industry. In this respect the role of OLGA has been relevant, but it should also be mentioned that OLGA did not came out of nowhere: its bases can be found in the underlying academic research and in the work of a number of scientists.
- ✓ In recent years OLGA showed a good attitude to renewal, which is probably supported by its dominant position. At the same time, new simulators are entering the market and the academic research is providing new ideas.
- ✓ The parallel development of the Information Technology opens the way to advanced methods, among which fine grid 1 D models appear to be mature for industrial applications.