Transport of oil in pipelines with core-annular flow

Flow transitions and regimes in core-annular pipe flow

C. Plana, B. Song, M. Avila, *Center of Applied Space Technology and Microgravity (ZARM), Universität Bremen*

In Short

- Core-Annular pipe flow has applications in transporting highly viscous fluid
- The core-annular flow is unstable to perturbations and can exhibit multiple flow configurations
- Bamboo waves flow configuration allows efficient transport of heavy oil, while slugging deteriorates the efficiency
- Goal: Investigate the flow transitions and the underlying bifurcation mechanism

In Core-annular flow, one type of fluid flows in the core area of a pipe and another type of fluid flows in the annulus near the pipe wall, surrounding the core flow. One of the applications of this flow in industry is the transport of highly viscous crude oil using water, which is hundreds of times less viscous than the crude, in the annulus near to pipe wall to reduce the friction drag. This strategy can greatly reduce the pumping energy cost compared to pumping pure oil in pipelines. Although perfect core annular flow is an ideal flow configuration for this purpose, it is in general linearly unstable [1]-[3], the flow configuration can not be kept because even infinitesimal perturbations suffice to significantly disturb the flow and to change the flow configuration. Depending on the operating condition, the destabilised flow can exhibit various configurations ranging from annular flow (such as bamboo-shaped waves), slug flows (the core flow appears as elongated slugs isolated by the other fluid), bubble flow, and droplets dispersed in the other fluid (see more detailed description of the different flow configurations in Fig. 1 and Fig. 2), and fully stratified flows in horizontal pipes if the two fluids have different density [1]. Different flow configurations are accompanied by different driving pressure gradient (pumping energy cost) and different oil transport efficiency. As the perfect core-annular flow usually cannot be maintained, the annular flow (bamboo waves, short bamboo waves and disturbed core-annular flow) allows the most efficient transport. However, the slugging will significantly deteriorate the efficiency and further lead the flow to bubble flow and dispersion flow. It is of both physical and practical importance to study the slugging process and the underlying bifurcation on the boundary between the annular flow and the slug flow regimes. Up to now there are very limited studies on this problem, especially theoretical studies. They are only limited to linear stability analysis of perfect core-annular flow [[2],[3]] and cannot shed light on more complex flow configurations and nonlinear regimes. The experimental studies of Ref. [1] and [4] gave some phase diagrams for water-oil system for vertical up-flow, vertical down-flow, and horizontal pipe system. Although the diagrams gave a description of the rich flow regimes, they are rather crude and the boundaries between different flow regimes (configurations) were not clearly determined. Therefore, the flow states very close to the boundaries are still unknown. Besides, the bifurcation leading to different flow regimes and the sensitivity of the phase-diagram on the initial condition has not be investigated. Hence, more accurate studies of the phase diagram in non-dimensional parameter space, and especially the transition mechanism between different regimes are highly desired for a better understanding of the rich dynamics of the core-annular flow and for general applications. The aim of this project is to investigate this problem using numerical simulation. The challenge to numerical simulation of multi-phase flows generally comes in two aspects: 1) to correctly capture the interfacial tension force, and 2) to correctly capture the interface topological changes such as the breaking of annular flow into slugs or merging of slugs into annular flows. To address these challenge, a good candidate is the phase-field method, which is thermodynamically consistent and can naturally capture the motion of the interface between different phases or fluids [5]. We developed a highly efficient in-house code using high-order finite difference and spectral method for discretisation and using phasefield method to simulate binary flow systems. The code is parallelised using MPI+OpenMP and this allows to efficiently utilise up to $\mathcal{O}(10^4)$ CPU cores [6]. It has been validated in various flows. Especially, we have successfully obtained the bamboo wave flow regime using our numerical tool in heavily oil-water system and got quantitative agreement with former studies in both the nonlinear regime and the linear regime that leads to the final bamboo wave [7]. Note that the very high viscosity ratio between heavy oil and water is a challenge for phase-field method. Besides, in our method, non-dimensional parameters such as Reynolds number for each fluid (defined by the nominal flow rate of each fluid), viscosity ratio, density

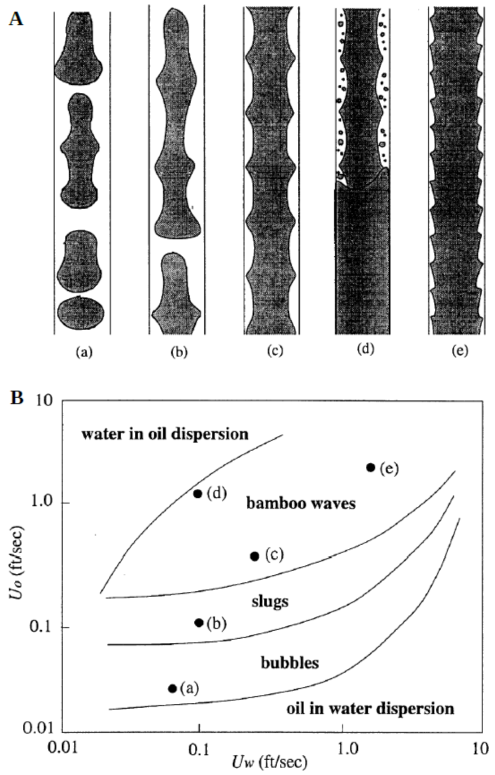

Figure 1: *Flow configuration diagram in up-flow condition in a vertical pipe in Ref. [1]. A: flow configurations. B: phase diagram..*

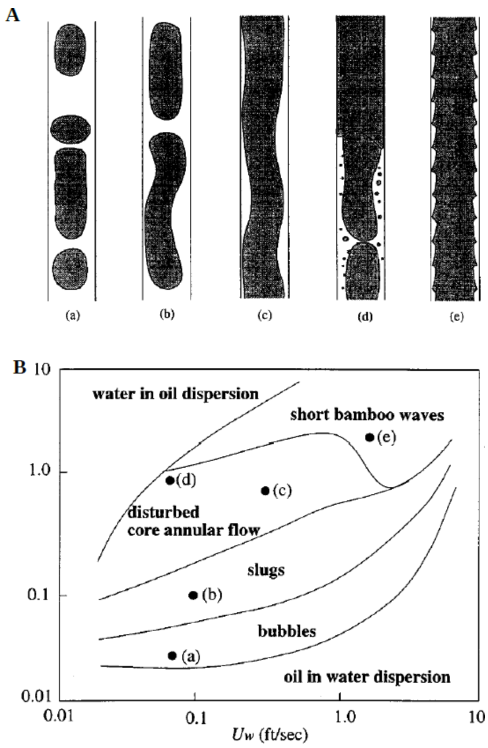

Figure 2: *Flow configuration diagram in down-flow condition in a vertical pipe in Ref. [1]. A: flow configurations. B: phase diagram..*

ratio, and surface tension (capillary number) etc. can be easily controlled for probing the boundaries between regimes and for determining the most relevant parameter in the transition from one regime to another. With this project, we will make clear the slugging process occuring in the oil-water core-annular system, and obtain theoretical understanding of the bifurcation on the regime boundary. Besides, methods that can stabilize the annular flow configuration will also be probed, for example, by properly changing the surface tension which can be achieved by adding surfactants.

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More Information

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