Investigation of three-phase flow regimes (water-hydrocarbon-gas) in horizontal pipes and feasibility of creating dimensionless pattern maps for such flows

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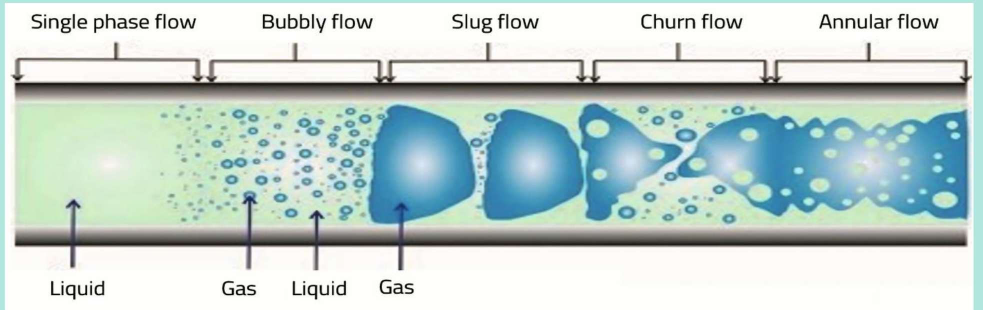
Abstract

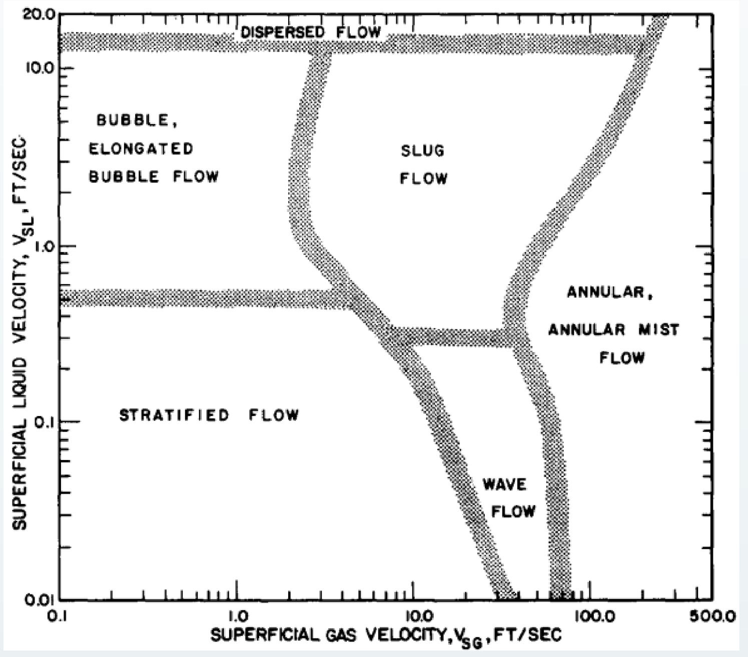
Multiphase flows often occur in nature and industry, especially in mining, nuclear, pharmaceutical, petrochemical, energy, and environmental sectors. Understanding these flows is crucial for describing heat transfer, momentum, and mass transfer processes in devices such as heat exchangers, reactors, bioreactors, distillation columns, and absorption systems. To study and analyze a multiphase flow, it is necessary to determine the geometry of the interfaces between the phases, representing the flow pattern or regime. The flow regime depends on the relative magnitudes of the forces acting on the fluid, including buoyancy, inertia, surface tension, and viscosity. The magnitude of these forces is also significantly influenced by the flow rate of each phase, pipe diameter, pipe inclination, and fluid properties. The objective of this study is to develop a dimensionless flow pattern map initially for two-phase flows (water-oil, water-air, and oil-air) and then to assess the feasibility of creating such maps for three-phase flows (water-hydrocarbon-gas) in horizontal pipes to determine the impact of the governing forces on each of the regimes. The innovation of this research lies in developing dimensionless regime maps and examining their practical applicability for three-phase flows of water-hydrocarbon-gas.



Introduction

The most important step in understanding the behavior of a multiphase flow is identifying the flow pattern, which is determined by the balance between the existing forces and competing mechanisms. The properties and flow rates of each phase, operating pressure and temperature, pipe diameter, shape, inclination, roughness, and the presence of any fittings in the pipeline (such as valves, elbows, T-junction, etc.) are determining factors for multiphase flow patterns. A flow regime map shows the areas corresponding to each regime and the transition boundaries between two different regimes. In a categorization, flow pattern maps can be divided into two categories: those that have axes based on dimensional variables and those that use dimensionless variables. In these studies, flow regime maps are functions of dimensional variables (surface velocities, volumetric or mass flow rates of each phase, mixture velocity, properties of the fluids used, and pipe geometry).

As a result, the conditions for transitioning between flow regimes are unique to each study. They cannot be applied to describe the flow of different fluids across varying geometric scales and flow conditions (such as pipe size, fluid properties, and flow rates).



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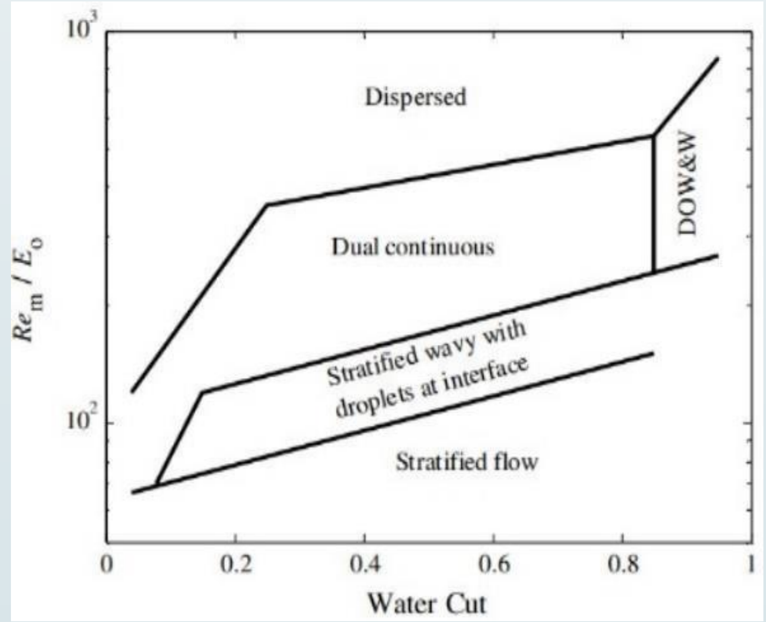
Dimensional flow regime map

The use of dimensionless groups derived from dimensional variables will lead to the development of flow regime maps for a wider range of applications.



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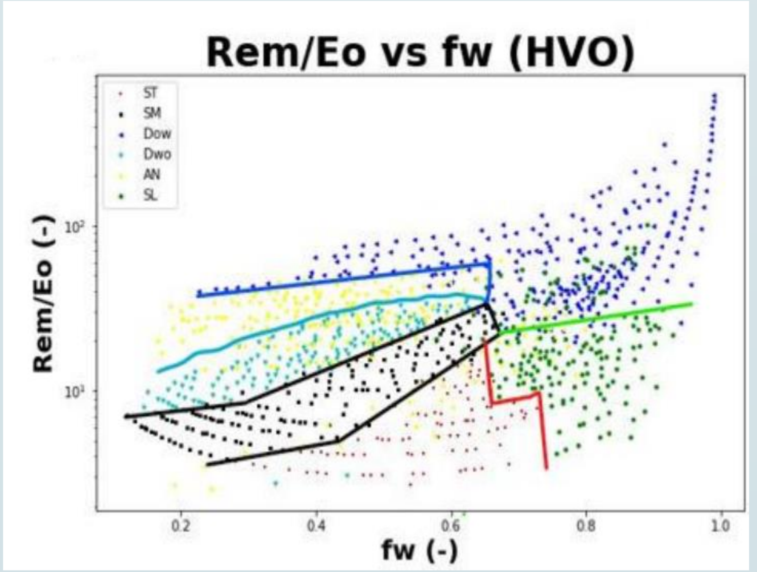

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Dimensionless flow regime maps

Materials and Methods

In this study, the collected data used to develop dimensionless maps were derived from experimental works published in scientific journals on horizontal two-phase flows. , the range of density for water, oil, and air is 987.78–1070.1, 831.4–889, and 1.204–1.225, respectively. The range of viscosity for water and oil is 0.00076–0.001026 and 0.0026–0.919, respectively. The surface tension ranges from 0.02 to 0.072, the pipe diameter ranges from 20 to 95.3, and the viscosity of air is approximately constant at 0.000018, with the units as mentioned in the table above.

The VOF (Volume of Fluid) model in ANSYS Fluent software was used to track the interface between the phases. In this model, both phases are considered as continuous phases that do not interact with each other, and the governing equations for the entire system (mixture) are solved by averaging the physical properties between the phases (Equations 1-4). The k-ω SST model was selected as the turbulence model for conditions where the flow was turbulent.

$$\frac{\partial \rho_m}{\partial t} + \nabla.(\rho_m.u) = 0 \quad (1)$$

$$\frac{\partial(\rho_m.u)}{\partial t} + \nabla(\rho_m.uu) = -\nabla P + \nabla\tau + \rho_m g + S = 0 \quad (2)$$

$$\frac{\partial \alpha}{\partial t} + \nabla(\alpha u) = 0 \quad (3)$$

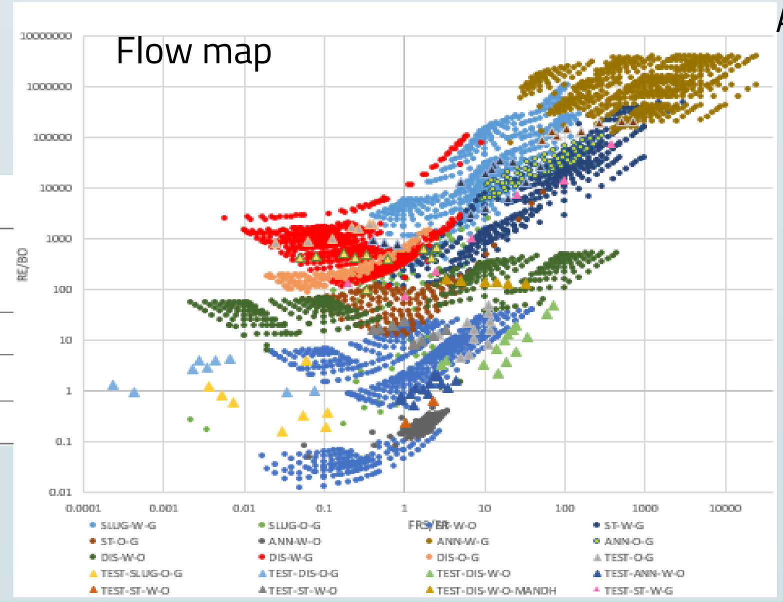
$$\rho_m = \sum \alpha_k \rho_k \quad (4)$$

Results and Discussion

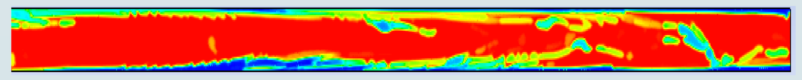
A total of 3,566 experimental data points were compiled from eight distinct laboratory conditions. Of these, approximately 31% represent oil–water flow, 56% correspond to water–gas flow, and the remaining 13% are associated with oil–gas flow. The number of data points corresponding to each two-phase flow type, and more specifically to each of their respective regimes, is summarized in the Table below. By examining 16 combinations of dimensionless numbers, the diagram below was obtained, which is capable of distinguishing the regions of each regime for different types of two-phase flows. Currently, the project is in the phase of extending this map to three-phase flows and validating it using laboratory data collected from published reputable articles and simulations.

Table. Number of data points for each two-phase flow and corresponding regimes

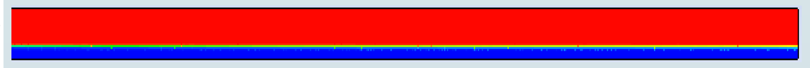
Type of Two-Phase Flow	ST	Disperse	Annular	Slug-Plug	Total
Oil-water	600	330	147	47	1124
Water-Air	391	637	520	468	2016
Oil-Air	152	119	82	73	426



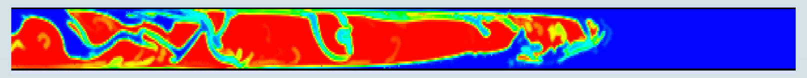
Annular, oil-air



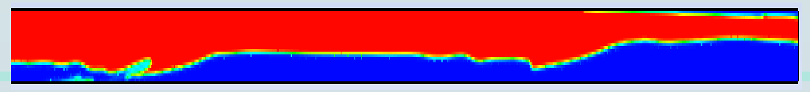
Stratified, oil-water



Annular, air-water



Stratified wavy, air-water



Keywords

Two-phase flows, Three-phase flows, Flow pattern, Dimensionless flow pattern map