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THE HYDRODYNAMİCS OF GAS-LİQUİD MİXTURE FLOW IN POROUS MEDIA

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ABSTRACT

Equations and models that describe the hydrodynamics of gas-liquid two-phase flows in porous media are becoming increasingly crucial for predicting their primary behaviors within porous structures. These models are essential in understanding the flow dynamics in various applications, such as enhanced oil recovery, soil treatment, and reactor design. The focus of this research was to examine the effects of capillary forces, viscous forces, inertial forces, and flow configurations on the hydrodynamic features of a gas-liquid two-phase flow within a glass micromodel. By conducting experiments, results were gathered and then compared with predictions made by three different established models. The two models, Fundamental Forces Balance and Fluid-Fluid Interface models, did not accurately capture the experimental behavior, despite the fact that the Fundamental Forces Balance model incorporates particular flow pattern characteristics. These models were not able to fully describe that real-word behavior of gas-liquid two-phase flow, indicating that improvements are necessary. On the other hand, semi-empirical models, such as the Relative Permeability model, provide a better representation of the physical flow characteristics. One key advantage of semi-empirical models is that they can be adjusted to account for additional effects, such as varying flow configurations and interfacial interactions, which are not initially included in the basic theoretical models. Traditionally, relative permeabilities have been almost exclusively linked to saturation conditions in porous media. However, this research concluded that liquid relative permeability is not solely dependent on saturation levels. Instead, is also depends on flow patterns and the Capillary number. These findings highlight the importance of incorporating multiple factors when developing more accurate and reliable models for gas-liquid two-phase flow in porous media.
Keywords: porous media; hydrodynamic models; flow patterns; gas-liquid two-phase flow; flow patterns; relative permeabilities.

Introduction

The hydrodynamics of gas-liquid mixture flow in porous media is a key topic in the study of multiphase flow processes, relevant to applications like fuel cells, oil recovery, paper production, and biomedical technologies. The reviewed paper discusses the fundamental aspects of such flows through the use of dynamic pore-network models. These models capture the complex interactions between gas and liquid phases governed by capillary and viscous forces, which are described by two key dimensionless numbers: viscosity ratio and capillary number. Compared to conventional continuum-scale simulations, pore-scale models provide deeper insights into phase displacement and trapping. Dynamic pore-network models consider transient behavior, incorporating both capillary entry pressures and time-dependent fluid motion influenced by local geometry and interfacial phenomena. Key applications include studying residual saturation, pressure field

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evolution, and nonequilibrium capillarity effects. The models also help in understanding ganglia flow (flow of disconnected fluid clusters), and how parameters like contact angle, pore geometry (aspect ratio and coordination number), and wettability influence flow regimes. Overall, the review summarizes computational methods, structural classifications of pore networks, and local rules (such as snap-off and piston-like movement), offering a comprehensive framework for analyzing gas-liquid flow dynamics in porous media.

The study of gas-liquid two-phase flow hydrodynamics in porous media is essential for various applications, including soil decontamination, enhanced oil recovery, nuclear reactor safety, multiphase reaction systems, and packed bed operations. Since the late 19th century, empirical models have been employed in reservoir engineering; however, they have been inadequate in accurately predicting the flow velocities observed during extraction. Consequently, the development of new models in necessary to better represent hydrodynamic behavior and improve flow rate predictions during reservoir exploitation. Several models have been proposed, including the force balance model, the fluid-fluid interfacial model, and the relative permeability model. The force balance and fluid-fluid interfacial models specifically incorporate drag forces on both phases, utilizing momentum balance principles at the fluid-fluid and fluid-solid interfaces on a pore-scale level. However, these models do not include tunable parameters, limiting their adaptability to account for additional transport effects. The relative permeability model, formulated at a macroscopic scale, is derived from Ergun's equation. This model the viscous and inertial forces involved in single-phase flow through packed beds, as well as the absolute permeability of the porous medium. With the extensions of Darcy's law to multiphase flow, relative permeability has been primarily linked to phase saturation. Additionally, the generalized Darcy's law that each phase flows either separately or in a connected manner. However, the significance of actual viscous effects has been widely debated in the literature. Studies have shown that when fluids move in a disconnected manner within porous media, the generalized Darcy's law fails to provide accurate predictions. The intricate structure of porous media and the interfacial interactions between fluids pose significant challenges in hydrodynamic studies of two-phase flow, making in difficult to develop purely theoretical models. As a result, centrain parameters must be adjusted to improve model accuracy [7],[8]. In practice, empricial and semi-empricial models are commonly employed to describe the hydrodynamics of such sysetems [5]. The key advantage of these models lies in their adjustable parameters, which allow for the inclusion of flow configurations, viscous effects, interfacial interfactions, and other phenomena that theoretical models may overlook. This study focused on assessing three astablished hydrodynamic modelsby comparing their predicted values with experimental data obtained from a 2D glass micromodel under gas-liquid two-phase flow conditions. Additionally, the research examined how the capillary nubmer and flow configurations influence the hydrodynamic characteristics of the system.

The configuration depicted in Figure 1 was developed to evaluate the characteristics of steady-state gas-liquid two-phase flow and is thoroughly documented in a previously conducted experimental investigation [18]. The gas phase consisted of air supplied from a pressurized cylinder (AC). A storage vessel (ST) held the liquid, which was propelled using a positive displacement pump (P) and its flow was controlled via a precision needle valve (V1). Both phases were concurrently introduced into a porous glass micromodel (GM) and connected to a pressure measuring device (T). A pressure indicator (I) was utilized to capture the pressure variation occurring within the micromodel.

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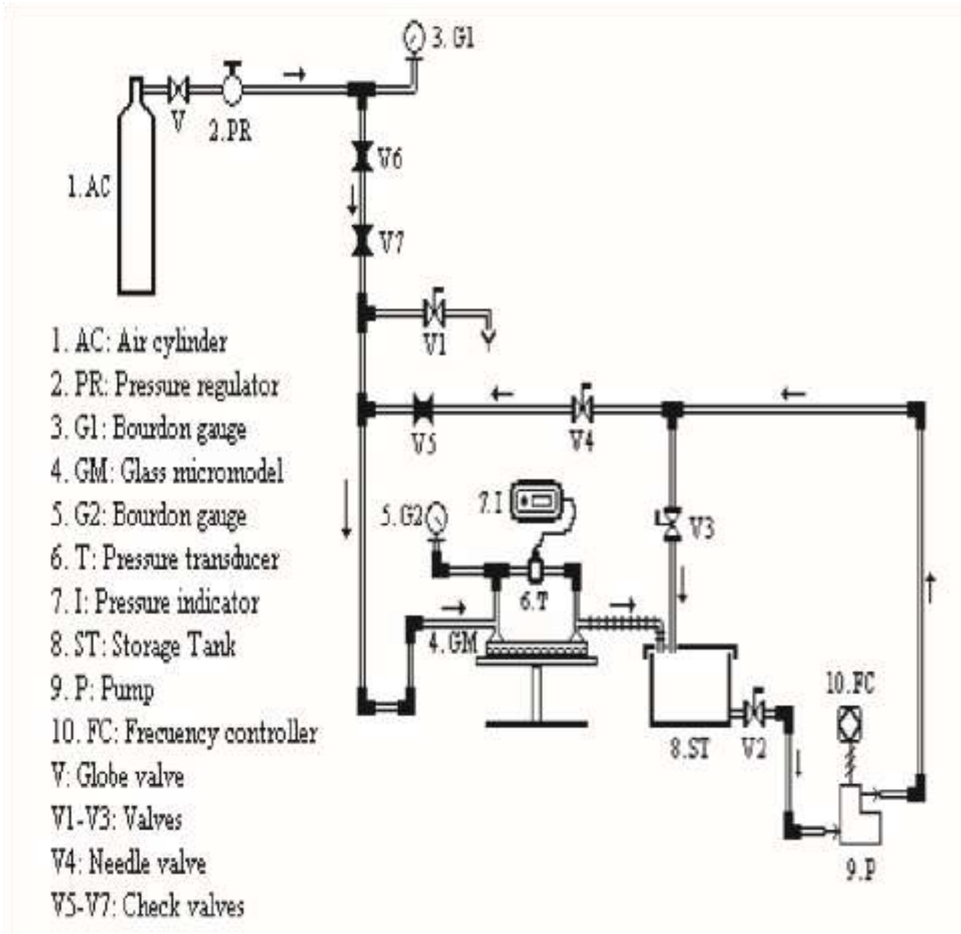

Figure 1. Experimental setup.

A porous glass model was used for this study. This model has 53% porosity (φ), an absolute permeability (*k*) of 18 Darcy, a transverse area (A_T) of 9 mm^2, and 0.1 mm of width. In Figure 2, we can see some of the properties of the porous glass micromodel.

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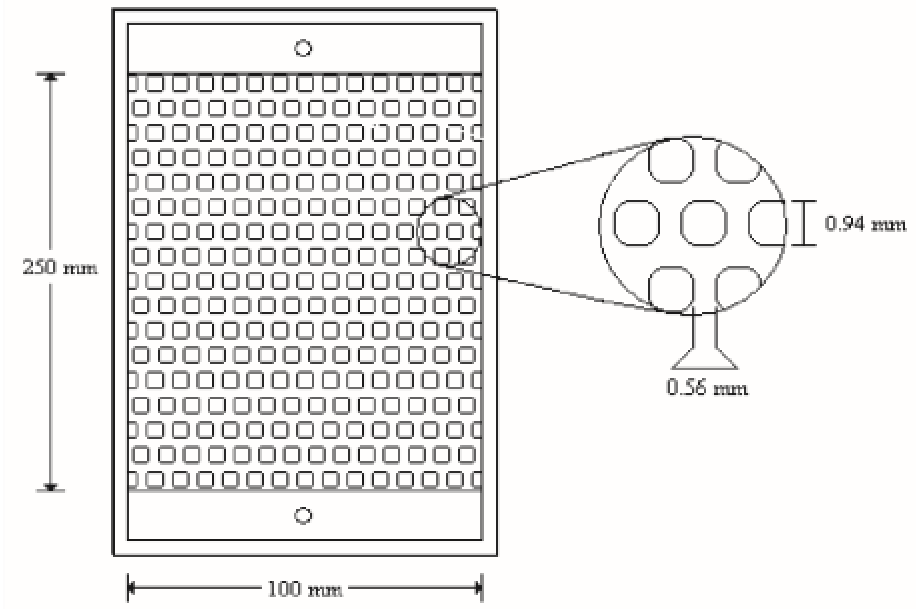

Figure 2. Glass micromodel

Diluted solutions of glycerin were used as the liquid phase. The surface tension was replaced by a non-ionic surfactant. The physical properties of the liquid phase are shown in Table 1.

Table 1. Physical properties of the liquid phase.

Substance	Density (ρ±1) kg/m^3	Viscosity μ mPa.s	Surface tension (σ±0,1) mN/m
Water	1048	1,0±0,1	72,5
Water-Tritón™ X-100	1043		53,1*
AG-1	1139	10±1	68,1
AGT-1	1149		50,7*
AG-2	1168	20±1	66,4
AGT-2	1166		50,4*
AG-3	1185	30±1	66,0
AGT-3	1198		50,3*
AG-4	1202	40±1	65,7
AGT-4	1205		50,2*

Objective

The analysis is solely focused on the continuous liquid phase. In the glass micromodel, two distinct flow patterns were identified: bubble flow and slug flow, both characterized using image processing techniques (IPT). Further details on these techniques and flow pattern characterization can be found in Gutierrez et al [6]. Bubble flow consisted of numerous small, spherical bubbles,

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whereas slug flow featured fewer but elongated bubbles. Measurements obtained through IPT included bubble diameter and length, with average 1b/Db ratios of 0.62 for bubble flow and 1.92 for slug flow. To compare experimental results with theoretical predictions, three hydrodynamic models for two-phase flow were analyzed: (1) Fundamental Forces Balance Model (FFBM) [1], (2) Fluid-Fluid Interfacial Model (FFIM) [2], and (3) Relative Permeability Model (RPM) [3]. All model assume a disconnected gas phase within as continuous liquid phase, these models are provided in Appendix A, and the discrepancy between experimental and theoretical values was assessed using average relative errors (eX).

Methods

Following the complete saturation of the micromodel pore space with the wetting phase (typically representing brine or a water-based analog), the non-wetting phase (gas or oil) was introduced under controlled injection conditions. For each experimental run, the injection pressure was regulated to a predefined constant value to ensure consistency across tests. This phase substitution process—where the non-wetting phase displaces the wetting phase—is representative of a drainage regime commonly encountered in porous media during primary hydrocarbon migration or gas injection operations.

The injection protocol involved a gradual increase in the flow rate ratio QNW/QW , enabling a controlled transition in flow regimes. Steady-state conditions were considered achieved when the differential pressure across the micromodel reached a plateau, indicating dynamic equilibrium within the pore network. At this point, high-resolution optical imaging was employed to capture the spatial distribution of the fluid phases, which subsequently allowed for the quantitative estimation of phase saturations via image analysis techniques.

Once steady-state flow was established and edge effects deemed negligible , the system was assumed to exhibit a uniform capillary pressure field throughout the micromodel domain. Under these conditions, the capillary pressure differential could be expressed as:

$$\Delta = \Delta p_W p_{NW}$$

Conclusion

Purely theoretical hydrodynamic models, such as the Fundemental Forces Balance Model (FFBM) [1] and the Fliud-Fluid Interfacial Model (FFIM) [2], fail to accurately describe the key hydrodynamic is characteristics of gas-liquid two-phase flow observed in the glass micromodel during this study. Although Tung & Dhir [1] incorporated flow patterns into their model, their predicted values did not align with the experimental results. In contrast, semi-empirical models like the Relative Permeability Model (RPM) [3], which are grounded in solid physical principles, offer greater flexibility. By incorporating adjustable parameters, these models can account for flow patterns and other experimentally observed effects that were not initially considered, making them a more practical approach. Traditionally, relative permeability (krL) has been linked primarily to phase saturations (SL) [3],[4],[5]. However, this study found that krL is not solely a function of SL but is also influenced by flow patterns, capillary forces, and bubble interactions. Future research will focus on developing correlations to more accurately describe the hydrodynamic behavior of gas-liquid two-phase flow in a 2D porous medium, potentially leading to significant advancements in understanding these phenomena at both the pore and reservoir scale.

Declarations
The manuscript has not been submitted to any other journal or conference.

Study Limitations
There are no limitations that could affect the results of the study.

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Competing Interests
No potential conflict of interest was reported by the authors.

REFERENCES

1. Attou, A., & Ferschneider, C. A simple model for pressure drop and liquid hold-up in packed-bed bubble reactors. Chem. Eng. Sci., 1999, 54, 5139-5144.
2. Aziz, K., "Petroleum Reservoir Simulation".- Gulf Publishing, 1985.
3. C.J. Rangel, "Gas-Liquid Flows in Porous Media", Transport in Porous Media, 2022.
4. D.A. Nield, A. Bejan - "Convection in Porous Media", Springer, 2020.
5. F. C. McCarthy - "The dynamics of gas-liquid interfaces in porous media", Physics of Fluids, 2019.
6. Gutierrez, B., Juarez, F., Ornelas, L., Zeppieri, S. & López de Ramos, A. Experimental Study of Gas–Liquid Two-Phase Flow in Glass Micromodels.// Int. J. Thermophys., 2008, 29(6), 2126-2135.
7. Gutierrez, B., Pirard, J., Blacher, S., & López, A. (Submitted). Image Analysis of the Gas Morphology in a Gas-Liquid Two-Phase Flow in a Porous Glass Micromodel.
8. H. Darcy - "The Public Fountains of the City of Dijon", translated version, 1856.
9. H. Masoudian et al. - "Two-phase flow dynamics in porous media".// Advances in Water Resources, 2020.
10. H. Sadeghi - "The dynamics of gas-liquid interfaces in porous media".// Journal of Fluid Mechanics, 2018.
11. H. Sun, T. Zhang - "Gas-liquid flow behavior in fractured porous media".// Journal of Hydrology, 2019.
12. J. Bear - "Dynamics of Fluids in Porous Media", Dover Publications, 1972.
13. Kazemi, H. - "Multiphase flow in porous media".// Journal of Petroleum Science and Engineering, 1997.
14. M. Sahimi - "Flow and Transport in Porous Media and Fractured Rock", Wiley, 2011.
15. Osoba, J. S., Richardson, J. G, Kerver, J. K, Hafford J. A & Blair P. M. Laboratory Measurements of Relative Permeability. Trans. AIME, 1951, 192, 47-56.

16. R. G. Hydrodynamics Parameters for Gas-Liquid Cocurrent Flow in Packed Beds. AIChE Journal, 1985, 31(1), 52-62.
17. R. S. Scheel, T. W. H. Chung - "The Effect of Gas-Liquid Interaction in Porous Media".//Journal of Hydrology, 2021.
18. R.E. Collins - "Flow of Fluids through Porous Materials", Pennwell Books, 1976.
19. S. B. Shontz et al. - "Modeling multiphase flow in porous media with application to gas-liquid flow",// Journal of Computational Physics, 2014.
20. S.J. Lee - "Multiphase Flow in Porous Media: A Review of Computational Methods", Advances in Water Resources, 2015.
21. Tung, V. X., & Dhir V. K. A hydrodynamic model for two-phase flow through porous media.// Int. J. Multiphase Flow, 1988, 14(1), 47-65.
22. Y. Zhang, G. Li - "Modeling gas-liquid two-phase flow in porous media: A review".// Journal of Hydrodynamics, 2015.

QAZ MAYE QARIŞIĞININ MƏSAMƏLİ MÜHİTDƏ HƏRƏKƏTİNİN HİDRODİNAMİKASI

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XÜLASƏ

Məsaməli mühitlərdə qaz-maye iki fazalı axınların hidrodinamikasını göstərən tənliklər və modellər, onların əsas davranışlarını məsamə strukturlarında proqnozlaşdırmaqdan ötrü getdikcə daha vacib hala gəlir. Bu modellər axın dinamikasını başa düşmək üçün vacibdir və müxtəlif tətbiqlərdə istifadə olunur. Bu tədqiqatın məqsədi, qaz-maye iki fazalı axının hidrodinamik xüsusiyyətlərinə kapilyar qüvvələrin, özlü qüvvələrin, inersiya qüvvələrinin və axın konfiqurasiyalarının təsirini araşdırmaqdır. Təcrübələr aparılmış, nəticələr toplanmış və sonda üç fərqli təsdiq edilmiş modelin proqnozları ilə müqayisə edilmişdir. İki model, Əsas Qüvvə Tarazlığı və Maye-Maye Səth İnterfeysi modelləri, eksperimental davranışı dəqiq formada əks etdirməmişdi, baxmayaraq ki, Əsas Qüvvə Tarazlığı modeli müəyyən axın nümunəsi xüsusiyyətlərini nəzərə alır. Bu modellər qaz-maye iki fazalı axının real şəraitdəki davranışını tam şəkildə təsvir edə bilmədi, bu da inkişafların mütləq olduğunu göstərir. Digəryandan, yarım-empirik modellər, məsələn, Nisbi Keçiricilik modeli, fiziki axın xüsusiyyətlərini daha yaxşı təsvir edir. Yarım-empirik modellərin əsas üstünlüyü ondan ibarıtdir ki, onlar əsas nəzəri modellərdə ilkin olaraq nəzərə alınmayan əlavə təsirləri hesaba almaq üçün dəyişdirilə bilər.Ənənəvi olaraq, nisbi keçiricilik yalnız doyma şərtləri ilə əlaqələndirilirdi. Lakin bu tədqiqatın nəticələrinə görə, maye nisbi keçiriciliyi yalnız doyma səviyyələrindən asılı deyil. O, həmçinin axın nümunələrindən və Kapilyar saydan asılıdır ki, bu faktorlar ənənəvi modellərdə əvvəlcədən nəzərə alınmamışdır. Bu tapıntılar, qaz-maye iki fazalı axınlar üçün daha dəqiq və etibarlı modellərin inkişafında bir neçə amilin nəzərə alınmasının vacibliyini vurğulayır.
Açar sözlər: hidrodinamik modellər; qaz-maye iki fazalı axın; axın nümunələri; nisbikeçiriciliklər; məsaməli mühitlər

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ГИДРОДИНАМИКА ТЕЧЕНИЯ ГАЗОЖИДКОСТНОЙ СМЕСИ В ПОРИСТЫХ СРЕДАХ

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РЕЗЮМЕ

Уравнения и модели, описывающие гидродинамику газ-жидкостных двухфазных потоков в пористых средах, становятся все более важными для предсказания их основных характеристик в пористых структурах. Эти модели имеют решающее значение для понимания динамики потока в различных приложениях, таких как улучшенная добыча нефти, очистка почвы и проектирование реакторов. Основной целью данного исследования было изучение воздействия капиллярных сил, вязких сил, инерционных сил и конфигураций потока на гидродинамические особенности газ-жидкостных двухфазных потоков в стеклянной микромодели. В ходе экспериментов были собраны результаты, которые затем сравнили с предсказаниями, сделанными тремя различными установленными моделями. Два из этих моделей — модель баланса основных сил и модель интерфейса жидкость-жидкость — не смогли точно отразить экспериментальные данные, несмотря на то, что модель баланса основных сил учитывает конкретные характеристики потока. Эти модели не смогли полноценно описать реальное поведение газ-жидкостного двухфазного потока, что указывает на необходимость их улучшения. С другой стороны, полу-эмпирические модели, такие как модель относительной проницаемости, предоставляют более точное описание физических характеристик потока. Одним из ключевых преимуществ полу-эмпирических моделей является то, что их можно адаптировать для учета дополнительных эффектов, таких как изменение конфигурации потока и взаимодействие на интерфейсе, которые не включены в первоначальные теоретические модели. Традиционно относительная проницаемость почти исключительно связывается с условиями насыщения в пористых средах.
Ключевые слова: гидродинамические модели; газ-жидкостные двухфазные потоки; конфигурации потока; относительные проницаемости; пористые среды

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