



EXPERIMENTAL DETERMINATION OF THE FLOW RATE OF LIQUIDS THROUGH FINE SAND IN A NARROW TUBE

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ABSTRACT

The flow rate of liquid has an essential applications in various field of building and civil engineering This research therefore investigates the flow dynamics of liquids through fine sand packed within a narrow tube, aimed to determine experimentally the rate of flow behaviour of five different liquids in fine sand of the same size. Darcy's method was used to acquire the results. The experimental setup involved liquids such as water, kerosene, petrol, vegetable oil, and palm oil labeled as Liquid A, B, C, D, and E respectively. Results revealed elaborate relationships between the nature of the liquid and flow rate; shedding light on the role of the density of the liquid and the ability of such liquid to flow through the sand pore in governing fluid movement. Hence, it contributes to a deeper understanding of the viscosity of the fluids and have potential applications in soil and hydro-engineering.

Keywords: Fluids, Flow rate, capillary tube, fine sand, Darcy's law, Viscosity.

Introduction

Fluid flow is a part of fluid mechanics that deals with the motion of a fluid subjected to unbalanced forces (Zhang and Kang, 2014; Georgiou et al., 2018; Theyab, 2018; Thomas, 2019; Tu et al., 2023). It involves the continuous and irrecoverable change of position of one part of the material relative to another part when under shear stress. Fluid dynamics is a sub-discipline of fluid mechanics and describes the flow of fluids (liquids and gases). It has several sub-disciplines, including aerodynamics (the study of air and other gases in motion) and hydrodynamics (the study of liquids in motion). Fluid dynamics has a wide range of applications, including

calculating forces and moments on aircraft, determining the mass flow rate of petroleum through pipelines, predicting weather patterns, understanding nebulae in interstellar space and modelling fission weapon detonation.

Fluid flow through porous media is a fundamental process with wide-ranging implications in various scientific and engineering domains (Jaeger et al., 1996; Tang and Wang, 2015). The determination of flow rates aids in clarifying fundamental principles but also has practical applications in optimizing processes and designing efficient systems. Porous media, such as fine sand, refers to materials that contain pores (voids). It exhibits complex structures characterized by interconnected void spaces and irregular particle arrangements. These features profoundly influence the transport properties of fluids, leading to diverse flow behavior depending on factors such as grain size, packing density, and fluid viscosity.

Determining the flow rate of liquids through fine sand in a narrow tube is important due to its wide-ranging applications in various fields such as engineering, environmental science, hydrology, and soil science. Studies such as those by Jones and Wright (1993), Adegoke (2004) highlighted the importance of accurately characterizing subsurface flow to manage and remediate contaminated groundwater effectively. In civil engineering, the stability of structures depends on understanding soil-water interactions. Rokochynskyi (2020) emphasized the importance of drainage and soil permeability in construction projects to prevent issues like waterlogging and foundation instability. Enhanced oil recovery methods rely on understanding fluid flow through porous media. Dullien and Batra (1992) provided comprehensive insights into the porous media flow dynamics essential for designing effective extraction techniques in the petroleum industry. Soil permeability affects water availability to crops, impacting agricultural productivity. Research by Pinheiro (2019) discussed how knowledge of soil hydraulic properties can optimize irrigation practices and improve water use efficiency in agriculture (Douglas and Yong, 1981; Andreotti et al., 2013; Fraggidakis et al., 2016).

Effective remediation of contaminated sites requires accurate models of how contaminants move through soil. Bear (2018), and Chen and Wilkinson (1985) discuss the principles of modeling contaminant transport in groundwater, which depends heavily on the hydraulic properties of soil and sand. Hydrological models require accurate soil hydraulic properties to predict water movement and manage water resources effectively. Bourouiba (2021) highlighted the role of soil hydraulic characteristics in developing precise hydrological models for water resource management and flood prediction. Industries using filtration systems benefit from understanding the flow of liquids through porous media. Filter design and efficiency can be improved by studying the flow rates through materials like fine sand, as Ruthven (1984) detailed in his work on adsorption and separation processes (Jiang & Tsuj, 2017; Jensen & Chernyavsky, 2019; Huang et al., 2021).

Research in scientific understanding and theoretical development contributes to the broader understanding of fluid dynamics. Bear (2018) and Whitaker (1986) provided foundational theories and models of fluid flow in porous media, validated and refined through empirical studies on sand flow rates (Hiscock et al., 1995; Henry, 2005; Gasperino et al., 2018).

Despite the extensive research conducted on fluid flow through porous media, there remains a need for comprehensive investigations specifically targeting the flow behavior in narrow tubes packed with fine sand. Such studies not only contribute to a deeper knowledge of the underlying

mechanisms but also provide insights into practical challenges encountered in various applications, including groundwater remediation, oil recovery, and filtration processes.

This research aims to address this gap by systematically examining the flow rate of liquids through fine sand packed within narrow tubes. By controlling key parameters such as sand grain size, and fluid properties, the study seeks to give insight into the flow behavior of different liquids through the same fine-grain sand size. Through experimental analysis, the research endeavors to uncover the fundamental principles governing flow dynamics in such confined porous media systems.

Materials and Method

The following materials were used for this study; fine sand with a known grain size distribution, a 2.0 mm sieve, a Polythene bag, a hand shovel, a Burette with clip, Liquids (water, kerosene, petrol, vegetable oil, and palm oil), Deionized water, Beaker, stopwatch, retort stand, include measuring cylinders, a stopwatch, a ruler or Vernier caliper, a balance, a thermometer, and tools like a funnel and spatula for filling the tube, and mathematical equations.

Sample Preparation

Sizeable quantities of fine sand samples were taken along Oke –Ose, Ilorin East local Government Area, Kwara State and was brought to the laboratory in polythene bags washed and rinsed using deionized water in order to remove organic materials that were in the process of decaying as a result of the work of soil microorganism This action was necessary so as to ascertain that no any other material was present except sand (Möbius *et al.*, 2001; Miao *et al.*, 2010; Lei *et al.*, 2019).

The resulting samples were sun-dried and thereafter heated. After the samples were allowed to cool down, the ‘stony’ particles and pebbles were removed using a sieve of 2.0 mm (Figure 1). After sieving, the grain was put into five different burette, each filled with 20 cm³ of the sand-tagged samples A-E. (A = burette filled with water, B = burette filled with kerosene, C= burette filled with petrol, D = burette filled with vegetable oil, and E= burette filled with palm oil).



Figure 1: Fine sand

The volume of the sand used was 20.0 cm^3 which was measured by a small measuring cylinder of 10ml . This volume was transferred into the dry clean burette ($0\text{-}50\text{cm}^3$). The liquid (A - E) are measured respectively with 20ml of the liquid poured into the burette. The total volume of the content in the burette (sand and liquid) makes 40cm^3 . With the burette clipped at the tip, the liquid is allowed to first saturate the sand before measuring the flow rate while the clip is removed to let out the liquid content.

The volume rate of liquid is the time taken by the liquid volume in the burette (Figure 2). The new volume of liquid is read after every 10 seconds for five consecutive time for each liquid, the difference between the initial and final volume is noted for five readings.

The terminal velocity of the liquid is obtained at a point where the liquid moves at a steady rate that is, where equal distance is moved in equal time taken for a particular liquid.



Figure 2: Flow of liquid through fine sand in a burette

Theoretical formula

The volume flow rate of liquid (or any fluid) through a porous medium can be determined using Darcy's Law, which is a fundamental equation describing the flow of fluid through porous media. The volume flow rate Q is given by:

$$Q = \frac{k}{\mu} A \frac{\Delta p}{L} \quad (1)$$

where: Q is the volumetric flow rate (m^3/s), k is the permeability of the porous medium (m^2), A is the cross-sectional area through which the fluid flows (m^2), ΔP is the pressure difference across the porous medium (Pa), M is the dynamic viscosity of the fluid ($\text{Pa}\cdot\text{s}$ or $\text{N}\cdot\text{s}/\text{m}^2$) and L is the length of the porous medium (m) (Hubber, 1956; Swartzendruber, 1962; Neuman, 1977; Keller, 2017).

Results and discussion

Each row of Table 1 represents a measurement point at a specific time interval. The columns indicate the time in seconds, followed by the volumes of water, kerosene, petrol, vegetable oil, and palm oil respectively, all in cm^3 . This data can be analyzed to understand the flow rates and possibly the viscosity or density differences between liquids under the conditions of the experiment.

The Table1 demonstrates the varying flow rates of five liquids—water, kerosene, petrol, vegetable oil, and palm oil—over time, revealing insights into their viscosity. Petrol, with the lowest viscosity, exhibits the highest flow rate, starting at 0.5 cm^3 at 10 seconds and increasing steadily to 0.62 cm^3 by 50 seconds. Water and kerosene, both low-viscosity liquids, show similar but slightly lower flow rates, with water stabilizing at 0.3 cm^3 by 40 seconds, while kerosene continues a slight increase to 0.33 cm^3 by 50 seconds. The consistent flow of these liquids suggests they encounter minimal resistance under the experimental conditions.

In contrast, vegetable oil and palm oil, both higher-viscosity liquids, exhibit delayed flow, with no measurable volume until 40 seconds. Vegetable oil reaches 0.15 cm³ by 50 seconds, and palm oil slightly less at 0.12 cm³, indicating significantly greater resistance to flow. This delay and lower flow rate underscore the importance of viscosity in fluid dynamics, particularly in industrial applications where the flow characteristics of liquids must be carefully managed. The data thus provide valuable insights for designing systems that handle fluids with varying viscosity (Oukhleif et al. 2023)

Table 1: The flow rates of the five different liquids (A – E).

SN	Time (secnds)	Volume of water (cm3)	Volume of kerosene (cm3)	Volume of Petrol (cm3)	Volume of vegetable oil (cm3)	Volume of Palm oil (cm3)
1	10	0.15	0.18	0.5	0	0
2	20	0.24	0.22	0.52	0	0
3	30	0.25	0.25	0.55	0	0
4	40	0.3	0.3	0.6	0.11	0.1
5	50	0.3	0.33	0.62	0.15	0.12

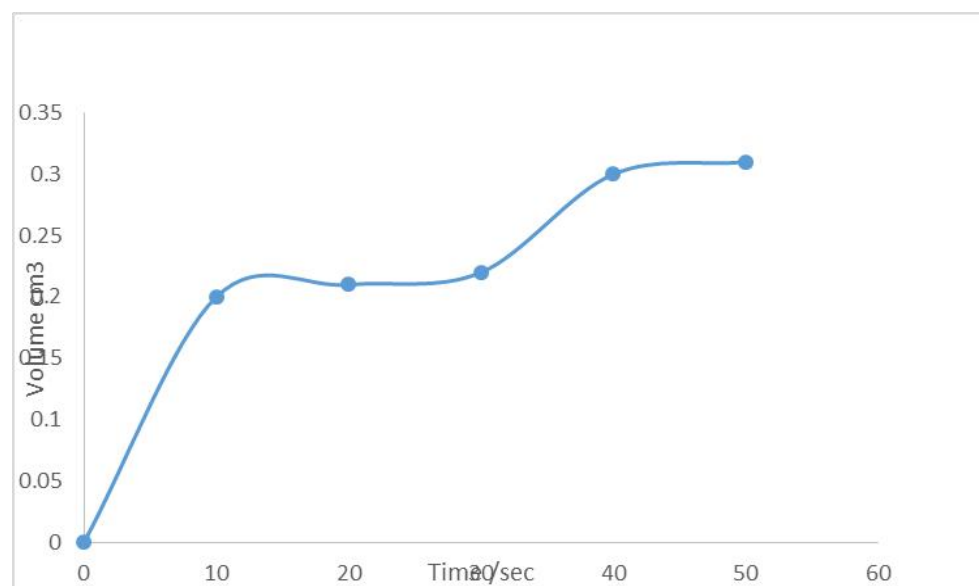


Figure 3: Volume of liquid A (water) against time

The Figure 3 shows the relationship between time (in seconds) and the volume of a liquid (in cm³), revealing distinct phases in the liquid's flow behavior over the course of the experiment. Initially, from 0 to 10 seconds, there is a steep increase in volume, indicating a rapid flow rate. This rapid rise suggests that the liquid flows easily at the beginning, likely due to low resistance

or the application of an initial force that quickly propels the liquid through the system. The sharp incline in the graph signifies that the liquid is encountering minimal resistance, allowing for a significant increase in volume in a short amount of time.

Following this initial phase, the graph enters a flat from approximately 10 to 30 seconds, where the volume increases only slightly. This flattening of the curve indicates that the flow rate has significantly decreased. The reduction in flow rate could be due to increased resistance within the system, such as friction or viscosity, or the liquid reaching a more stable flow condition. Between 30 and 40 seconds, there is another rise in volume, suggesting a change in the flow dynamics, possibly due to a decrease in resistance or an adjustment in the driving force. After 40 seconds, the graph levels off again, indicating that the flow has stabilized, with the volume remaining constant around 0.3 cm³. This final plateau suggests that the liquid has reached a steady-state flow, where the inflow and outflow are balanced, and the volume no longer increases with time

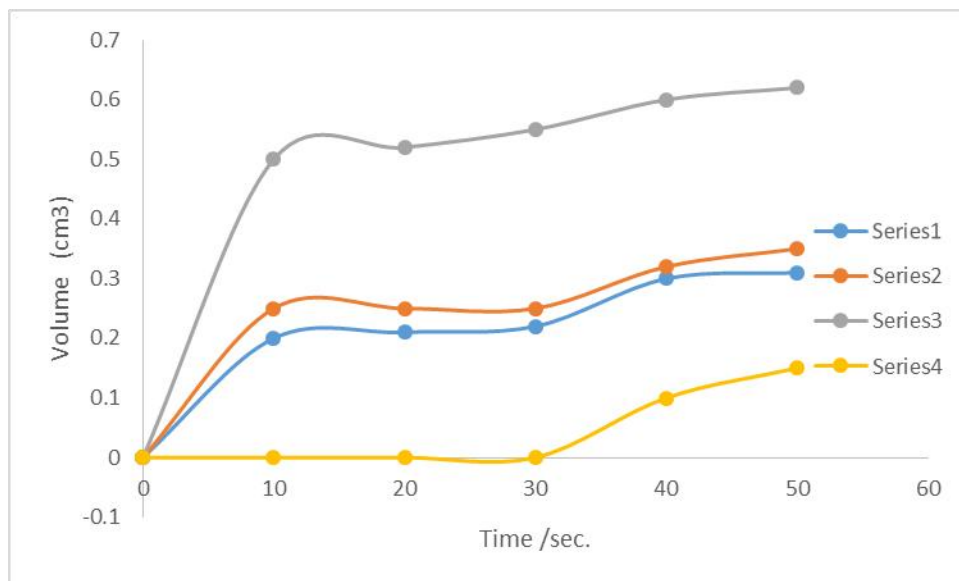


Figure 4: Volume of liquid A, B, C and D against time

The Figure 4 illustrates the flow behaviors of four different liquids [Series 1(Label A), Series 2(Label B), Series 3(Label C), and Series 4 (Label D)] over a 50-second period, highlighting their distinct viscosity and resistances to flow. Series 1, represented by the blue line, shows an initial rapid increase in volume, reaching about 0.3 cm³ within the first 10 seconds. This sharp rise indicates that Series 1(Label A) is a low-viscosity liquid, allowing it to flow quickly with minimal resistance. After this initial surge, the flow rate stabilizes, with only slight increases in volume, suggesting that the liquid reaches a steady state early in the experiment.

Series 2 (Label B), depicted by the orange line, has a more moderate initial increase in volume, reaching about 0.25 cm³ by 10 seconds. This slower start implies a higher viscosity or greater resistance compared to Series 1. However, Series 2 continues to increase slightly after the initial phase, eventually reaching a similar volume to Series 1 by 50 seconds. This gradual rise

indicates that while Series 2 flows less readily at first, it eventually achieves a steady flow similar to that of Series 1, albeit with a delayed response.

Series 3 (Label C), shown by the gray line, stands out with the highest and fastest increase in volume, reaching nearly 0.6 cm^3 by 10 seconds. This indicates that Series 3 is the least viscous or encounters the least resistance, allowing it to flow more freely and in greater volume than the other liquids. After the initial surge, the flow rate of Series 3 stabilizes but continues to rise slightly, reaching about 0.65 cm^3 by 50 seconds. This suggests that Series 3 maintains a high and stable flow rate throughout the experiment, making it the most efficient flowing liquid among the four.

In contrast, Series 4 (Label D), represented by the yellow line, has the slowest flow rate, with a very gradual increase in volume reaching only about 0.05 cm^3 by 10 seconds. This slow start indicates that Series 4 has the highest viscosity or faces significant resistance. However, unlike the other series, Series 4 continues to rise steadily throughout the experiment, reaching about 0.15 cm^3 by 50 seconds. This behavior suggests that while Series 4 (Label D) flows slowly, it does so consistently, gradually overcoming its resistance over time. The differences in flow behavior among these four series highlight the importance of viscosity and resistance in determining how liquids move under similar conditions, providing valuable insights for applications that require precise control of liquid flow.

Conclusion

The experimental investigation of the flow dynamics of liquids through fine sand packed within a narrow tube was carried out using five different liquids. The results revealed clear differences in the flow rates of various liquids, emphasizing the important role viscosity and fluid dynamics play in determining how liquids behave, under similar conditions. The data indicate that petrol flows the fastest, with the highest volume reached in the shortest time. This suggests that petrol has the lowest viscosity among the tested liquids, allowing it to move through the system with minimal resistance. The rapid flow rate of petrol underscores its suitability for applications requiring quick and efficient fluid transfer, such as in fuel systems where high flow rates are essential. In contrast, liquids like vegetable oil and palm oil exhibit much slower flow rates, with significant delays before any measurable volume is recorded. These oils, with their higher viscosity, require more time to overcome internal resistance and begin flowing. The steady but slow increase in volume over time for these oils highlights their thick, viscous nature, which limits their flow rate. This characteristic is important in contexts where the controlled release of liquids is needed, such as in lubrication or food processing industries.

Reference

- Adegoke, J.A. (2004). The effects of porosity, angle of hydrostatic equilibrium, volume flux and rate on groundwater flow through riverbed sand. Ph.D Thesis. Department of Physics. University of Ibadan.
- Andreotti, B., Forterre, Y. & Pouliquen, O.(2013). Granular media: between fluid and solid. Cambridge University Press. 425(6958), 556–557
- Bear, J., & Bear, J. (2018). Poromechanics and Deformation. Modeling Phenomena of Flow and Transport in Porous Media, 625-660.

- Bourouiba, L. (2021). The fluid dynamics of disease transmission. *Annual Review of Fluid Mechanics*, 53(1), 473-508.
- Chen, J.-D. & Wilkinson, D. (1985). Pore-scale viscous fingering in porous media. *Phys. Rev. Lett.* 55, 1892–1895
- Douglas, E. and Yong, N.R., (1981). Validity of Darcy's Law for one dimensional, unsaturated flow in kaolinite – water – NaCl systems. *Transactions of the American society of Agricultural Engineers*, 24(3):657 – 662.
- Dullien, F. A. & Batra, V. K. (1992) Determination of the structure of porous media. *Industrial & Engineering Chemistry* 62(10), 25–53
- Fraggedakis, D., Pavlidis, M., Dimakopoulos, Y. & Tsamopoulos, J. (2016). On the velocity discontinuity at a critical volume of a bubble rising in a viscoelastic fluid. *J. Fluid Mech.* 789, 310–346
- Gasperino, D., Baughman, T., Hsieh, H. V., Bell, D. & Weigl, B. H. 2018 Improving lateral flow assay performance using computational modeling. *Annu. Rev. Analyt. Chem.* 11, 219–244
- Georgiou, T., Schmitt, S., Olhofer, M., Liu, Y., Bäck, T., & Lew, M. (2018). Learning fluid flows. In 2018 International Joint Conference on Neural Networks (IJCNN), IEEE. (pp. 1-8).
- Henry, D.F.(2005). Fundamentals of soil science. 8th Edition. John Wiley and sons, New York, 95-99.
- Hiscock, K M., Loveit, A.A., Brainard, J. S. and Parfitt, J.P. (1995). Groundwater vulnerability assessment: two case studies using GIS Methodology *Quarterly Journal Engineering Geology*, 28: 179-194
- Huang, X., Liu, G., Xia, C., & Yang, M. (2021). Simulated groundwater dynamics and solute transport in a coastal phreatic aquifer subjected to different tides. *Marine Georesources & Geotechnology*, 39(6), 719-734.
- Hubbert, M. K. (1956). Darcy's law and the field equations of the flow of underground fluids. *Transactions of the AIME*, 207(01), 222-239.
- Jaeger, H. M., Nagel, S. R. & Behringer, R. P. (1996). Granular solids, liquids, and gases. *Mod. Phys* 68, 1259–1272.
- Jensen, O. E. & Chernyavsky, I. L. (2019). Blood flow and transport in the human placenta. *Annu. Rev. Fluid Mech.* 51, 25–47.
- Jiang, F. & Tsuji, T. (2017). Estimation of three-phase relative permeability by simulating fluid dynamics directly on rock-microstructure images. *Water Resour. Res.* 53, 11–32.
- Jones, N. L., & Wright, S. G. (1993). Subsurface characterization with solid models. *Journal of geotechnical engineering*, 119(11), 1823-1839. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1993\)119:11\(1823\)](https://doi.org/10.1061/(ASCE)0733-9410(1993)119:11(1823))
- Keller, J. B. (2017). Darcy's law for flow in porous media and the two-space method. In *Nonlinear partial differential equations in engineering and applied science* pp. 429-443
- Lei, W., Xie, C., Wu, T., Wu, X. & Wang, M. (2019). Transport mechanism of deformable micro-gel particle through micropores with mechanical properties characterized by AFM. *Sci. Rep.* 9, 1453–1453
- Miao, X. X., Wang, C. S. & Bai, H. B.(2010) Hydrogeologic characteristics of mine water hazards in Shendong mining Area. *Journal of Mining & Safety Engineering* 27(3), 285–291

- Möbius, M. E., Lauderdale, B. E., Nagel, S. R. & Jaeger, H. M. (2001). Brazil-nut effect: Size separation of granular particles. *Nature* 414(6861), 270–270.
- Mohammed, R. H., Mesalhy, O., Elsayed, M. L., Su, M., & Chow, L. C. (2018). Revisiting the adsorption equilibrium equations of silica-gel/water for adsorption cooling applications. *International Journal of Refrigeration*, 86, 40-47.
- Neuman, S. P. (1977). Theoretical derivation of Darcy's law. *Acta mechanica*, 25(3), 153-170.
- Oukhlef, A., Latrache, N., Champmartin, S., & Maiss, M. (2023). Identification of the pore size distribution of a porous medium using oscillating Newtonian fluids. *Physics Letters A*, 460, 128615.
- Pinheiro, E. A. R., van Lier, Q. D. J., & Šimůnek, J. (2019). The role of soil hydraulic properties in crop water use efficiency: a process-based analysis for some Brazilian scenarios. *Agricultural Systems*, 173, 364-377.
- Rokochynskiy, A., Volk, P., Turcheniuk, V., Tokar, L., Volk, L., Mazhayskiy, Y., & Chernikova, O. (2020). The drainage module is an important factor in the design of drainage systems reconstruction and construction projects in the polesia region. *Engineering for rural development*, 36-47.
- Swartzendruber, D. (1962). Modification of Darcy's law for the flow of water in soils. *Soil Science*, 93(1), 22-29.
- Tang, G., Li, C., & Wang, Y. (2015). Experimental and numerical study of non-Newtonian fluid flow in porous media. *Transport in Porous Media*, 110(1), 169-191.
- Theyab, M. A. (2018). Fluid flow assurance issues: literature review. *SciFed Journal of Petroleum*, 2(1), 1-11.
- Thomas, J. H. (2019). Fluid dynamics of cerebrospinal fluid flow in perivascular spaces. *Journal of the Royal Society Interface*, 16(159), 20190572.
- Whitaker, S. (1986). Flow in porous media I: A theoretical derivation of Darcy's law. *Transport in Porous Media*, 1(1), 3-25.
- Zhang, L., & Kang, Q. J. (2014). Experimental study of fluid flow through a packed bed of glass spheres using magnetic resonance imaging. *Chemical Engineering Science*, 116, 692-703.