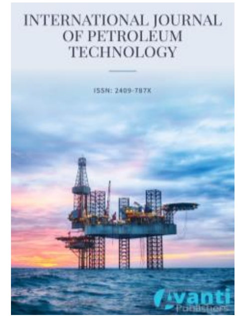
Published by Avanti Publishers

International Journal of Petroleum Technology

ISSN (online): 2409-787X



A Review on Fundamentals and Capturing Petroleum Fluid Hysteresis Through Experiments

Murtada A. Elhaj*

Department of Process Engineering, Memorial University of Newfoundland, St. John's, NL, Canada

ARTICLE INFO

Article Type: Research Article

Academic Editor: Ruifang Huang

Keywords:
Viscosity
Hysteresis
Wettability
Capillary pressure
Interfacial tension

Timeline:
Received: June 08, 2023
Accepted: July 31, 2023
Published: September 07, 2023

Citation: Elhaj MA. A review on fundamentals and capturing petroleum fluid hysteresis through experiments. Int J Petrol Technol. 2023; 10: 39-52.

DOI: https://doi.org/10.15377/2409-787X.2023.10.4

ABSTRACT

Hysteresis is proven to have a significant role in petroleum fluids and other disciplines for better understanding and evaluation. This shows a need to be explicit about precisely what is meant by the word "hysteresis." For a long time, the term hysteresis has been used and has attracted the attention of most researchers and investigators. Despite its common usage, hysteresis is used in different disciplines to mean different things. Thus, hysteresis has many definitions depending on the book or paper's area of interest. While various definitions of the term 'hysteresis' have been suggested, this paper will focus on the definition in the oil and gas industry. Hysteretic impacts petroleum fluids either positively or negatively. Therefore, accurately estimating fluid properties curves is vital in evaluating hydrocarbon recovery processes. This paper addresses and discusses a comprehensive review of the hysteresis of different petroleum fluid properties and their applications. This paper reviews many fluid properties of hysteresis and investigates them experimentally. Numerous laboratory studies in hysteresis are present in the literature and critically reviewed and highlighted in this research. This paper aims to review the experimental processes of fluid hysteresis extensively. To satisfy this aim, this paper offers insights into and explanations for experiments that have been used in fluid hysteresis. The outcomes highlight some missing concepts of the existing models and experimental processes for fluid hysteresis. Furthermore, this paper tracks the current development of hysteresis and gives insight into the future trends in the application of hysteresis.

*Corresponding Author

Email: aelhaj@mun.ca
Tel: +(1) 709 743 8440

1. Introduction

A more detailed account of the importance of hysteresis in petroleum fluids is given in the following section. Since the definition of hysteresis varies among researchers, it is essential to clarify how it plays a vital role from one discipline to another. As reported by many researchers, the hysteresis phenomenon is recognized in many disciplines, such as magnetic hysteresis [1], economics [2], biology [3], chemistry [4], mathematics [5], civil engineering [6], and petroleum engineering [7-14]. Due to the uses of hysteresis in many sciences, the definition varies from one discipline to another. Regarding magnetics, Mayergoyz [15] proves that the hysteresis transducer occurs when its input-output relationship is non-linear, which means the output does not follow the same input track when branch-to-branch transitions occur. Gross *et al*. [2] define hysteresis in economics by considering a system with input and output; both are a function of time. The system is a hysteresis if, at time t, the output is calculated by the input history, not just the scalar of input. In chemistry, Paska [4] finds that the hysteresis effect exists in field-effect transistors, which a transistors used to handle the electrical behavior when surface hydroxyl (Si-OH) sites ($Si\text{-}O^-$, $Si\text{-}OH_2^+$, OH^-, or H^+ species) initially exist. However, because of the lag response that happens in the forward and backward of the current against voltage, hysteresis occurs in field-effect transistors [16, 17]. Hydraulic hysteresis is well known in civil engineering as Wheeler *et al*. [6] propose in their study that if two samples from the same soil are tested against suction, one is in the drying stage, and the other is in the wetting stage, the two samples will be at different values of the degree of saturation.

Many oil and gas industry researchers study hysteresis using various fluid parameters [11, 12, 14, 18-20]. For example, Elizabeth *et al*. [9] studied the effect of relative permeability on the field-scale predictions of water alternating gas (WAG). They define the hysteresis on three-phase relative permeability based on the saturation path and the saturation history. Accordingly, their definition is characterized by a series of three-phase drainage and imbibition cycles. Many other researchers study the relative permeability hysteresis in different reservoir types and against various tests. Still, all these researchers define hysteresis based on experimental or simulation studies [7, 10, 21-24]. Another investigation focuses on permeability and porosity hysteresis done by Teklu *et al*. [25]. The study tests these two parameters against net stress in consolidated and unconsolidated porous media. They define hysteresis based on the discrepancy of the following path when permeability and porosity are exposed to an increase or decrease of net stress. Furthermore, Ahmadzadeh *et al*. [22] studied the effect of interfacial tension (IFT) and hysteresis on capillary pressure. Their study observes the effect of hysteresis in two cases, oil-wet, and water-wet, during the imbibition and drainage process.

2. Applications of Hysteresis in Various Fields

Hysteresis is a phenomenon widely used in different scientific areas. This section describes and explains several recent cases of hysteresis. The applications discussed in this paper are, first, engineering fields, which are petroleum, electrical, mechanical, and civil engineering. Secondly, applications of hysteresis in biology include neuroscience and cornea—lastly, hysteresis in economics and finance. A summary of the standard features of these applications is identified at the end of this section.

According to all these researchers, hysteresis generally be defined as "a phenomenon that happens in a system when a characteristic looping behavior of the input-output graph is displayed" [17]. For a general and better understanding, see Fig. (**1**), which shows the general hysteresis loop for any system. Path A represents the track of the first process for any parameter; in most cases, it is a system's input, while path B represents the track of the second process; in most cases, it is a system output. Some cases show this behavior only on the positive sides of the X and Y axes; another covers all sides of the two axes, as shown in Fig. (**1**). Not necessary for hysteresis's paths to be a curve; in some cases, it can be a square, rectangle, or trapezium [26]. In other words, the input or output may take linear or non-linear forms depending on the process that is conducted in the system.

2.1. Application of Hysteresis in Engineering

Engineering is one of the fields that has a hysteresis application. Many researchers study hysteresis applications in different engineering disciplines. For example, in petroleum engineering, capillary pressure with saturation are the first parameters that use the hysteresis concept [27]. Following the same track, many studies investigate rock parameters such as porosity, permeability, saturation, net stress, pressure, and temperature [7, 22, 23, 25, 28-36]. On the other hand, fluid parameters are also investigated, such as interfacial tension, wettability, and foam [7, 27, 37]. Another example from engineering is electrical; Irmak *et al*. [38] study the electrical properties with thermal hysteresis. Mechanical engineering also investigates some parameters to study hysteresis; for instance, Longbaio [39] explores the effect of loading and unloading, temperature, and oxidation on mechanical hysteresis. Lastly, civil engineering also uses the hysteresis phenomenon to study stress-strain behavior in soils, as Wheeler [6] reported in his paper.

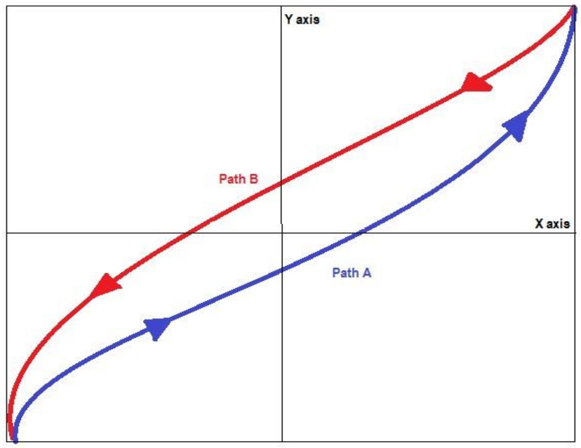


Figure 1: A hysteresis loop for a system.

2.2. Application of Hysteresis in Biology

Biology with hysteresis has a much shorter history than engineering with hysteresis, especially mathematical approaches. Mathematical models of hysteresis with biology have recently been used, including dynamics of metabolic networks, neuroscience, and cornea [3]. In his recent book, Noori [3] studies the hysteresis phenomenon in protein-DNA interactions, microscopic cellar signaling pathways with bistable molecular cascades, neuroscience, and cornea. Other recent scholars study hysteresis in biologies, such as Spiteri *et al*. [40], Chatterjee *et al*. [41], and Qiao *et al*. [42].

2.3. Application of Hysteresis in Economics

The application of hysteresis effects in the economic system is introduced by Cross *et al*. [2]. The main goal of his book is to incorporate hysteretic products into mathematical models in the financial system. Geogresu-Roegen [43] is one of the first scholars to investigate economics hysteresis. Cross *et al*. divide the hysteresis into weak, strong, and passive hysteresis depending on the relationship between input and output. If the system contains a limited number of points, then the system has weak hysteresis; elsewhere, it has strong hysteresis. While the loop of hysteresis is counterclockwise, the system has a passive hysteresis. Gocke [44] investigates the presentence hysteresis phenomenon in microeconomics and macroeconomics.

2.4. Summary and Observations in Different Disciplines

Table **1** summarizes, analyses, and shows some observations on using hysteresis in different fields. Moreover, it shows the parameters used in the investigation of hysteresis. In general, the table shows how applications of hysteresis are different from one field to another depending on the parameters. Therefore, the outcomes are various, but all the studies show the general concept of hysteresis, which is taking one path in the first process and taking another path in the second process. This section focuses on the applications of hysteresis in the engineering field, especially petroleum engineering; therefore, many studies in petroleum engineering are reported.

Table 1: Summarizes the most recent work in hysteresis in various fields.

Field	Sub-Field	Author	Considered Parameters	Outcomes	Observations
Engineering	Petroleum	Teklu [25]	Porosity and Permeability vs. Net Stress	Porosity and permeability increase when net stress decreases and both decrease when net stress increase	• An experimental study in low-permeability formations • Outcrops used in this study made it only applicable to limited options
	Electrical	Irmak [38]	Electrical properties for Lanthanum, Manganese, and Oxygen compound vs. thermal	Thermal hysteresis influences electrical properties upon cooling or warming, either increasing or decreasing.	• This study uses a wide range of temperatures in two samples, which gives the validity of the method that is used in this study to be used in others
	Mechanical	Longbaio [39]	Tensile, tension, temperature, and oxidation vs. loading/unloading effects	Predict the mechanical hysteresis for the interested parameters in different loading types at room and 800 temperatures.	• This study uses experimental and numerical approaches to investigate mechanical hysteresis • The author suggests more future studies on shear stress and broken fibers
	Civil	Wheeler *et al*. [6]	Pore air and pore water pressures vs. saturation of soil	The percentage of saturation in soil has a significant effect on the stress-strain behavior in drying and wetting paths	• A new model for elastic-plastic constitutive for soil is developed in this study. • An experimental study was conducted to verify the developed model
Biology	Neuroscience	Noori [3]	Neuron cells vs. perisynaptic glial cells	The neuron and glia cells are the main two types of cells in the nervous system and have a dynamic reciprocal feedback relationship	• Two hysterons are connected in a parallel way in the hysteresis diagram
	Cornea	Derek and H. Noori [3, 45]	Air pressure vs. light signal	The hysteresis behavior reflects an intrinsic viscoelastic biomechanical property of the cornea	• The main reason for hysteresis to be happening is the flattening of the cornea
Economics	Economic and finance	Cross [2]	Any input vs. output of an economic system	The idea of considering hysteresis in economics and finance came from micromagnetics and was adopted to be used in various contexts of economic activates	• Authors incorporate time in hysteresis concepts • Mathematical models along with theoretical explanations are both used in this article

3. Experimental Studies in Fluid Hysteresis

Many experimental works have been performed to study the effect of hysteresis behavior on rock and fluid properties. Fluid properties have gotten most of the researchers' attention in investigating hysteresis experimentally since early times compared to rock properties. Several experimental studies have been conducted on fluid properties, such as capillary pressure [14, 46-49] wettability [46, 50-52], and interfacial tension [50-54].

Recently, many researchers have experimentally tested the hysteresis phenomenon in rock properties [7, 9, 37, 48, 51, 52, 55-60]. In this paper, different fluid properties will be reviewed, discussed, and addressed experimentally for the hysteresis phenomenon.

Laboratory investigations into fluid hysteresis started many decades ago to observe and explain how and why fluid hysteresis occurs. Brown [49] and Benner *et al*. [54] are among the first scholars who studied fluid hysteresis experimentally.

3.1. Wettability

In their study, Benner *et al*. [54] and Elhaj *et al*. [13] found different values of the interfacial contact angle for the oil-water system against the quartz-silica in the case of increasing or decreasing water. The contact angle was either less or greater than 90 degrees for water receding or advancing. The difference between these two angles is well-known as hysteresis. The study used three types of oil to test the wettability against hysteresis at atmospheric pressure. Because of the non-availability of the oil-field brain, distilled water was used instead. The sessile drop technique was used in this study. The reason for the phenomenon of wettability was not explained; instead, Benner *et al*. [54] stated that the effect of hysteresis on wettability has been mysterious, and none of the studies offered an accurate explanation, as reported by Bartell [61]. Although this study attempts to explain the phenomenon of hysteresis, it is limited because of the conditions of the experiment, such as using distilled water instead of brain water, as well as conducting the investigation in room conditions instead of reservoir conditions.

Michaels *et al*. [62] examined the contact angles between a drop of water and a gel surface. A series of recordings were conducted by increasing and decreasing these angles to examine hysteresis. Their study considered time as a variable factor, so the reported values for angles were time-dependent. However, this study fails to explain the cause of hysteresis in contact angle, but Michaels *et al*. [62] categorized the theories that attempted to explain the hysteresis phenomenon into three groups. The first group of these theories explained that hysteresis occurred due to interfacial free energy variations. The second group demonstrated the cause of hysteresis due to surface geometry. The molecular structure of the solid surface was the opinion of the third group.

Grundke *et al*. [63] studied contact angle hysteresis on polymer surfaces using sessile liquid droplets and air bubbles. The study used scanning electron microscopy (SEM) and scanning force microscopy (SFM) to characterize the polymer surfaces in terms of their structure and element composition. Therefore, several surface types were used, such as soft and rough surfaces. This study used the effect of swelling and reorientation of the liquid/solid angle to explain the hysteresis phenomenon. This study concludes that a surface with roughness less than one-hundred-nanometer diameter does not affect contact angle hysteresis [64].

By tracking these studies, contact angle, which leads to wettability, has a different aspect of hysteresis depending on the surfaces or the fluids used. However, all these studies generally agreed on the common fundamental of hysteresis, which is increasing or decreasing the contact angle when the fluids or surfaces are exposed to an external element. Wettability hysteresis is significant when injecting water into porous media or adsorption at liquid/solid interfaces such as painting or coating [65].

Many other studies investigate wettability hysteresis, such as Extrand [64, 66, 67], Reyssat [68], Moradi [69], and Restango [70]. Table **2** summarizes and shows some examples of experimental studies in wettability hysteresis, while Fig. (**2**) explains the change of contact angles during hysteresis effects.

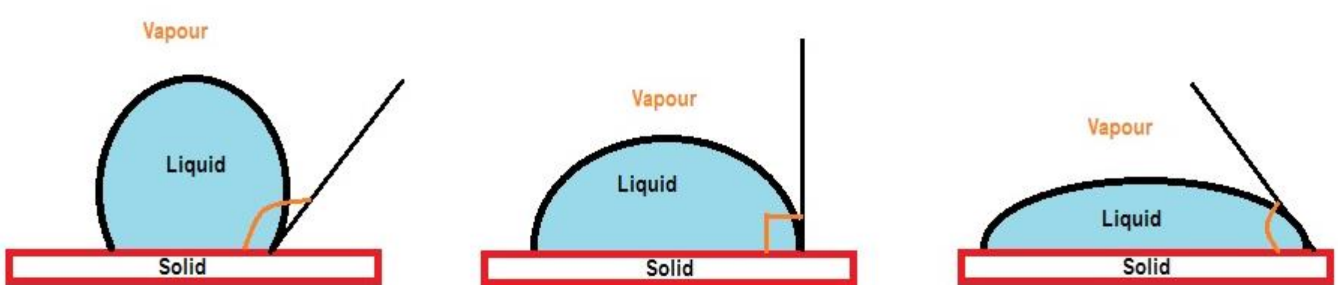


Figure 2: Change of contact angle during the hysteresis process.

Table 2: Analysis of some experimental studies in wettability hysteresis.

Author	Conditions	Variables	Effect on Hysteresis	Time-Dependent
Benner [54]	• Room temperature • Atmospheric pressure	Oil-water system and sandstone surface (quartz-silica)	An increase in contact angle tends to increase hysteresis	No
Michaels *et al*. [62]	• Liquid heated to 90 degrees and cooled to 40 degrees • Poured into a rectangular glass cuvette	A drop of water and gel surface	The hysteresis varies depending on the gel concentrations, advancing, or deciding the angle	Yes
Grundke *et al*. [63]	• Laplace equation is used to determine the shape of a drop • The drop profile is axisymmetric	Sessile liquid, air bubbles, and polymer surfaces	Surfaces with roughness <100 nm have no hysteresis effects	Yes
Extrand [64]	• The surface is small plaques • Room temperature	Adhesion between water and polyamide	Hysteresis increases with contact angle while it decreases with amide contents	No

3.2. Capillary Pressure

Brown [49] is one of the first researchers to investigate the hysteresis behavior in capillary pressure using the restored state and the mercury-injection methods. The results were compared to dynamic capillary pressure measurements conducted by the Hassler technique [14, 71, 72]. Although his lab work was not mainly focused on hysteresis, he compared two methods he used for dynamic capillary pressure measurements, the Hassler technique; and the concept of drainage and imbibition, later known as hysteresis regarding capillary pressure.

Gardner *et al*. [71] use dynamic measurement techniques to measure capillary pressure using sandstone and carbonate samples. They concluded that hysteresis must be considered in capillary pressure measurements when these measurements depend on the premier distribution of fluid in the cylinder. Their experimental results showed the relationship between capillary pressure, saturation, and hysteresis, which is that as the saturation increases, the capillary pressure decreases; therefore, the hysteresis increases.

Kleppe *et al*. [47] used laboratory capillary pressure measurements on the gas-oil system to investigate and simulate hysteresis. The porous plate method, one of the three methods used to measure capillary method (mercury methods, porous-plate methods, and centrifuge methods), is shown in Fig. (**3**). For more details about the porous plate methods, see [73, 74]. Kleppe *et al*. presented a new method in the gas-oil system to determine hysteresis capillary pressure based on the history of saturation and capillary pressure bounding curves. This method, as well, can be used in reservoir simulation models.

Wang *et al*. [75] and Masalmeh [76] analyzed capillary pressure hysteresis under experimental study. The experimental results showed that hysteresis is more noticeable under low salinity conditions during imbibition compared to high salinity conditions. The study also identified multi-phase flow hysteresis during fluid flow in porous media. They claimed that multi-phase flow is not only a function of saturation but of hysteresis as well. Furthermore, they stated that this phenomenon in multi-phase flow occurred because of contact angle hysteresis, trapping of the nonwetting phase, and wettability. The study explained that hysteresis is significant in low salinity, such as mineral dissolution and wet water samples.

All these studies show the importance of capillary pressure hysteresis in porous media. Some studies considered one path, either drainage or imbibition, to investigate hysteresis [47, 49, 62, 71, 77]; others focused on both imbibition and drainage [75, 76, 78]. As reported in the literature, for a better understanding of multi-phase flow in porous media, it is necessary to understand capillary pressure hysteresis because it is the key to describing flow in porous media. Table **3** lists some works that have been done in capillary pressure hysteresis.

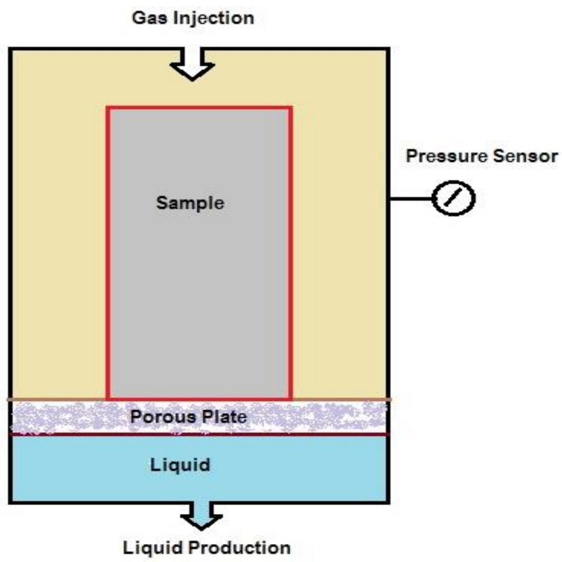


Figure 3: The porous plate method used in Kleppe *et al*. [47] experimental study (redrawn).

Table **3** compares results from several studies in capillary pressure hysteresis. These studies show diverse types of methods used to investigate hysteresis. On the one hand, some studies used the oil-water system; others used the gas-oil system. On the other hand, several studies used different methods to determine capillary pressure, including porous plate, mercury injection, restored state, and dynamic measurement technique. A few studies used the centrifuge method but were not reported in this paper; for more details about how to use the centrifuge method [79, 80]. General observations were made according to the methods used in the study, missing assumptions, and some other observations.

Table 3: Summary and observations for some studies in capillary pressure hysteresis.

Study	Methods	Imbibition	Drainage	Results	Observations
Brown [49]	• The Restored-state method • The mercury-injection methods	No	Yes	Comparison between two methods and dynamic capillary pressure measurements by Hassler technique	He did not use the term hysteresis, but later his work was used as an inspiration
Gardner *et al*. [71]	• Sandstone and carbonate samples used • Using dynamic measurement technique	Yes	No	The increase in saturation and decrease in the capillary pressure leads to an increase in hysteresis	In their study, they assumed fluid flow a horizontal and the viscosity and density of the air were negligible, which gave the limitation for this study
Kleppe *et al*. [47]	• Gas-oil system • The porous plate method	Yes	Yes	A new method in gas-oil system to determine hysteresis capillary pressure	This study shows the imbibition and drainage in physical equations, which make it easier to understand hysteresis behavior
Wang *et al*. [75]	• High and low salinity • Reservoir conditions	Yes	No	Hysteresis is more prominent under low salinity compared to high salinity	Time varies been considered in this study in the modeling part

3.3. Interfacial Tension

Interfacial tension is a phenomenon that occurs in the presence of two phases. It is rare to see interfacial tension hysteresis in literature; however, some researchers highlighted its relationship with temperature, pressure, or fluid composition [81-84], but not in terms of hysteresis. Jain *et al*. [50] presented that the interfacial tension has a role in relative permeability hysteresis behavior along with pore geometry and the condition of the experiment. Denoyelle and Lemonnier [53] also showed the importance of interfacial tension in relative permeability hysteresis.

Peltonen and Yliruusi [85] investigated Sorbitan monoesters' interfacial properties, including interfacial intention. They studied the surface pressure hysteresis in terms of a compression-expansion cycle for different Sorbitan monoesters. The study also focused on the effect of the concentration of sorbitan monoesters on interfacial tension by showing that as the concentration increases, the interfacial tension decreases but differently depending on which type of sorbitan monoesters.

Recently, Ghorbani and Mohammadi [84] experimentally studied the effect of temperature, pressure, and fluid composition on gas-oil interfacial tension. Although their study did not focus on hysteresis behavior, it highlighted these variables' effect on interfacial tension and which one has more effectiveness. Pressure has more influence on interfacial tension rather than temperature, and fluid composition might change from one fluid to another; that is what their study proved.

By looking at the literature, interfacial tension hysteresis did not take researchers' attention. It might be because most of the research has been done in contact angle or relative permeability, which strongly connects with interfacial tension. Another reason, as Ghorbani and Mohammadi [84] report, temperature has no significant effect on interfacial tension. It does not have a specified trend, indicating hysteresis might not even exist in interfacial tension.

3.4. Viscosity

The term "hysteresis of viscosity" is not that famous in terms of fluid viscosity. Still, it is well known in the magnetic field when Jubb and McCurrie [86] experimentally studied the hysteresis phenomenon in magnetic viscosity. Their study was based on the theory of Gaunt [87] which showed the relationship between magnetic viscosity and temperature. Jubb and McCurrie [86] confirmed experimentally the hysteresis loop for the thermally and magnetic viscosity. A study aligned with what Jubb and McCurrie investigated was done by Stamps [87], in which he studied hysteresis in dynamic magnetic and viscosity in exchange systems.

According to Murshed and Estelle [88], the first attempt at studying hysteresis in fluid viscosity was made by Nguyen *et al*. [89]. The study by Nguyen *et al*. is considered the first evidence of an experimental study of the hysteresis phenomenon for nanofluids viscosity under two conditions, temperature and nanoparticle concentration. Furthermore, this study raised serious attention to using nanofluids for thermal-enhanced oil recovery.

Another study highlighted the effect of nanofluids hysteresis in heat transfer enhancement done by Nguyen *et al*. [90]. As demonstrated in their previous study, Nguyen *et al*. [87] raised concern about using nanofluids as a thermal-enhanced oil recovery; they continued their study by investigating the heat transfer phenomenon in viscosity. They concluded that at a critical temperature, the viscosity increases with the temperature increase inversely to what is known. From that point, the phenomenon of hysteresis occurred in a cooling phase. As the study demonstrated, the reason is that once critical temperature is reached, the fluid particles seem to be irreversibly altered. For more details about how the nanofluids can be used in confined flow situations [91-97].

Thermal hysteresis in viscosity also has been investigated by Walz *et al*. [97] by measuring different viscosity temperatures in the phase diagram of the triblock copolymer solved in water. Before melting occurred at 44 C, a highly viscous crystalline fcc was found. The different shapes and paths of the particle during heating and cooling have been observed for the first time for this material, which is called hysteresis.

3.5. Summary and Observations

Hysteresis in fluid properties occurs in different ways depending on the property. For example, it may have happened when the fluid is exposed to heating or cooling temperature or also for different percentages of fluid concentrations such as in viscosity [86, 87, 89, 90]. Another example is when the fluid is tested with loading or unloading pressure, such as interfacial tension [54, 85]. Furthermore, at different saturations, the hysteresis concept occurred in capillary pressure [46, 75, 76, 78].

The Recent growth of annual publications on fluid hysteresis is shown in Fig (**4**). For the last seventeen years, fluid hysteresis has gradually increased, indicating it drew the researchers' attention. As shown in Fig. (**4**), a significant share of the reported publication on hysteresis belongs to capillary pressure hysteresis (45%), followed by wettability (20%) and viscosity (20%). Interfacial tension has fewer reported publications (16%) compared to others. Nevertheless, viscosity and interfacial tension have increased slightly in recent years, as shown in Fig (**4**). However, researchers have not paid attention to interfacial tension hysteresis that much because of its difficulty or not playing an important role in fluid hysteresis. Fig. (**4**) was generated from the record of published conference papers, journals, patents, and books on the "ScienceDirect" and "Onepetro" websites; the research occurred on 3 June 2023.

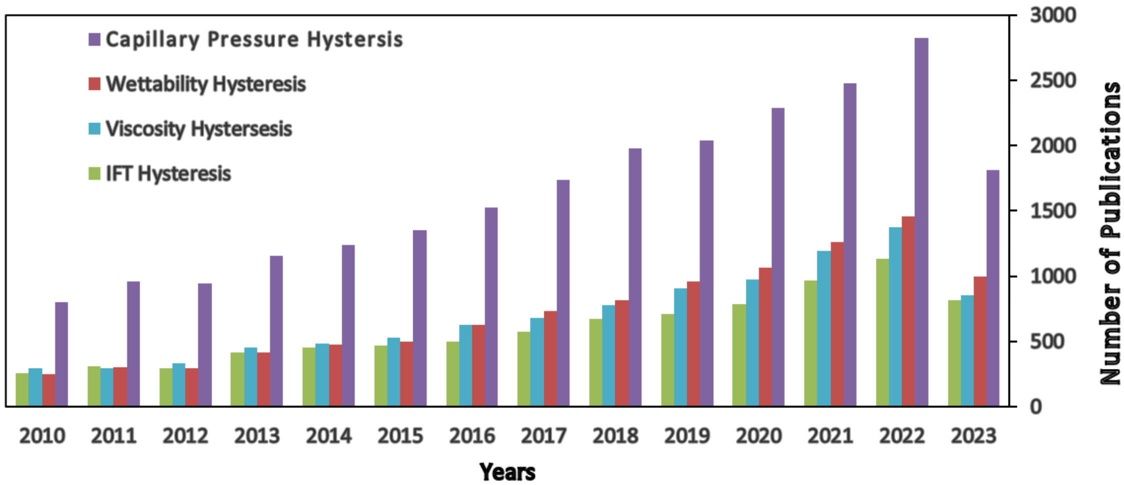


Figure 4: Publications records on different properties of fluid hysteresis from Webs of Science and Onepetro.

4. Conclusions and Recommendations

This paper extensively reviews and presents hysteresis for fluid properties. The focus was on experimental work done in these properties in terms of petroleum engineering. The applications of hysteresis in other disciplines, such as economics, biology, chemistry, physics, civil engineering, and mechanical engineering, are covered briefly in this paper.

The primary concern of this paper is fluid hysteresis, such as capillary pressure, wettability, viscosity, and interfacial tension hysteresis. All these properties have a different common feature of hysteresis type, depending on the system. For example, there is thermal hysteresis when the fluid property is exposed to heating and cooling, such as viscosity. Another example is when the interfacial tension is under loading or unloading stress, another type of hysteresis is obtained.

In the literature, no attempt is made to refer to and review more than one fluid property of hysteresis in one article because of the numerous publications in this area, either books, journal papers, or conference papers. Based on this fact, this article is considered one of a kind, and it is the first attempt to provide a complete and comprehensive review of the fluid properties of hysteresis. Although covering the hysteresis phenomenon in both fluid properties in one article is almost a real challenge for authors, this paper covers the experimental works that have been done in most fluid properties well.

Finally, the following observations and recommendations can be considered regarding the hysteresis phenomenon:

1. The experimental study was conducted in special conditions and exceptional cases. Therefore, the universal hysteresis concept for fluid properties is missing from the literature.
2. Following the previous point, no attempt was reported in the literature to use the experimental data to develop a general model applicable to predicting any conditions rather than experimental ones. However, some studies highlighted the data's use in developing a model but not in a general form. So, a numerical model must be developed for at least one fluid property.
3. Comparing the number of publications in fluid properties hysteresis to that in rock properties hysteresis, the fluid properties have more attention than the rock properties, which might be because of the effect that played or because of the long history of hysteresis in the fluid than in rock, such as capillary pressure hysteresis has a long history.
4. This paper did not cover some fluid properties, such as the fluid density, formation volume factor, and solution gas oil ratio. Thus, more investigation and review of these properties may be needed.

Conflict of Interest

Murtada Elhaj's report was provided by Memorial University of Newfoundland. His association with the university encompasses employment.

References

[1] Mayergoyz I. Mathematical models of hysteresis and their application. Elsevier Inc. 1986; 22: 603-8. https://doi.org/10.1109/TMAG.1986.1064347

[2] Cross R, Grinfeld M, Lamba H. Hysteresis and economics. IEEE Control Syst. 2009; 29: 30-43. https://doi.org/10.1109/MCS.2008.930445

[3] Noori HR. Hysteresis phenomena in biology. Springer; Heidelberg: 2014. https://doi.org/10.1007/978-3-642-38218-5

[4] Paska Y, Haick H. Interactive effect of hysteresis and surface chemistry on gated silicon nanowire gas sensors. ACS Appl Mater Interfaces. 2012; 4: 2604-17. https://doi.org/10.1021/am300288z

[5] Mielke A, Theil F. A mathematical model for rate-independent phase transformations with hysteresis. Universit at Hannover Welfengarten, 1999.

[6] Wheeler SJ, Sharma RS, Buisson MSR. Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils. Géotechnique. 2003; 53: 41-54. https://doi.org/10.1680/geot.2003.53.1.41

[7] Lotfollahi M, Kim I, Beygi MR, Worthen AJ, Huh C, Johnston KP, *et al*. Experimental studies and modeling of foam hysteresis in porous media. SPE Improved Oil Recovery Conference, Tulsa, Oklahoma, USA, April 2016, SPE-179664-MS. https://doi.org/10.2118/179664-MS

[8] Teklu TW, Zhou Z, Li X, Abass H. Cyclic permeability and porosity hysteresis in mudrocks - Experimental study. 50th US Rock Mechanics / Geomechanics Symposium June 26-29, 2016, Houston: 2016, ARMA-2016-108.

[9] Spiteri EJ, Juanes R. Impact of relative permeability hysteresis on the numerical simulation of WAG injection. J Pet Sci Eng. 2006; 50: 115–39. https://doi.org/10.1016/j.petrol.2005.09.004

[10] Fatemi SM, Sohrabi M. Experimental and theoretical investigation of water/gas relative permeability hysteresis: Applicable to water alternating gas (WAG) injection and gas storage processes. Abu Dhabi International Petroleum Exhibition and Conference November 11–14, 2012, Abu Dhabi: SPE; 2012; SPE-161827-MS. https://doi.org/10.2118/161827-MS

[11] Elhaj M, Imtiaz SA, Naterer GF, Zendehboudi S. Production Optimization of Hydrocarbon Reservoirs by Entropy Generation Minimization. J Nat Gas Sci Eng. 2020; 83: 103538. https://doi.org/10.1016/j.jngse.2020.103538.

[12] Elhaj MA, Imtiaz SA, Naterer GF, Zendehboudi S. Entropy Generation Minimization of Two-Phase Flow Irreversibilities in Hydrocarbon Reservoirs. Energies (Basel), 2023; 16(10): 4096. https://doi.org/10.3390/en16104096.

[13] Elhaj MA, Enamul Hossain M, Imtiaz SA, Naterer GF. Hysteresis of wettability in porous media: a review. J Pet Explor Prod Technol. 2020; 10: 1897-905. https://doi.org/10.1007/s13202-020-00872-x

[14] Elhaj MA, Miah MI, Hossain ME. State-of-the-art on capillary pressure hysteresis: Productive techniques for better reservoir performance. Upstream Oil Gas Technol. 2021; 7: 100040. https://doi.org/10.1016/j.upstre.2021.100040

[15] Jang H, Lee J, Han Lee J, Seo S, Park B-G, Myong Kim D, *et al*. Analysis of hysteresis characteristics of silicon nanowire biosensors in aqueous environment. Appl Phys Lett. 2011; 99: 1–4. https://doi.org/10.1063/1.3669409

[16] Kawashima T, Saitoh T, Komori K, Fujii M. Synthesis of Si nanowires with a thermally oxidized shell and effects of the shell on transistor characteristics. Thin Solid Films. 2009; 517: 4520-6. https://doi.org/10.1016/j.tsf.2008.12.042

[17] Elhaj MA, Hashan M, Hossain ME. A critical review and future trend on relative permeability hysteresis. Society of Petroleum Engineers June 25–26, 2018; SPE-191260-MS. https://doi.org/10.2118/191260-MS

[18] Elhaj MA, Barri A, Hashan M, Hossain ME. State of the art on porosity and permeability hysteresis: Useful techniques for hydrocarbon recovery. Society of Petroleum Engineers - SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition 2018, Dammam: 2018, SPE-192409-MS. https://doi.org/10.2118/192409-MS

[19] Elhaj MA, Enamul Hossain M, Imtiaz SA, Naterer GF. Hysteresis of wettability in porous media: a review. J Pet Explor Prod Technol 2020; 10: 1897-905. https://doi.org/10.1007/s13202-020-00872-x

[20] Hashan M, Jahan LN, Uz Zaman T, Elhaj M, Imtiaz S, Hossain ME. Modelling of fluid flow in a petroleum reservoir using an engineering approach. SPE Trinidad and Tobago Section Energy Resources Conference 25-26 June, Port of Spain, Trinidad and Tobago: 2018, SPE-191153-MS. https://doi.org/10.2118/191153-MS

[21] Ahmadzadeh PH, Masihi M, Al-Ajmi A, Al-Wahaibi T, Al-Wahaibi Y. Experimental study of the effects of IFT and hysteresis on resistivity and capillary pressure of carbonate rocks. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2015; 37: 1346-53. https://doi.org/10.1080/15567036.2011.567232

[22] Heriot-watt MS. Cyclic hysteresis of three-phase relative permeability curves applicable to WAG injection under low gas/oil IFT: Effect of immobile water saturation, injection scenario and rock permeability. EAGE Annual Conference & Exhibition incorporating SPE Europec June 10–13, 2013, London: 2013; SPE-164918-MS. https://doi.org/10.2118/164918-MS

[23] Okazawa T, Serres AJ, Rancier DG, Corry KE. Novel push-pull displacement method to determine relative permeability hysteresis in heavy oil reservoirs. SPE Annual Technical Conference and Exhibition September 30–October 3, 2001, New Orleans: 2001; SPE-71501-MS. https://doi.org/10.2118/71501-MS

[24] Teklu TW, Zhou Z, Li X, Abass H. Experimental investigation on permeability and porosity hysteresis in low-permeability formations. The SPE Low Perm Symposium held in Denver May 5–6, 2016, Denver: 2016; SPE-180226-MS. https://doi.org/10.2118/180226-MS

[25] Morris KA. What is hysteresis? Appl Mech Rev. 2011; 64(5): 050801. https://doi.org/10.1115/1.4007112

[26] Morrow NR, Cram PJ, McCaffery FG. Displacement studies in dolomite with wettability control by octanoic acid. Soc Pet Eng J. 1973; 13: 221-32. https://doi.org/10.2118/3993-PA

[27] Fatemi SM, Sohrabi M, Jamiolahmady M, Ireland S. Experimental and theoretical investigation of gas/oil relative permeability hysteresis under low oil/gas interfacial tension and mixed-wet conditions. Energy Fuels. 2012; 26: 4366-82. https://doi.org/10.1021/ef300386b

[28] Shahverdi H, Sohrabi M. An improved three-phase relative permeability and hysteresis model for the simulation of a water-alternating-gas injection. SPE J. 2013; 18: 841-50. https://doi.org/10.2118/152218-PA

[29] Sinha S, Braun EM, Determan MD, Passey QR, Leonardi SA, Boros JA, *et al*. Steady-state permeability measurements on intact shale samples at reservoir conditions - Effect of stress, temperature, pressure, and type of gas. SPE Middle East Oil and Gas Show and Conference March 10–13, 2013, Manama: 2013; SPE-164263-MS. https://doi.org/10.2118/164263-MS

[30] Shahrokhi O, Fatemi M, Sohrabi M, Ireland S, Ahmed K, *et al*. Assessment of three phase relative permeability and hysteresis models for simulation of water-alternating-gas WAG injection in water-wet and mixed-wet systems. SPE Improved Oil Recovery Symposium April 12–16, Tulsa: 2014; SPE-169170-MS. https://doi.org/10.2118/169170-MS

[31] Total SA. Comparison of history-matched water flood, tertiary polymer flood relative permeabilities and evidence of hysteresis during tertiary polymer flood in very viscous oils. Society of Petroleum Engineers - SPE Asia Pacific Enhanced Oil Recovery Conference, EORC 2015, Tulsa: 2015; SPE-174682-MS. https://doi.org/10.2118/174682-ms

[32] Miah MI, Elhaj MA, Ahmed S, Hossain ME. Modeling of temperature distribution and oil displacement during thermal recovery in porous media: A critical review. Fuel 2018; 226: 423-40. https://doi.org/10.1016/j.fuel.2018.04.018

[33] Zhu H. View of study on the influence law of temperature profile of water injection well. Int J Pet Technol. 2023; 10: 1-13.

[34] Hansong M, Luo H, Haitao L, Yuxing X, Qin Z, Ying L. Study on the influence law of temperature profile of vertical wells in gas reservoirs. Int J Pet Technol. 2022; 9: 54-66. https://doi.org/10.15377/2409-787X.2022.09.7

[35] Van Geel PJ, Sykes JF. The importance of fluid entrapment, saturation hysteresis and residual saturations on the distribution of a lighter-than-water non-aqueous phase liquid in a variably saturated sand medium. J Contam Hydrol. 1997; 25: 249-70. https://doi.org/10.1016/S0169-7722(96)00038-1

[36] Fatemi SM, Sohrabi M, Jamiolahmady M, Ireland S. Cyclic hysteresis in three-phase relative permeability applicable to WAG injection: Water-wet and mixed-wet systems under low gas/oil IFT. SPE Annual Technical Conference and Exhibition, San Antonio: 2012; SPE-159816-MS. https://doi.org/10.2118/159816-MS

[37] Irmak AE, Taşarkuyu E, Coşkun A, Acet M, Samanciołlu Y. Magnetic and electrical transport properties of $La_{0.65}Ca_{0.30}Pb_{0.05}Mn_{0.90}Cu_{0.10}O_3$ compounds: Thermal hysteresis. Physica B Condens Matter. 2015; 411: 56-63. https://doi.org/10.1016/j.physb.2015.04.027

[38] Longbiao L. Effects of loading type, temperature and oxidation on mechanical hysteresis behavior of carbon fiber-reinforced ceramic-matrix composites. Eng Fract Mech. 2017; 169: 336-53. https://doi.org/10.1016/j.engfracmech.2016.10.010

[39] Angeli D, Ferrell JE, Sontag ED. Detection of multistability, bifurcations, and hysteresis in a large class of biological positive-feedback systems. Proc Natl Acad Sci. 2004; 101: 1822-7. https://doi.org/10.1073/pnas.0308265100

[40] Chatterjee A, Kaznessis YN, Hu W-S. Tweaking biological switches through a better understanding of bistability behavior. Curr Opin Biotechnol. 2008; 19: 475-81. https://doi.org/10.1016/j.copbio.2008.08.010

[41] Qiao L, Nachbar RB, Kevrekidis IG, Shvartsman SY. Bistability and oscillations in the Huang-Ferrell model of MAPK signaling. PLoS Comput Biol. 2007; 3: 1819-26. https://doi.org/10.1371/journal.pcbi.0030184

[42] Georgescu-Roegen N. The Entropy Law and the Economic Process. vol. 10. Cambridge: Harvard University Press; 1985. https://doi.org/10.4159/harvard.9780674281653

[43] Gocke M. Various concepts of hysteresis applied in economics. J Econ Surv. 2002; 16: 167-88. https://doi.org/10.1111/1467-6419.00163

[44] DelMonte DW, Kim T. Anatomy and physiology of the cornea and related structures. J Cataract Refract Surg. 2011; 37: 588-98. https://doi.org/10.1016/j.jcrs.2010.12.037

[45] Wang X. Effects of low-salinity waterflooding on capillary pressure hysteresis. SPE Improved Oil Recovery Conference, Tulsa: 2016; SPE-179562-MS. https://doi.org/10.2118/179562-MS

[46] Kleppe J, Delaplace P, Lenormand R, Hamon G, Chaput E. Representation of capillary pressure hysteresis in reservoir simulation. Proceedings of the SPE Annual Meeting, San Antonio: 1997; SPE-38899-MS. https://doi.org/10.2118/38899-MS

[47] Bouchard AJ, Hawkins JT. Reservoir-engineering implications of capillary-pressure and relative-permeability hysteresis. Log Analyst. 1992; 33: 415–20.

[48] Brown HW. Capillary pressure investigations. J Pet Technol. 1951; 3: 67–74. https://doi.org/10.2118/951067-G

[49] Jain V, Bryant S, Sharma M. Influence of wettability and saturation on liquid-liquid interfacial area in porous media. Environ Sci Technol. 2003; 37: 584–91. https://doi.org/10.1021/es020550s

[50] Braun EM, Holland RF. Relative permeability hysteresis: Laboratory measurements and a conceptual model. SPE Reser Eng. 1995; 10: 222-8. https://doi.org/10.2118/28615-PA

[51] Carlson FM. Simulation of relative permeability hysteresis to the nonwetting phase. SPE Annual Technical Conference and Exhibition October 4–7, 1981, San Antonio, Texas: October 1981; SPE-10157-MS. https://doi.org/10.2118/10157-MS

[52] Denoyelle LC, Lemonnier P. Simulation Of CO_2 huff "n" puff using relative permeability hysteresis. The 62nd Annual Technical Conference and Exhibition of the Society of Petroleum Engineers September 27–30, Dallas: 1987; SPE-16710-MS. https://doi.org/10.2118/16710-MS

[53] Benner FC, Dodd CG, Bartell FE. Evaluation of effective displacement pressures for petroleum oil-water silica systems. In: Drilling and Production Practice, New York: 1942; p.169-77.

[54] Bedrikovetsky P, Marchesin D, Oil MS, Academy G. Mathematical model for immiscible displacement honouring hysteresis. SPE Latin America/Caribbean Petroleum Engineering Conference, April 23-26, 1996. Port-of-Spain, Trinidad: SPE-36132-MS. https://doi.org/10.2118/36132-MS

[55] Mantia MRTRW, Fegley E. Prediction of hysteresis performance of storage reservoirs. SPE Gas Technology Symposium March 15-18, Calgary, Alberta, Canada: 1998. SPE-39992-MS. https://doi.org/10.2118/39992-MS

[56] Al-Kaabi AU, Mimoune K, Al-Yousef HY. Effect of hysteresis on the Archie saturation exponent. Middle East Oil Show and Conference March 15-18, Bahrain: 1997, SPE-37738-MS. https://doi.org/10.2118/37738-ms

[57] Nguyen B-L, Bruining J, Slob EC. Hysteresis in dielectric properties of fluid-saturated porous media. SPE Asia Pacific Improved Oil Recovery Conference October 25-26, Kuala Lumpur: 1999; SPE-57305-MS. https://doi.org/10.2118/57305-MS

[58] Kossack CA. Comparison of reservoir simulation hysteresis options. SPE Annual Technical Conference and Exhibition October 1-4, Dallas: 2000, SPE-63147-MS. https://doi.org/10.2118/63147-MS

[59] Bartell FE, Cardwell PH. Reproducible contact angles on reproducible metal surfaces. I. Contact angles of water against silver and gold1. J Am Chem Soc. 1942; 64: 494-7. https://doi.org/10.1021/ja01255a007

[60] Denney D. Relative permeability hysteresis: Water-alternating-gas injection and gas storage. J Pet Technol. 2013; 65: 90–2. https://doi.org/10.2118/0813-0090-JPT

[61] Michaels AS, Lummis RC. Contact angle hysteresis on aquagels. AIChE/SPE Joint Symposium on Wetting and Capillarity in Fluid Displacement Processes May 17-20, Kansas City, Missouri, USA: 1959, SPE-1274-G. https://doi.org/10.2118/1274-G

[62] Grundke K, Pöschel K, Synytska A, Frenzel R, Drechsler A, Nitschke M, *et al*. Experimental studies of contact angle hysteresis phenomena on polymer surfaces — Toward the understanding and control of wettability for different applications. Adv Colloid Interface Sci. 2015; 222: 350–76. https://doi.org/10.1016/j.cis.2014.10.012

[63] Extrand CW. Contact angles and their hysteresis as a measure of liquid-solid adhesion. Langmuir. 2004; 20: 4017–21. https://doi.org/10.1021/la0354988

[64] Gao L, McCarthy TJ. Contact angle hysteresis explained. Langmuir. 2006; 22: 6234–7. https://doi.org/10.1021/la060254j

[65] Extrand CW. Model for contact angles and hysteresis on rough and ultraphobic surfaces. Langmuir. 2002; 18: 7991–9. https://doi.org/10.1021/la025769z

[66] Extrand CW. Contact angles and hysteresis on surfaces with chemically heterogeneous islands. Langmuir. 2003; 19: 3793–6. https://doi.org/10.1021/la0268350

[67] Reyssat M, Quéré D. Contact angle hysteresis generated by strong dilute defects. J Phys Chem B. 2009; 113: 3906–9. https://doi.org/10.1021/jp8066876

[68] Moradi S, Englezos P, Hatzikiriakos SG. Contact angle hysteresis of non-flattened-top micro/nanostructures. Langmuir. 2014; 30: 3274–84. https://doi.org/10.1021/la500277n

[69] Restagno F, Poulard C, Cohen C, Vagharchakian L, Léger L. Contact angle and contact angle hysteresis measurements using the capillary bridge technique. Langmuir. 2009; 25: 11188–96. https://doi.org/10.1021/la901616x

[70] Gardner GHF, Acheson WP. Dynamic measurements of capillary pressure. SPE Production Research Symposium April 12-13, Tulsa, Oklahoma: 1962, SPE-301-MS. https://doi.org/10.2118/301-MS

[71] Omoregie ZS. Factors affecting the equivalency of different capillary pressure measurement techniques. SPE Formation Evaluation. 1988; 3: 147–55. https://doi.org/10.2118/15384-PA

[72] Dernaika M, Bjorn Wilson O, M. Skjæveland S. Drainage capillary pressure and resistivity index from short-wait porous plate experiments. European Association of Geoscientists & Engineers; GEO 2010, Mar 2010, cp-248-00221. https://doi.org/10.3997/2214-4609-pdb.248.224

[73] Kee ST, Lee SH, Park WT. Submerged porous plate wave absorber. Proceedings of the 31st IAHR World Congress September 11-16, Seoul: 2005 p. 595–9.

[74] Wang X, Alvarado V. Analysis of capillary pressure and relative permeability hysteresis under low-salinity waterflooding conditions. Fuel. 2016; 180: 228–43. https://doi.org/10.1016/j.fuel.2016.04.039

[75] Masalmeh SK. Experimental measurements of capillary pressure and relative permeability hysteresis. Paper SCA. 2001; 23: 17–9.

[76] Purcell WR. Interpretation of capillary pressure data. J Pet Technol. 1950; 2: 369-71. https://doi.org/10.2118/950369-G

[77] Cao X, Pop IS. Two-phase porous media flows with dynamic capillary effects and hysteresis: Uniqueness of weak solutions. Comput Math Appl. 2015; 69: 688–95. https://doi.org/10.1016/j.camwa.2015.02.009

[78] Ajufo AO, Daneshjou DH, Warne JD. Capillary pressure characteristics at overburden pressure using the centrifuge method. SPE Gas Technology Symposium June 28-30, Calgary, Alberta, Canada: 1993, SPE-26148-MS. https://doi.org/10.2118/26148-MS

[79] Van Spronsen E. Three-phase relative permeability measurements using the centrifuge method. SPE Enhanced Oil Recovery Symposium April 4-7, Tulsa, Oklahoma, 1982, SPE-10688-MS. https://doi.org/10.2118/10688-MS

[80] Paper T, Subject IS, Correction TO. The effects of sulfonate molecular and salt concentration on the interfacial tension of oil -brine-surfactant systems by. Society of Petroleum Engineers, 1976.

[81] Hough EW, Rzasa MJ, Wood BB, Oil S, Co G. Interfacial tensions at reservoir pressures and temperatures; Apparatus and the water-methane system. J Pet Trans. 1951; 3: 57-60. https://doi.org/10.2118/951057-G

[82] Chimienti ME, Illiano SN, Najurieta HL. Influence of temperature and interfacial tension on spontaneous imbibition process. SPE Latin American and Caribbean Petroleum Engineering Conference Proceedings April 21–23, Caracas, Venezuela: 1999, SPE-53668-MS. https://doi.org/10.2118/53668-ms

[83] Ghorbani M, Mohammadi AH. Effects of temperature, pressure and fluid composition on hydrocarbon gas - oil interfacial tension (IFT): An experimental study using ADSA image analysis of pendant drop test method. J Mol Liq. 2017; 227: 318–23. https://doi.org/10.1016/j.molliq.2016.11.110

[84] Peltonen LJ, Yliruusi J. Surface pressure, hysteresis, interfacial tension, and CMC of four sorbitan monoesters at water–air, water–hexane, and hexane–air interfaces. J Colloid Interface Sci. 2000; 227: 1–6. https://doi.org/10.1006/jcis.2000.6810

[85] Jubb G, McCurrie R. Hysteresis and magnetic viscosity in a Nd-Fe-B permanent magnet. IEEE Trans Magn. 1987; 23: 1801–5. https://doi.org/10.1109/TMAG.1987.1065064

[86] Stamps RL. Dynamic magnetic hysteresis and anomalous viscosity in exchange bias systems. Phys Rev B. 2000; 61: 12174–80. https://doi.org/10.1103/PhysRevB.61.12174

[87] Murshed SMS, Estellé P. A state of the art review on viscosity of nanofluids. Renew Sustain Energy Rev. 2017; 76: 1134–52. https://doi.org/10.1016/j.rser.2017.03.113

[88] Nguyen CT, Desgranges F, Roy G, Galanis N, Maré T, Boucher S, *et al*. Temperature and particle-size dependent viscosity data for water-based nanofluids – Hysteresis phenomenon. Int J Heat Fluid Flow. 2007; 28: 1492–506. https://doi.org/10.1016/j.ijheatfluidflow.2007.02.004

[89] Nguyen CT, Desgranges F, Galanis N, Roy G, Maré T, Boucher S, *et al*. Viscosity data for Al2O3–water nanofluid—hysteresis: is heat transfer enhancement using nanofluids reliable? Int J Thermal Sci. 2008; 47: 103–11. https://doi.org/10.1016/j.ijthermalsci.2007.01.033

[90] Daungthongsuk W, Wongwises S. A critical review of convective heat transfer of nanofluids. Renew Sustain Energy Rev. 2007; 11: 797-817. https://doi.org/10.1016/j.rser.2005.06.005

[91] Chein R, Huang G. Analysis of microchannel heat sink performance using nanofluids. Appl Therm Eng. 2005; 25: 3104–14. https://doi.org/10.1016/j.applthermaleng.2005.03.008

[92] Maïga SEB, Palm SJ, Nguyen CT, Roy G, Galanis N. Heat transfer enhancement by using nanofluids in forced convection flows. Int J Heat Fluid Flow. 2005; 26: 530–46. https://doi.org/10.1016/j.ijheatfluidflow.2005.02.004

[93] El Bécaye Maïga S, Tam Nguyen C, Galanis N, Roy G, Maré T, Coqueux M. Heat transfer enhancement in turbulent tube flow using Al2O3 nanoparticle suspension. Int J Numer Methods Heat Fluid Flow. 2006; 16: 275–92. https://doi.org/10.1108/09615530610649717

[94] Palm SJ, Roy G, Nguyen CT. Heat transfer enhancement with the use of nanofluids in radial flow cooling systems considering temperature-dependent properties. Appl Therm Eng. 2006; 26: 2209-18. https://doi.org/10.1016/j.applthermaleng.2006.03.014

[95] Cho YI. Hydrodynamic and heat transfer study of dispersed fluid with submicron metallic oxide particles. Exp Heat Transf. 1998; 11: 151–70. https://doi.org/10.1080/08916159808946559

[96] Xuan Y, Li Q. Investigation on convective heat transfer and flow features of nanofluids. J Heat Transf. 2003; 125: 151-5. https://doi.org/10.1115/1.1532008

[97] Walz M, Wolff M, Voss N, Zabel H, Magerl A. Micellar crystallization with a hysteresis in temperature. Langmuir. 2010; 26: 14391-s4. https://doi.org/10.1021/la102415x