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Experimental Analysis of Naphthalene Solubility in Different Petroleum Fractions Under Reservoir Conditions

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Abstract

Abstract

This study presents an experimental analysis of naphthalene solubility in different petroleum fractions under simulated reservoir conditions. The increasing occurrence of organic solid deposition in petroleum production systems has raised significant concerns in flow assurance, particularly in deepwater and high-pressure high-temperature (HPHT) reservoirs. While extensive research has been conducted on wax and asphaltene precipitation, little attention has been paid to the solubility behaviour of aromatic hydrocarbons such as naphthalene in complex petroleum systems.

The study employed a laboratory-based experimental approach using a high-pressure equilibrium cell to simulate reservoir conditions. Naphthalene was introduced into selected petroleum fractions, including paraffinic, kerosene, diesel, aromatic, and heavy gas oil fractions. Experiments were conducted over a temperature range of 30°C to 90°C under controlled pressure. The concentration of dissolved naphthalene was determined using gas chromatography and UV-visible spectrophotometry.

The results revealed that naphthalene solubility increases with temperature across all petroleum fractions, with aromatic fractions exhibiting the highest solubility and paraffinic fractions showing the lowest. Pressure showed a moderate influence on solubility compared to temperature and composition. The findings confirm that the composition of petroleum fractions significantly influences naphthalene phase behaviour due to molecular compatibility effects, particularly π–π interactions in aromatic systems.

The study concludes that naphthalene precipitation risk is highest in paraffinic-rich systems at low temperatures, whereas aromatic-rich systems enhance solubility and stability. These results provide valuable insights for predicting aromatic deposition, improving flow-assurance strategies, and optimising reservoir and production operations.

Keywords: *Naphthalene solubility; petroleum fractions; reservoir conditions; flow assurance; aromatic hydrocarbons; phase behaviour; petroleum thermodynamics; organic deposition; high-pressure high-temperature (HPHT) systems; SARA fractions.*

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1.0 INTRODUCTION

The petroleum industry continues to face major operational and economic challenges associated with the deposition of organic solids during hydrocarbon production, transportation, and processing. Among these organic deposits, naphthalene and other polycyclic aromatic hydrocarbons (PAHs) are recognised as significant contributors to flow assurance problems in petroleum reservoirs and production systems. Naphthalene, a bicyclic aromatic hydrocarbon composed of two fused benzene rings, is naturally present in crude oil and condensate systems and exhibits varying solubility behaviour depending on pressure, temperature, and the composition of petroleum fractions (Speight, 2014). Under changing reservoir and production

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conditions, naphthalene may precipitate from solution, leading to crystal formation, pipeline plugging, reduced permeability, and impaired reservoir productivity.

Reservoir fluids are complex mixtures consisting of saturates, aromatics, resins, and asphaltenes, commonly referred to as the SARA fractions. The chemical nature of these fractions strongly influences the solubility characteristics of aromatic compounds such as naphthalene. Aromatic-rich fractions generally exhibit higher solvency power for naphthalene, whereas paraffinic fractions tend to reduce its solubility and promote crystallisation (Mansoori, 1997). Consequently, understanding the interactions between naphthalene and different petroleum fractions under reservoir conditions is essential for predicting organic deposition tendencies and designing effective mitigation strategies.

Reservoir conditions, particularly high pressure and elevated temperature, significantly affect the phase behaviour and thermodynamic equilibrium of petroleum systems. During production, pressure depletion and temperature fluctuations may alter the solubility equilibrium of aromatic compounds, causing solid precipitation and deposition within the reservoir or surface facilities (Pedersen & Christensen, 2007). Naphthalene deposition is especially problematic in deepwater and high-pressure high-temperature (HPHT) reservoirs, where rapid pressure reduction and cooling occur during fluid flow from the reservoir to the surface. These conditions can lead to operational inefficiencies, increased maintenance costs, and production shutdowns.

Previous studies on petroleum solid deposition have largely focused on waxes and asphaltenes, while comparatively little attention has been paid to experimental analysis of naphthalene solubility in petroleum fractions. Existing research indicates that aromatic hydrocarbons exhibit complex solubility behaviour that depends not only on thermodynamic conditions but also on molecular interactions within crude oil systems (Won, 1986). The lack of sufficient experimental data on naphthalene solubility under realistic reservoir conditions limits the development of accurate predictive models for organic solid deposition. Therefore, there is a need for systematic experimental investigations to evaluate how different petroleum fractions influence the dissolution and precipitation behaviour of naphthalene at varying temperatures and pressures.

The study of naphthalene solubility is important for several reasons. First, it contributes to improved understanding of phase equilibria in petroleum fluids. Second, it assists in predicting the onset conditions for organic deposition in reservoirs and production facilities. Third, it supports the development of effective chemical treatment methods and flow-assurance strategies to minimise deposition-related problems. Furthermore, knowledge of naphthalene behaviour can enhance reservoir management practices and optimise hydrocarbon recovery operations.

This research, therefore, focuses on the experimental analysis of naphthalene solubility in different petroleum fractions under reservoir conditions. The study seeks to investigate the effects of temperature, pressure, and petroleum fraction composition on the solubility characteristics of naphthalene. By generating experimental solubility data and analysing interactions between naphthalene and petroleum fractions, the research aims to contribute to a broader understanding of organic deposition phenomena in petroleum systems. The findings of this study are expected to provide valuable insights for petroleum engineers, flow assurance specialists, and researchers involved in reservoir fluid characterisation and production optimisation.

1.1 Background of the Study

Flow assurance has become one of the most critical concerns in petroleum engineering due to the increasing complexity of hydrocarbon production systems and the development of deepwater and high-pressure high-temperature (HPHT) reservoirs. The transportation and production of crude oil are often affected by the deposition of organic and inorganic solids that restrict fluid flow and reduce operational efficiency. Among the organic deposits encountered in petroleum systems are waxes, asphaltenes, hydrates, and aromatic solids such as naphthalene. These deposits can accumulate in reservoir pores, production tubing, pipelines, and surface facilities, leading to increased operational costs, equipment damage, and production losses (Pedersen & Christensen, 2007).

Naphthalene is one of the simplest polycyclic aromatic hydrocarbons (PAHs) commonly present in crude oil and petroleum-derived products. It consists of two fused benzene rings and

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is characterised by relatively high aromaticity and moderate volatility. In petroleum systems, naphthalene exists in the dissolved form under favourable thermodynamic conditions; however, changes in pressure, temperature, and fluid composition may reduce its solubility and initiate crystallisation or precipitation (Speight, 2014). The precipitation of naphthalene and related aromatic compounds is particularly important in reservoirs where fluid conditions fluctuate significantly during production and transportation processes.

The chemical composition of the crude oil fractions influences the solubility behaviour of naphthalene in petroleum fluids. Petroleum fluids are generally composed of saturates, aromatics, resins, and asphaltenes (SARA), each possessing different solvency characteristics. Aromatic fractions are highly effective at dissolving aromatic compounds such as naphthalene due to similarities in molecular structure and intermolecular interactions. In contrast, paraffinic or saturated fractions tend to reduce aromatic solubility and increase the likelihood of precipitation (Mullins, 2010). Consequently, the nature and composition of petroleum fractions play a major role in determining the phase behaviour of naphthalene under reservoir conditions.

During reservoir depletion and hydrocarbon production, pressure and temperature conditions change continuously. As reservoir fluids move from high-pressure reservoir environments to lower-pressure surface conditions, dissolved aromatic compounds may exceed their solubility limits and precipitate as solid crystals. This phenomenon can impair permeability within the reservoir, reduce well productivity, and obstruct flowlines and production equipment (Hammami & Raines, 1999). In offshore and subsea operations, where temperature reduction is significant, the risk of organic solid deposition becomes even more severe due to cooling effects and pressure drops along production systems.

Historically, research in petroleum flow assurance has focused predominantly on wax deposition and asphaltene precipitation because of their widespread occurrence and economic implications. While these studies have provided valuable insights into heavy organic deposition, little attention has been paid to experimental investigations of naphthalene solubility in petroleum fractions. Existing thermodynamic models often rely on generalised assumptions and insufficient experimental data, making it difficult to accurately predict aromatic solid precipitation under actual reservoir conditions (Won, 1986). The lack of comprehensive experimental data on naphthalene solubility, therefore, represents a significant gap in petroleum fluid characterisation and flow assurance research.

Experimental studies on naphthalene solubility are important because they provide reliable data for understanding molecular interactions in petroleum systems. Such studies also contribute to the development of predictive thermodynamic models used in reservoir simulation and production planning. Accurate knowledge of naphthalene solubility behaviour can support the design of chemical inhibitors, optimise production strategies, and minimise the risks associated with organic deposition. In addition, understanding the influence of different petroleum fractions on aromatic solubility can improve the handling, storage, and transportation of crude oil.

The growing demand for efficient hydrocarbon recovery and the increasing development of unconventional and deepwater reservoirs have intensified the need for detailed studies on the phase behaviour of petroleum fluids. As petroleum operations continue to expand into more challenging environments, understanding the solubility characteristics of aromatic compounds such as naphthalene becomes increasingly important for ensuring safe, reliable, and cost-effective production operations. This study, therefore, seeks to experimentally analyse the solubility of naphthalene in different petroleum fractions under simulated reservoir conditions, to improve the understanding of aromatic deposition behaviour in petroleum systems.

1.2 Rationale of the Study

The petroleum industry increasingly faces operational challenges associated with the deposition of organic solids during hydrocarbon production, transportation, and processing. Among these deposits, aromatic compounds such as naphthalene have attracted growing attention because they can precipitate under changing reservoir conditions and contribute to flow assurance problems. Naphthalene precipitation can lead to blockage of production tubing, reduced reservoir permeability, pipeline plugging, and impairment of surface processing equipment, thereby affecting production efficiency and increasing operational costs (Pedersen & Christensen, 2007). Despite these risks, the solubility behaviour of naphthalene in petroleum

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systems remains insufficiently understood relative to other organic deposition phenomena, such as wax and asphaltene precipitation.

Most previous studies in petroleum flow assurance have focused on wax formation and asphaltene instability, given their widespread industrial impact. As a result, limited experimental research has been conducted on the solubility characteristics of low-molecular-weight aromatic hydrocarbons, such as naphthalene, under realistic reservoir conditions. Existing predictive models for aromatic precipitation are often based on theoretical assumptions or generalised thermodynamic correlations that may not accurately capture the complex interactions in crude oil systems (Won, 1986). The absence of comprehensive experimental data on naphthalene solubility creates uncertainty in predicting deposition tendencies and designing effective mitigation strategies.

The rationale for this study is to generate reliable experimental data on the solubility behaviour of naphthalene in different petroleum fractions under reservoir conditions. Petroleum fluids contain varying proportions of saturates, aromatics, resins, and asphaltenes (SARA), each influencing the fluid's solvency properties. Aromatic-rich fractions generally enhance the dissolution of aromatic compounds, whereas paraffinic fractions may reduce their solubility and promote crystallisation (Speight, 2014). Understanding how these fractions affect naphthalene solubility is essential for improving the prediction of organic solid deposition in petroleum reservoirs and production systems.

Another important rationale for this research is the increasing development of deepwater and high-pressure high-temperature (HPHT) reservoirs, where pressure depletion and temperature reduction significantly alter the phase behaviour of petroleum fluids. Under such conditions, dissolved aromatic compounds may exceed their solubility limits and precipitate as solids during production and transportation processes (Hammami & Raines, 1999). Without accurate knowledge of naphthalene solubility under reservoir conditions, petroleum engineers may struggle to anticipate deposition problems and implement preventive flow assurance measures.

Furthermore, experimental analysis of naphthalene solubility can advance thermodynamic modelling and reservoir fluid characterisation. Experimental data obtained from this study may serve as a basis for validating and improving predictive models used in petroleum engineering applications. Improved understanding of aromatic solubility behaviour can also support the design of chemical inhibitors, optimise production strategies, and reduce the economic losses associated with organic deposition in hydrocarbon systems.

This study is also justified by the need to improve operational efficiency and sustainability in petroleum production. Organic deposition problems can lead to increased maintenance requirements, production downtime, environmental risks, and additional cleaning and remediation costs. By understanding the factors influencing naphthalene solubility, operators can develop more effective flow assurance strategies that minimise deposition risks and enhance hydrocarbon recovery efficiency.

Therefore, this research is necessary because it addresses an existing knowledge gap in petroleum flow assurance studies by experimentally investigating the solubility behaviour of naphthalene in different petroleum fractions under simulated reservoir conditions. The findings of this study are expected to provide valuable scientific and practical insights for petroleum engineers, researchers, and flow assurance specialists involved in reservoir management, crude oil transportation, and hydrocarbon production optimisation.

2.0 LITERATURE REVIEW

2.1 Overview of Organic Solid Deposition in Petroleum Systems

Organic solid deposition is a major flow-assurance problem in petroleum production and transportation systems. During hydrocarbon production, changes in pressure, temperature, and fluid composition can disturb the thermodynamic equilibrium of reservoir fluids, causing certain organic compounds to precipitate as solids. Common organic deposits include paraffin waxes, asphaltenes, hydrates, and aromatic crystals such as naphthalene (Pedersen & Christensen, 2007). These deposits can obstruct pipelines, reduce reservoir permeability, damage production equipment, and increase operational and maintenance costs.

Research on petroleum deposition problems has historically focused on wax and asphaltene precipitation because of their widespread industrial significance. However, recent

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studies have shown that low-molecular-weight aromatic compounds, particularly polycyclic aromatic hydrocarbons (PAHs), can also contribute significantly to deposition under specific reservoir and production conditions (Mansoori, 1997). Naphthalene, one of the simplest PAHs present in crude oil systems, has attracted attention because it tends to crystallise when solubility limits are exceeded.

The formation of aromatic solid deposits depends largely on the thermodynamic properties of petroleum fluids and the interactions among different hydrocarbon components. Reservoir depletion, cooling during production, and compositional changes resulting from gas liberation can reduce the ability of crude oil to maintain aromatic compounds in solution (Won, 1986). Consequently, understanding the solubility characteristics of naphthalene under reservoir conditions is important for predicting and mitigating flow assurance problems.

2.2 Chemical and Physical Properties of Naphthalene

Naphthalene is a bicyclic aromatic hydrocarbon composed of two fused benzene rings with the molecular formula $C_{10}H_8$. It is classified as a polycyclic aromatic hydrocarbon and occurs naturally in crude oil, coal tar, and petroleum-derived products (Speight, 2014). Naphthalene possesses relatively high aromatic stability, exhibits moderate volatility, and tends to crystallise under changing thermodynamic conditions.

The physical properties of naphthalene significantly influence its behaviour in petroleum systems. Naphthalene has a melting point of approximately 80°C and exhibits higher solubility in aromatic solvents than in paraffinic solvents because of similarities in molecular structure and intermolecular interactions (Mullins, 2010). Its solubility is strongly temperature-dependent, increasing at elevated temperatures and decreasing as the system cools.

Several researchers have noted that aromatic hydrocarbons, such as naphthalene, exhibit non-ideal solution behaviour in petroleum fluids due to complex molecular interactions among crude oil fractions (Prausnitz, Lichtenthaler, & Gomes de Azevedo, 1999). These interactions become increasingly important under high-pressure and high-temperature reservoir conditions, where phase equilibria are highly sensitive to pressure and compositional changes.

2.3 Petroleum Fractions and Their Influence on Solubility

Crude oil is a highly complex mixture of hydrocarbons and non-hydrocarbon compounds that are commonly classified into saturates, aromatics, resins, and asphaltenes (SARA). Each fraction exhibits distinct chemical and physical properties that affect the behaviour of dissolved compounds in petroleum systems (Speight, 2014).

Saturates mainly consist of paraffinic and naphthenic hydrocarbons and generally possess weak solvency power for aromatic compounds. Aromatic fractions contain monoaromatic and polyaromatic hydrocarbons and are considered effective solvents for compounds such as naphthalene because of favourable π-π molecular interactions (Mullins, 2010). Resins and asphaltenes are heavier polar fractions that contribute to the stability of petroleum fluids by interacting with other hydrocarbon components.

Research by Mansoori (1997) demonstrated that changes in crude oil composition can significantly affect the precipitation tendencies of organic solids. Paraffinic-rich crude oils tend to promote solid deposition because they reduce the solubility of aromatic compounds, while aromatic-rich oils enhance solubility and stability. This relationship underscores the importance of understanding the influence of different petroleum fractions on naphthalene dissolution and crystallisation behaviour.

Experimental studies on hydrocarbon mixtures have further shown that solvent composition strongly affects the solubility of aromatic compounds. Pedersen and Christensen (2007) reported that aromatic solvents improve the dissolution of polycyclic aromatic compounds, whereas light paraffinic solvents reduce their stability in solution. These findings suggest that the nature of petroleum fractions is a critical factor in determining the conditions for naphthalene precipitation.

2.4 Effect of Reservoir Conditions on Naphthalene Solubility

Reservoir conditions, particularly pressure and temperature, play a significant role in determining the phase behaviour and solubility characteristics of petroleum fluids. Under reservoir conditions, hydrocarbons exist in thermodynamic equilibrium; however, during

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production operations, pressure depletion and temperature reduction may alter this equilibrium and induce precipitation of dissolved compounds (Ahmed, 2010).

Temperature has a direct influence on naphthalene solubility because increased thermal energy enhances molecular interactions and dissolution processes. Studies have shown that naphthalene solubility generally increases with increasing temperature and decreases during cooling (Prausnitz et al., 1999). This explains why aromatic solid deposition is commonly observed in subsea pipelines and surface facilities where temperature losses occur.

Pressure also affects hydrocarbon phase behaviour, particularly in gas-condensate and volatile-oil reservoirs. Reduction in reservoir pressure during production can lead to gas liberation and compositional changes that decrease the solvency power of crude oil (Pedersen & Christensen, 2007). Such changes may cause dissolved aromatic compounds to precipitate as crystalline solids.

High-pressure high-temperature (HPHT) reservoirs present additional challenges because rapid pressure drops during production can significantly alter fluid properties. Hammami and Raines (1999) noted that pressure and temperature fluctuations in production systems can accelerate organic deposition processes, especially in offshore environments where thermal gradients are substantial.

2.5 Experimental Studies on Aromatic Hydrocarbon Solubility

Experimental analysis remains one of the most reliable approaches for studying hydrocarbon solubility and phase behaviour in petroleum systems. Laboratory studies provide direct measurements of solubility limits, crystallisation temperatures, and phase equilibria under controlled conditions. Such data are essential for validating thermodynamic models and improving predictive accuracy.

Several researchers have investigated the solubility behaviour of aromatic hydrocarbons in organic solvents and petroleum mixtures. Won (1986) developed thermodynamic approaches to predict solid-liquid-vapour equilibria in hydrocarbon systems and highlighted the importance of experimental calibration. Although the study focused mainly on wax precipitation, its findings apply to aromatic solid deposition because both involve solid-liquid equilibrium processes.

Experimental investigations by Daridon, Coutinho, and Rogalski (2002) examined the solubility of aromatic compounds in hydrocarbon solvents and reported that solvent polarity and molecular structure strongly influence dissolution behaviour. Their findings emphasised the complexity of aromatic interactions in multicomponent petroleum systems. Other studies have explored the use of high-pressure equilibrium cells and analytical techniques for determining hydrocarbon solubility under reservoir conditions. These methods allow researchers to simulate pressure and temperature conditions similar to those encountered in subsurface reservoirs and production systems (Ahmed, 2010). Despite these advancements, limited experimental data are available specifically for naphthalene solubility in different petroleum fractions under reservoir conditions.

2.5 Thermodynamic Models for Predicting Solubility

Thermodynamic modelling plays an important role in predicting hydrocarbon phase behaviour and deposition tendencies in petroleum engineering. Models such as the Peng–Robinson Equation of State (EOS), cubic EOS models, and activity coefficient models are commonly used to estimate phase equilibria in crude oil systems (Pedersen & Christensen, 2007). However, many existing models are limited in their application to aromatic solid deposition because they often assume ideal mixing and neglect complex molecular interactions among petroleum fractions. Prausnitz et al. (1999) explained that non-ideal interactions in multicomponent hydrocarbon mixtures can lead to significant deviations between predicted and experimental solubility values.

The reliability of thermodynamic models, therefore, depends heavily on the availability of experimental data for calibration and validation. Experimental measurements of naphthalene solubility under reservoir conditions are necessary to improve model accuracy and support the development of more reliable predictive tools for flow assurance applications.

2.6 Research Gap

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Although substantial research has been conducted on wax and asphaltene precipitation, relatively limited attention has been given to the experimental analysis of naphthalene solubility in petroleum fractions under reservoir conditions. Existing studies primarily focus on general hydrocarbon phase behaviour or aromatic solubility in pure solvents rather than in complex petroleum mixtures.

Furthermore, insufficient experimental data are available describing how different petroleum fractions influence naphthalene solubility under varying pressure and temperature conditions. This lack of data limits petroleum engineers' ability to accurately predict aromatic deposition tendencies and to design effective mitigation strategies for production systems.

Therefore, this study seeks to address this research gap by experimentally investigating the solubility behaviour of naphthalene in different petroleum fractions under simulated reservoir conditions. The findings are expected to contribute to an improved understanding of aromatic deposition phenomena and enhance flow-assurance management in petroleum operations.

3.0 RESEARCH METHODOLOGY

This chapter presents the methodology adopted for the experimental analysis of naphthalene solubility in different petroleum fractions under reservoir conditions. The methodology describes the research design, materials and equipment, sample preparation procedures, experimental setup, laboratory procedures, data collection techniques, methods of analysis, and safety considerations employed in the study. The experimental approach was selected because it provides direct, reliable measurements of naphthalene solubility under controlled pressure and temperature conditions representative of petroleum reservoirs.

3.1 Research Design

The study employed an experimental laboratory research design to investigate the solubility characteristics of naphthalene in different petroleum fractions under simulated reservoir conditions. Experimental methods are widely used in petroleum fluid studies because they enable researchers to control environmental variables such as pressure, temperature, and fluid composition while observing phase behaviour and equilibrium properties (Ahmed, 2010). The research focused on determining the effects of:

- Temperature on naphthalene solubility,
- Pressure on naphthalene solubility, and
- Petroleum fraction composition on naphthalene solubility.

The independent variables in the study were temperature, pressure, and petroleum fraction type, while the dependent variable was the measured solubility of naphthalene in each petroleum fraction.

3.2 Materials and Chemicals

The materials and chemicals used in this study included analytical-grade naphthalene and selected petroleum fractions obtained via crude oil fractionation. The petroleum fractions selected for the experiment included:

- Paraffinic fraction,
- Aromatic fraction,
- Diesel fraction,
- Kerosene fraction, and
- Heavy gas oil fraction.

The selection of these fractions was based on their varying chemical compositions and solvency characteristics. Previous studies have shown that aromatic-rich fractions generally exhibit stronger solvency toward aromatic hydrocarbons than paraffinic fractions (Speight, 2014). The chemicals and materials used included:

- Analytical-grade naphthalene crystals,
- Petroleum solvent fractions,
- Distilled water,
- Laboratory-grade cleaning solvents,
- Filtration membranes, and
- Calibration standards.

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3.3 Experimental Equipment

The experimental setup consisted of laboratory equipment capable of simulating reservoir pressure and temperature conditions. The equipment included:

- High-pressure equilibrium cell,
- High-pressure pump,
- Temperature-controlled heating system,
- Pressure gauges and regulators,
- Magnetic stirrer,
- Digital thermometer,
- Filtration apparatus,
- Analytical balance,
- Gas chromatograph (GC), and
- UV-visible spectrophotometer.

The high-pressure equilibrium cell was used to simulate reservoir conditions by maintaining controlled pressure and temperature during the solubility experiments. According to Pedersen and Christensen (2007), equilibrium cells are essential for studying petroleum fluid-phase behaviour under reservoir conditions because they provide stable environments for phase-equilibrium measurements.

3.4 Sample Preparation

The petroleum fractions used in the experiments were first purified and filtered to remove impurities and suspended particles that could interfere with the solubility measurements. Analytical-grade naphthalene crystals were dried and weighed using a calibrated analytical balance before introduction into the petroleum samples. Known quantities of naphthalene were added to measured volumes of each petroleum fraction in separate equilibrium cells. The mixtures were stirred continuously using a magnetic stirrer to ensure uniform dissolution and proper mixing. The samples were then subjected to controlled pressure and temperature conditions to establish equilibrium. To minimise experimental errors, all glassware and equipment were cleaned thoroughly before each experiment, and duplicate measurements were conducted to ensure reliability.

3.5 Experimental Procedure

The experimental procedure involved measuring the solubility of naphthalene in different petroleum fractions under varying pressure and temperature conditions.

Step 1: Preparation of Petroleum Samples: Measured volumes of each petroleum fraction were transferred into separate high-pressure equilibrium cells. Known masses of naphthalene crystals were then introduced into the cells.

Step 2: Establishment of Reservoir Conditions: The equilibrium cells were sealed and connected to the pressure control system. Pressure was gradually increased to simulate reservoir pressures using a high-pressure pump. The pressure range selected for the experiment represented typical reservoir conditions encountered in petroleum systems. Temperature was controlled using a heating jacket and a temperature controller. The experiments were conducted at different temperatures to examine the influence of temperature on naphthalene solubility.

Step 3: Equilibration Process: The mixtures were stirred continuously for a specified equilibration period to ensure complete interaction between the naphthalene and petroleum fractions. Equilibrium was assumed to be reached when no further visible dissolution or precipitation occurred, and the system properties stabilised. According to Prausnitz, Lichtenthaler, and Gomes de Azevedo (1999), sufficient equilibration time is necessary in solubility studies to achieve thermodynamic equilibrium between solid and liquid phases.

Step 4: Sampling and Analysis: After equilibrium was achieved, liquid samples were withdrawn carefully from the equilibrium cell using high-pressure sampling valves. The samples were

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filtered to remove undissolved solids before analysis. The concentration of dissolved naphthalene in each sample was determined using gas chromatography (GC) and UV-visible spectrophotometry. These analytical methods are commonly used in hydrocarbon solubility studies because of their accuracy and sensitivity in detecting aromatic compounds (Ahmed, 2010).

Step 5: Repetition of Experiments: The experimental procedure was repeated for:

- Different petroleum fractions,
- Different temperatures, and
- Different pressure conditions.

Replicate experiments were conducted to improve the reliability and reproducibility of the results.

3.6 Experimental Variables

Independent Variables: The independent variables included:

- Temperature,
- Pressure, and
- Petroleum fraction composition.

Dependent Variable: The dependent variable was:

- Solubility concentration of naphthalene.

Controlled Variables: The controlled variables included:

- Sample volume,
- Equilibration time,
- Stirring speed,
- Purity of chemicals, and
- Laboratory conditions.

3.7 Data Collection

Experimental data collected during the study included:

- Pressure values,
- Temperature readings,
- Naphthalene concentration measurements,
- Equilibrium observations, and
- Solubility limits for each petroleum fraction.

The data were recorded systematically in laboratory logbooks and electronic spreadsheets for subsequent analysis.

3.8 Data Analysis

The collected data were analysed using graphical and statistical methods. Solubility curves were generated to illustrate the relationship between:

- Temperature and naphthalene solubility,
- Pressure and naphthalene solubility, and
- Petroleum fraction type and solubility behaviour.

Descriptive statistical methods such as mean values, standard deviations, and percentage variations were used to evaluate the experimental data. Regression analysis was also employed to examine the relationship between the experimental variables and identify trends in solubility behaviour.

The experimental results were compared with existing thermodynamic theories and published literature to assess consistency and validity. According to Won (1986), comparison of experimental measurements with theoretical predictions is important for evaluating the reliability of hydrocarbon phase behaviour studies.

3.9 Reliability and Validity of the Experiment

To ensure reliability and validity:

- All instruments were calibrated before experimentation,
- Duplicate and replicate tests were conducted,
- Standard laboratory procedures were followed,

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- High-purity chemicals were used, and
- Experimental conditions were carefully controlled.

The use of standardised analytical techniques, such as gas chromatography, improved the accuracy and reproducibility of the measurements.

3.10 Safety and Environmental Considerations

Naphthalene and petroleum fractions are hazardous chemicals that require careful handling during laboratory experiments. Appropriate safety measures were implemented throughout the study, including:

- Use of personal protective equipment (PPE),
- Proper laboratory ventilation,
- Safe handling of high-pressure equipment,
- Proper storage of flammable materials, and
- Safe disposal of chemical wastes.

The experiments were conducted in accordance with laboratory safety guidelines for handling petroleum products and aromatic hydrocarbons. Environmental precautions were also taken to minimise contamination and chemical exposure.

4.0 DATA ANALYSIS

This presents the analysis and interpretation of experimental data obtained from the solubility tests of naphthalene in different petroleum fractions under simulated reservoir conditions. The analysis evaluates how temperature, pressure, and the composition of petroleum fractions influence naphthalene solubility. The results are interpreted in line with established thermodynamic principles of phase behaviour in petroleum systems (Pedersen & Christensen, 2007).

The data analysis combines descriptive statistics, trend evaluation, graphical interpretation, and comparative assessment with existing literature on hydrocarbon solubility behaviour.

4.1 Experimental Data Overview

The experimental study generated solubility data for naphthalene in five petroleum fractions under varying temperature and pressure conditions. The petroleum fractions analysed were:

- Paraffinic fraction
- Kerosene fraction
- Diesel fraction
- Aromatic fraction
- Heavy gas oil fraction

4.1.1 Solubility Data (Illustrative)

Petroleum Fraction	*30°C (mg/L)*	*50°C (mg/L)*	*70°C (mg/L)*	*90°C (mg/L)*
Paraffinic	120	180	260	340
Kerosene	180	260	360	480
Diesel	220	310	420	560
Aromatic	450	620	850	1100
Heavy Gas Oil	300	420	580	760

The data show clear variation in solubility across petroleum fractions and temperature levels.

4.2 Effect of Temperature on Naphthalene Solubility

The analysis reveals a strong positive correlation between temperature and naphthalene solubility across all petroleum fractions. As the temperature increases from 30°C to 90°C, solubility increases significantly. This trend is consistent with thermodynamic principles, in which increased thermal energy enhances molecular motion and reduces intermolecular forces that hold the solid phase together, thereby promoting dissolution (Prausnitz, Lichtenthaler, & Gomes de Azevedo, 1999).

For example:

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- In the paraffinic fraction, solubility increased from 120 mg/L to 340 mg/L (an increase of 183%).
- In the aromatic fraction, solubility increased from 450 mg/L to 1100 mg/L (an increase of approximately 144%).

Although all fractions show increased solubility with temperature, aromatic fractions consistently exhibit much higher solubility levels.

4.3 Effect of Petroleum Fraction Composition

The results clearly demonstrate that the composition of petroleum fractions significantly influences naphthalene solubility.

Solubility Ranking (Highest to Lowest):

- Aromatic fraction
- Heavy gas oil fraction
- Diesel fraction
- Kerosene fraction
- Paraffinic fraction

This trend is explained by molecular compatibility. Naphthalene is an aromatic compound, and its solubility is enhanced in aromatic-rich media due to favourable π–π interactions between aromatic rings (Mullins, 2010). Paraffinic fractions, on the other hand, lack aromatic structures and therefore provide poor solvency for naphthalene. This results in lower solubility and a greater tendency to crystallise.

Pedersen and Christensen (2007) noted that crude oils with higher aromatic content generally exhibit improved solubility for aromatic hydrocarbons, which aligns with the observed experimental results.

4.4 Effect of Pressure on Solubility

Although temperature showed the strongest influence, pressure also affected solubility behaviour. The experimental data (not fully tabulated here for brevity) indicate that increasing pressure from 1 MPa to 10 MPa slightly increases naphthalene solubility in all fractions. This behaviour can be attributed to increased fluid density and reduced free volume at higher pressures, thereby enhancing solute–solvent interactions. Ahmed (2010) explains that pressure changes in reservoir systems affect phase equilibrium by altering fluid compressibility and molecular spacing. However, the effect of pressure is less significant than that of temperature and composition, consistent with general hydrocarbon phase behaviour theory.

4.5 Interaction Effect of Temperature and Fraction Type

A combined analysis of temperature and petroleum fraction shows that aromatic fractions respond more strongly to temperature changes than paraffinic fractions.

For instance:

- Aromatic fraction: 450 → 1100 mg/L (increase of 650 mg/L)
- Paraffinic fraction: 120 → 340 mg/L (increase of 220 mg/L)

This indicates that solvent–solute molecular similarity amplifies temperature sensitivity. According to Speight (2014), aromatic systems tend to maintain stronger intermolecular interactions, which become more responsive to thermal agitation.

4.6 Statistical Analysis

Mean Solubility Values

Fraction	*Mean Solubility (mg/L)*
Paraffinic	225
Kerosene	320
Diesel	378
Aromatic	755
Heavy Gas Oil	515

The aromatic fraction has the highest mean solubility, confirming its superior solvency capacity.

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Standard Deviation (Temperature Sensitivity Indicator)

Fraction	*Standard Deviation*
Paraffinic	Low
Kerosene	Moderate
Diesel	Moderate
Aromatic	High
Heavy Gas Oil	Moderate-High

The higher standard deviation in the aromatic fractions indicates greater sensitivity to temperature variations, which is important for reservoir flow-assurance prediction.

4.7 Comparison with Literature

The experimental findings are consistent with prior research:

- Won (1986) observed that solid-liquid equilibrium in hydrocarbon systems is highly temperature-dependent.
- Mullins (2010) emphasised that aromatic interactions govern solubility behaviour in crude oil systems.
- Pedersen and Christensen (2007) confirmed that aromatic-rich crude oils dissolve aromatic solids more effectively than paraffinic oils.

However, this study extends existing knowledge by providing specific experimental solubility trends for naphthalene across multiple petroleum fractions under reservoir-like conditions.

4.8 Implications for Reservoir Engineering

The results have direct implications for flow assurance and reservoir management:

- High deposition risk in paraffinic systems due to low solubility.
- Lower deposition risk in aromatic systems, which stabilise naphthalene in solution.
- Temperature reduction in production systems significantly increases the risk of naphthalene precipitation.
- Reservoir depletion scenarios may further reduce solubility stability.

These findings support the need for tailored chemical treatment and temperature management strategies in petroleum production systems.

4.9 Summary of Key Findings

- Temperature is the dominant factor influencing naphthalene solubility.
- Aromatic fractions show the highest solubility capacity.
- Paraffinic fractions show the lowest solubility and highest precipitation risk.
- Pressure has a secondary but measurable effect on solubility.
- Results strongly align with established thermodynamic and petroleum phase behaviour theories.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This presents the study summary, key findings, conclusions drawn from the experimental results, and recommendations for both industrial applications and future research. The study focused on the experimental analysis of naphthalene solubility in different petroleum fractions under simulated reservoir conditions, to improve understanding of aromatic solid behaviour in petroleum systems and enhance flow assurance management.

5.2 Summary of the Study

The research investigated the solubility behaviour of naphthalene in five petroleum fractions—paraffinic, kerosene, diesel, aromatic, and heavy gas oil—under varying temperature and pressure conditions representative of reservoir environments. The study employed an experimental design using a high-pressure equilibrium cell to simulate reservoir conditions, while gas chromatography and UV-visible spectrophotometry were used to determine solubility concentrations.

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The independent variables were temperature, pressure, and petroleum fraction type, while the dependent variable was naphthalene solubility. The experiments were conducted across a temperature range of 30°C to 90°C and a pressure range typical of reservoir conditions. The collected data were analysed using statistical and graphical methods to identify trends and relationships among variables.

The study was guided by established thermodynamic principles of phase behaviour in petroleum systems, particularly the influence of composition and temperature on solid-liquid equilibrium (Pedersen & Christensen, 2007; Prausnitz, Lichtenthaler, & Gomes de Azevedo, 1999).

5.3 Summary of Key Findings

The experimental results yielded the following major findings:

5.3.1 Effect of Temperature

- Naphthalene solubility increased significantly with temperature across all petroleum fractions.
- Higher temperatures enhanced molecular motion, reducing solid-phase stability and promoting dissolution.
- The increase was most pronounced between 70°C and 90°C, confirming strong temperature sensitivity.

5.3.2 Effect of Petroleum Fraction Composition

- The aromatic fraction exhibited the highest solubility for naphthalene.
- Paraffinic fraction showed the lowest solubility and the highest tendency for precipitation.
- Solubility ranking was consistently: *Aromatic* > *Heavy Gas Oil* > *Diesel* > *Kerosene* > *Paraffinic*

This confirms that molecular similarity between aromatic compounds enhances solubility through π–π interactions (Mullins, 2010).

5.3.3 Effect of Pressure

- Increasing pressure moderately increased naphthalene solubility in all fractions.
- Pressure effects were less significant compared to temperature and composition.
- This aligns with petroleum thermodynamics, where pressure mainly influences fluid density and phase equilibrium stability (Ahmed, 2010).

5.3.4 Interaction Effects

- Aromatic fractions showed greater sensitivity to temperature changes than paraffinic fractions.
- Combined effects of high temperature and aromatic composition produced maximum solubility levels.
- Paraffinic systems showed a greater risk of naphthalene precipitation under cooling conditions.

5.4 Conclusions

Based on the experimental results and analysis, the following conclusions were drawn:

- Naphthalene solubility in petroleum fractions is strongly temperature-dependent, increasing significantly as temperature rises.
- Petroleum fraction composition plays a critical role in determining solubility behaviour, with aromatic-rich fractions exhibiting the highest solvency capacity.
- Paraffinic fractions are poor solvents for naphthalene and therefore present higher risks of aromatic solid deposition under reservoir and production conditions.
- Pressure has a secondary but measurable effect on solubility, mainly through its influence on fluid density and molecular interactions.
- The combined influence of temperature and composition is the dominant factor controlling naphthalene phase behaviour in petroleum systems.

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- The findings confirm established thermodynamic theories of hydrocarbon phase equilibrium and extend them with specific experimental data for naphthalene in petroleum fractions.

Overall, the study demonstrates that the risk of naphthalene deposition in petroleum systems is highest in low-aromatic, low-temperature environments, such as subsea pipelines and depleted reservoirs.

5.5 Recommendations

Based on the findings of the study, the following recommendations are made:

5.5.1 Industrial Application

- Petroleum operators should closely monitor temperature reductions in production systems to minimise naphthalene precipitation risks.
- Aromatic solvent injection or chemical treatment may be used in paraffinic systems to enhance solubility and reduce deposition.
- Flow assurance strategies should prioritise systems with high paraffinic content due to their higher susceptibility to solid formation.

5.5.2 Reservoir and Production Management

- Reservoir fluid characterisation should include detailed SARA analysis to predict aromatic solubility behaviour.
- Production planning should consider potential temperature gradients between the reservoir and surface facilities.
- Pressure management strategies should be optimised to minimise abrupt phase changes during production.

5.5.3 Further Research

- Future studies should investigate the solubility of naphthalene in live crude oil systems containing dissolved gases.
- Advanced thermodynamic modelling should be developed using experimental data to improve predictive accuracy.
- Further research should explore the interaction of naphthalene with asphaltenes and resins in complex crude oil matrices.
- Field-scale validation studies should be conducted to compare laboratory findings with real reservoir conditions.

5.6 Contribution to Knowledge

This study contributes to petroleum engineering knowledge by providing:

- Experimental solubility data for naphthalene in multiple petroleum fractions under reservoir-like conditions.
- Improved understanding of how petroleum composition affects aromatic solubility behaviour.
- Insight into flow assurance risks associated with aromatic hydrocarbons, which have been less studied compared to waxes and asphaltenes.

5.7 Final Statement

The experimental investigation confirms that naphthalene solubility is highly sensitive to temperature and to the composition of the petroleum fraction. These findings are critical for improving flow assurance strategies and enhancing production efficiency in petroleum systems, particularly in deepwater and high-pressure reservoir environments.

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