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Introducing a Next-Generation Tool for Asphaltene Precipitation Modeling for Improved Reservoir Simulation and Production Flow Assurance

Rahman Ashena, Smart Energy Data Analytics Group, Houston, USA; Siroos Azizmohammadi, Montanuniversität Leoben, Austria

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Abstract

This study presents the development of a next-generation asphaltene precipitation modeling module integrated into a novel PVT analysis software, specifically engineered for accurate prediction of asphaltene-induced formation damage. The objective is to deliver a reliable and field-applicable tool that surpasses existing commercial simulators in accuracy and computational performance. The module is built upon an optimized implementation of the PC-SAFT equation of state and is designed to support reservoir and production engineers in evaluating solid deposition risks under variable pressure–temperature conditions.

The modeling framework employs a rigorous thermodynamic formulation using PC-SAFT, combined with an intelligent calibration workflow based on experimental saturation pressures, asphaltene onset pressures, and precipitated mass data. Once tuned, the model accurately predicts phase behavior and asphaltene precipitation across operating conditions relevant to depletion, gas injection, and compositional changes with high fidelity. Validation was conducted using two asphaltenic crude oil systems and benchmarked against two industry-standard PVT simulators.

Comparative evaluation demonstrates that the developed tool consistently achieves the highest accuracy. For the first crude oil, the module attained average absolute relative deviations (AARD) of 2.13% for asphaltene onset pressure and 1.32% for bubble-point pressure, markedly outperforming commercial simulators, which generated AARDs of 6.73% and 5.07%, and 10.11% and 10.93%, respectively. For the second crude oil, the new module provided the most accurate match to experimental precipitated asphaltene mass and predicted bubble-point pressure with an AARD of 3.1%, compared with 7.46% and 13.51% from the two reference tools.

These improvements result from an optimized parameter-estimation algorithm and an efficient numerical implementation of PC-SAFT. By directly linking advanced thermodynamic modeling with practical reservoir engineering workflows, the software enables rapid assessment of deposition severity and supports proactive decisions in well design, production management, and chemical mitigation. Overall, the results confirm that the proposed module is the most accurate, robust, and operationally relevant tool currently available for managing asphaltene-related risks in petroleum reservoirs.

Keywords: Novel PVT Tool Analyzer, Asphaltene Phase Behavior, PC-SAFT, Onset Pressures, Asphaltene Precipitation, Sustainable Production

Introduction

Sustainable production can be achieved through a combination of strategies, including production optimization, targeted reservoir stimulation, and effective flow-assurance management (Ashena et al., 2021). Asphaltene precipitation remains a persistent and costly challenge in petroleum production, posing significant risks to well productivity, flow assurance, and reservoir integrity. These high-molecular-weight, polyaromatic constituents of crude oil remain solubilized under native reservoir conditions but can destabilize during pressure depletion, compositional alterations (e.g., gas injection), or temperature changes (Speight, 1991; Kord et al., 2019; Dakhelpour-Ghoveifel et al., 2024). Once precipitated, asphaltenes may deposit in pore throats near the wellbore, drastically reducing effective permeability by over 70% and triggering severe formation damage that is difficult and expensive to remediate (Mousavi Dehghani, 2007; Mohammed et al., 2021). In extreme cases, complete wellbore plugging has been reported, leading to premature well abandonment (Daryasafar et al., 2025).

Critically, the ability to mitigate such damage hinges on the accuracy and timeliness of asphaltene precipitation prediction. Formation damage is not caused solely by precipitation, but by the transport, deposition, and retention of solid particles within the porous medium, processes that are strongly influenced by the amount, timing, and location of precipitation relative to the wellbore (Kontogeorgis and Folas, 2009). An inaccurate model may either underestimate precipitation (leading to unanticipated damage) or overpredict it (prompting unnecessary chemical inhibition or production constraints). Thus, high-fidelity prediction of onset conditions and quantitative precipitation profiles across the pressure–temperature trajectory of production is essential to: (i) identify critical pressure thresholds below which damage initiates, (ii) estimate the spatial extent of the damaged zone, and (iii) design targeted mitigation strategies such as solvent squeezes, inhibitor injection rates, or controlled drawdown schedules before damage occurs (Doryani et al., 2018; Huang et al., 2022). In this context, thermodynamic modeling transcends academic exercise, becoming a decision-enabling tool for preserving reservoir deliverability.

Given these operational imperatives, thermodynamic modeling has emerged as the cornerstone of asphaltene risk assessment. Among available frameworks, the Perturbed-Chain Statistical Associating Fluid Theory (PC-SAFT) equation of state has gained widespread recognition for its rigorous treatment of molecular interactions, association effects, and chain flexibility in complex hydrocarbon mixtures (Daryasafar et al., 2020; AlHammadi et al., 2015; Panuganti et al., 2012). PC-SAFT enables quantitative prediction of phase equilibria without relying on empirical correlations, making it particularly suitable for asphaltenic systems where compositional complexity defies simple modeling approaches.

Despite its theoretical advantages, the practical application of PC-SAFT in commercial PVT software often encounters limitations that hinder its integration into real-time reservoir workflows. These include: (i) tedious and non-unique parameter calibration, often requiring expert intervention; and (ii) high computational cost during regression and phase stability analysis (AlHammadi et al., 2015; Panuganti et al., 2012). Consequently, engineers frequently face delays in decision-making or resort to conservative operating envelopes that limit production potential.

To address these gaps, we introduce a next-generation PVT analysis platform featuring a fully integrated asphaltene precipitation module based on an optimized PC-SAFT implementation. The designed tool combines automated calibration (using saturation pressures, onset data, or precipitation mass) with accelerated phase stability calculations, delivering accurate precipitation profiles that can be readily used by reservoir engineers to evaluate near-wellbore deposition risk and potential formation damage. By translating thermodynamic predictions into spatially and temporally resolved deposition risk, the software enables engineers to proactively anticipate permeability impairment and optimize mitigation measures.

This paper presents the development, validation, and performance evaluation of a developed asphaltene module in a newly designed PVT analyzer. Using two real asphaltenic crude oil samples, one under nitrogen injection and another under pressure-depletion conditions, we benchmark its accuracy and efficiency against two leading commercial simulators. Key metrics include the prediction of onset and saturation pressure, as well as precipitated asphaltene mass. Furthermore, we discuss how the precipitation profiles generated by the designed analyzer provide a reliable basis for evaluating formation damage potential and identifying operating conditions that pose a high risk of permeability impairment. The results confirm that this new tool offers a more accurate and operationally relevant solution for managing asphaltene-related challenges in modern field development and production operations.

Perturbed-Chain Statistical Associating Fluid Theory (PC-SAFT)

The accurate prediction of asphaltene phase behavior in complex petroleum mixtures requires a thermodynamic model that can capture non-ideal interactions, molecular association, and the influence of heavy fractions. Among advanced equations of state (EOS), the Perturbed-Chain Statistical Associating Fluid Theory (PC-SAFT) has emerged as a robust framework for modeling asphaltenic systems due to its physically grounded representation of molecular architecture and intermolecular forces (Gross and Sadowski, 2001).

PC-SAFT extends the original SAFT theory by accounting for the non-spherical (chain-like) shape of hydrocarbon molecules, making it particularly suited for long-chain alkanes, aromatics, and resins, key components in crude oil. The residual Helmholtz free energy in PC-SAFT is expressed as the sum of three contributions (Gross and Sadowski, 2001):

$$\tilde{a}^{res} = \tilde{a}^{hc} + \tilde{a}^{disp} + \tilde{a}^{assoc} \quad (1)$$

Where \tilde{a} is the reduced Helmholtz free energy. \tilde{a}^{hc} represents the hard-chain contribution, which captures the entropic effects arising from the formation of flexible chains of tangent hard spheres, \tilde{a}^{disp} denotes the dispersion term, accounting for attractive van der Waals forces between molecular segments; and \tilde{a}^{assoc} corresponds to the association contribution, which models specific, directional interactions such as hydrogen bonding or acid–base interactions through the incorporation of association sites on molecules.

Each term is expressed in terms of three pure-component parameters:

m_i : number of segments (related to molecular size),

σ_i : segment diameter [\AA],

ε_i/k : segment energy parameter [K], where k is Boltzmann's constant.

For mixtures, combining rules (typically Lorentz–Berthelot) are applied, and binary interaction parameters (BIPs) may be introduced for non-ideal cross-interactions.

The hard-chain contribution is derived from the Carnahan–Starling equation for hard spheres, extended to chains via Wertheim's first-order thermodynamic perturbation theory:

$$\tilde{a}^{hc} = \bar{m}\tilde{a}^{hs} - \sum_i x_i (m_i - 1) \ln g_{ii}^{hs}(\sigma_{ii}) \quad (2)$$

Where x , m , g_{ii} , and σ_{ii} represent mole fraction, number of segments, radial distribution function, and segment diameter, respectively. \tilde{a}^{hs} is the hard sphere term of Helmholtz free energy (Daryasafar et al., 2020).

The dispersion term is then added as a perturbation:

$$\tilde{a}^{disp} = -2\pi\rho I_1 (\overline{m^2\varepsilon\sigma^3}) - \pi\rho\bar{m}C_1 I_2 (\overline{m^2\varepsilon^2\sigma^3}) \quad (3)$$

I_1 and I_2 are temperature-dependent Integrals, and C_1 is the compressibility term defined as:

$$C_1 = \left(1 + \frac{m}{1-\eta} \frac{8\eta - 2\eta^2}{(1-\eta)^4} + (1-m) \frac{20\eta - 27\eta^2 + 12\eta^3 - 2\eta^4}{[(1-\eta)(2-\eta)]^2} \right)^{-1} \quad (4)$$

In the above equation, η is the packing fraction.

The association term is formulated using Wertheim's multi-density formalism and requires the specification of association sites (e.g., one proton-donor and one acceptor site per molecule). For asphaltenes, which contain heteroatoms (N, O, S) and exhibit strong self-association, this term is essential to capture solubility limits and precipitation onset. $\tilde{\alpha}^{assoc}$ is determined by:

$$\tilde{\alpha}^{assoc} = \sum_i x_i \left[\sum_{A_i} \left(\ln X^{A_i} - \frac{X^{A_i}}{2} \right) + \frac{M_i}{2} \right] \quad (5)$$

Where M_i is the molecular weight of component i , and X^{A_i} is the mole fraction of component i not bonded at site A (Daryasafar et al., 2024).

Asphaltenes are typically modeled as a single pseudo-component (or a few fractions) with fitted or group-contribution-derived PC-SAFT parameters. Their strong self-association and interaction with resins are captured either through:

- Explicit association sites (e.g., one or two electron-donor/acceptor sites per molecule)
- Effective dispersion parameters that implicitly account for polar interactions when association is not explicitly modeled

Phase equilibrium is determined by minimizing the total Gibbs free energy, enforcing equality of chemical potential across phases. For asphaltene precipitation, this involves solving a liquid–solid (or liquid–asphaltene-rich liquid) equilibrium problem. The asphaltene phase is often treated as an incompressible solid or a dense pseudo-liquid, with its fugacity defined relative to a reference state.

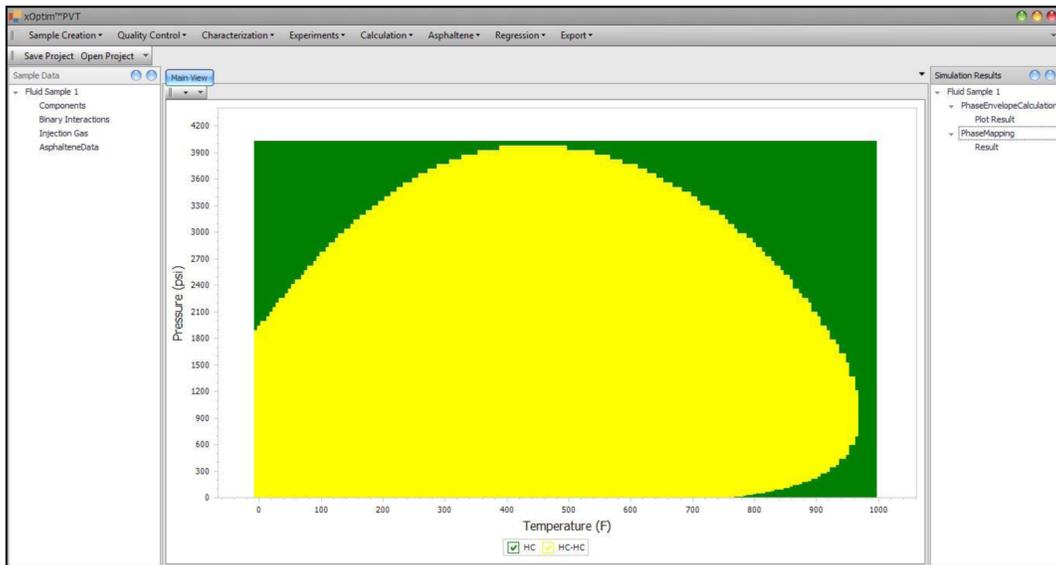
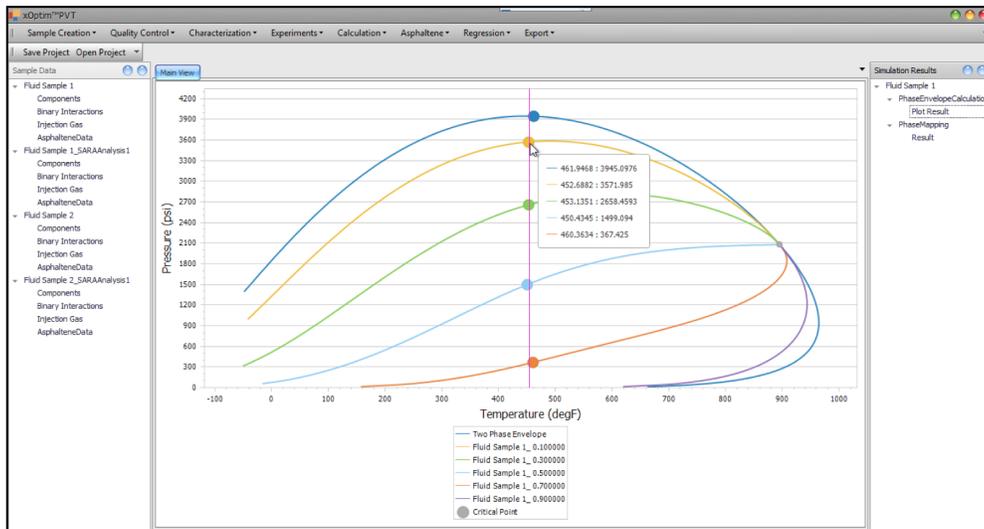
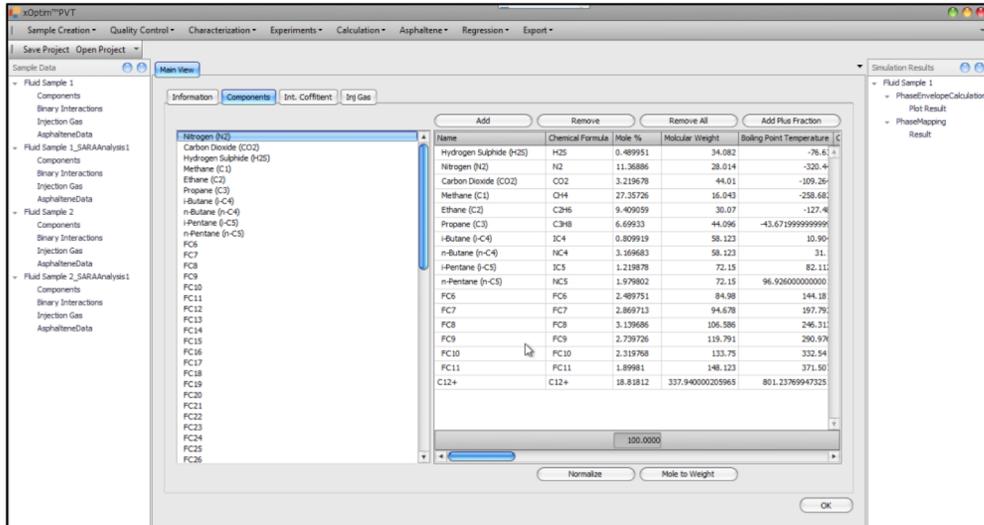
A key advantage of PC-SAFT over cubic EOS (e.g., Peng–Robinson) is its reduced reliance on binary interaction parameters (BIPs) and its ability to predict phase behavior from molecular characteristics. However, calibration against experimental data such as saturation pressure, asphaltene onset pressure, and precipitation yield remains essential to constrain the parameters of the heaviest fractions, which are not directly measurable.

In this work, PC-SAFT is implemented in a new PVT analyzer tool with a numerically efficient phase stability and flash algorithm. The model's parameters are then tuned using experimental PVT and asphaltene precipitation data. The resulting model enables a reliable prediction of asphaltene dropout under varying pressure–temperature conditions, forming the thermodynamic backbone for assessing formation damage risk in reservoir operations.

Methodology

Platform of the Newly Designed Tool for Asphaltene Phase Behavior Modeling

An integrated, next-generation PVT analysis software was designed to unify experimental data management, fluid characterization, thermodynamic modeling, and flow assurance prediction within a single environment. The platform supports the full spectrum of conventional PVT analyses, including constant composition expansion (CCE), differential vaporization (DVF), separator tests, swelling tests, and viscosity measurements, as well as advanced phase behavior modeling for complex systems such as gas condensates, volatile oils, and asphaltenic crudes. The software features a user-friendly interface for importing data, performing automated quality control, model tuning, and visualization of phase envelopes, swelling factors, and precipitation profiles. Critically, all modeling workflows, from fluid definition to prediction, are traceable, reproducible, and exportable for integration into reservoir or production simulators. Figure 1 presents a snapshot of the main platform interface.



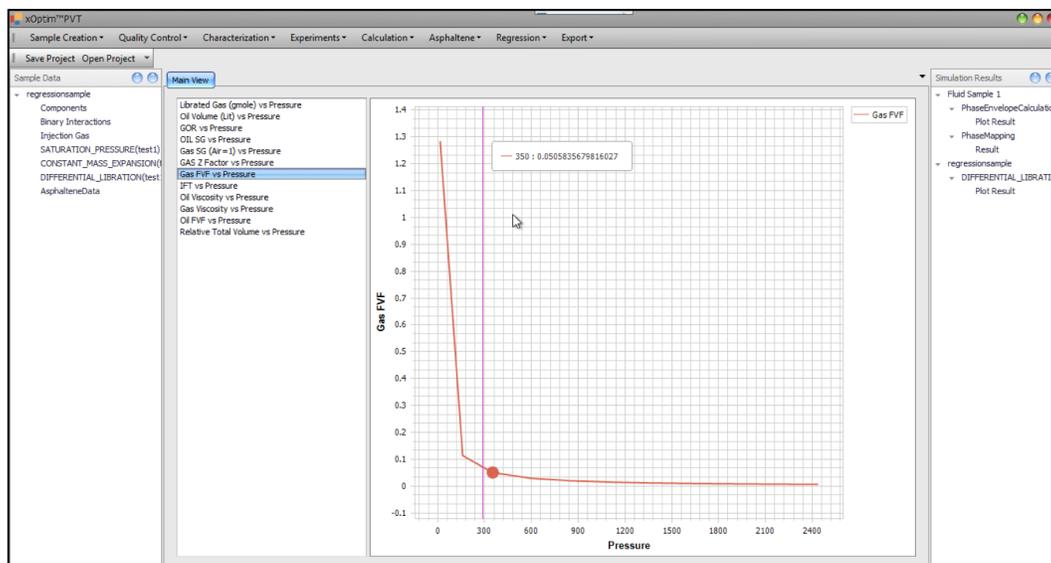


Figure 1—Newly designed PVT analyzer platform

The asphaltene phase behavior module in the designed tool follows a systematic, stepwise workflow that begins with the definition of the fluid sample and culminates in a quantitative prediction. The process is fully integrated into the software's PVT analysis framework and requires only standard laboratory data as input. The software supports both solid model and PC-SAFT EOS for modeling and simulation of asphaltene phase behavior.

Accurate modeling of asphaltene phase behavior requires that each crude oil first be characterized in terms of a finite set of components or pseudocomponents. Two characterization schemes are considered in the software, based on only the asphaltene content of the sample, and based on saturate, aromatic, resin, asphaltene (SARA) analysis, Figure 2. In the first scheme of fluid characterization, which was proposed by Arya et al. (2016), the sample is divided into CO₂, H₂S, N₂, C₁, C₂, C₃, iC₄, nC₄, iC₅, nC₅, C₆, heavy component (HC) and asphaltene. The splitting and grouping of components heavier than C₆ into hydrocarbon (HC) and asphaltene pseudo-components are based on the molar masses of the individual heavy fractions, as well as the determined molar mass of the asphaltene fraction. In the second scheme, proposed by Panuganti et al. (2013) and Tavakkoli et al. (2014), the crude oil composition consists of CO₂, H₂S, N₂, C₁, and four pseudo-components: heavy gas, saturates, aromatics, resins, and asphaltene. In this study, the second scheme was used for modeling asphaltene phase behavior and evaluating the performance of various software.

Pure-component PC-SAFT parameters (m , σ , ϵ/k) for C₁–C₆ and inorganic gases are assigned from the software's built-in database (validated against NIST and DIPPR). For pseudo-components, the proposed correlations are utilized (Tavakkoli et al., 2014; Gonzalez et al., 2007). These initial estimates are then refined during regression.

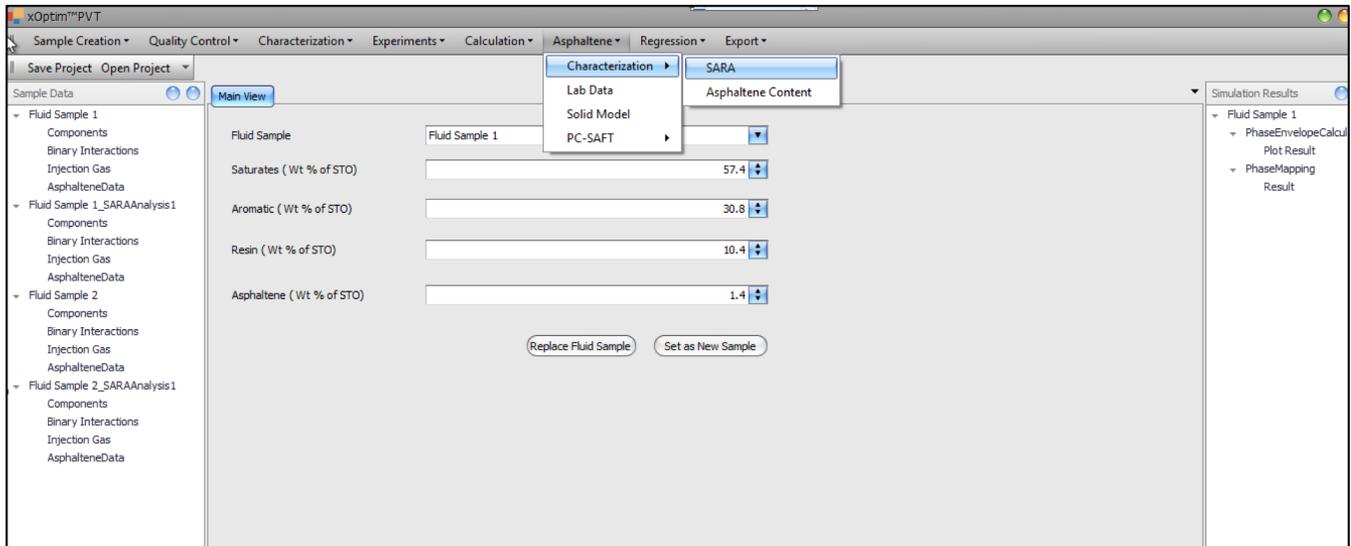
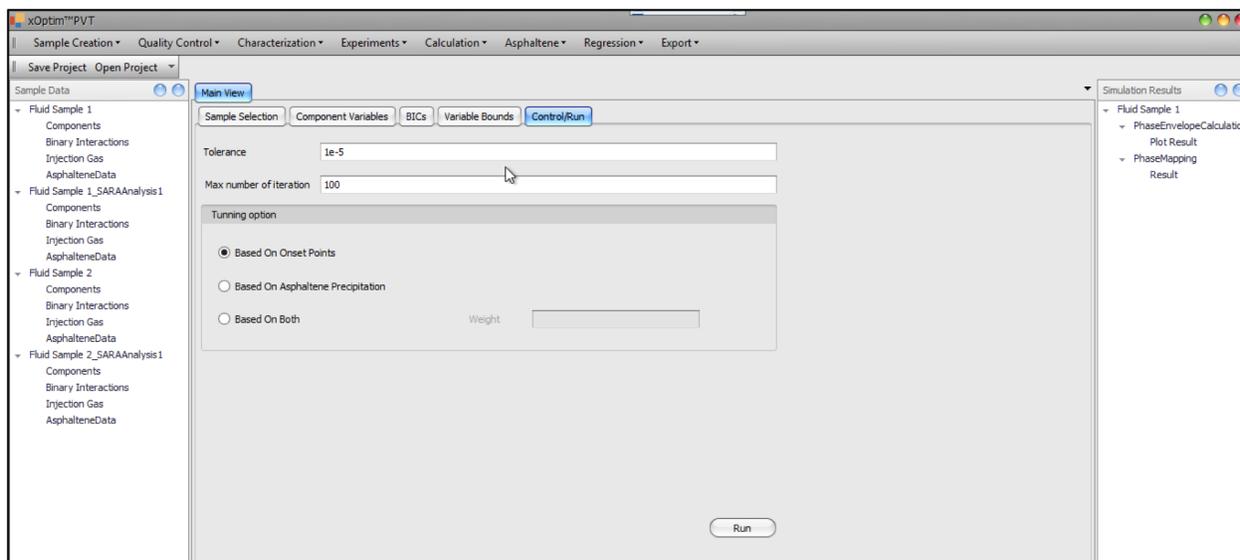


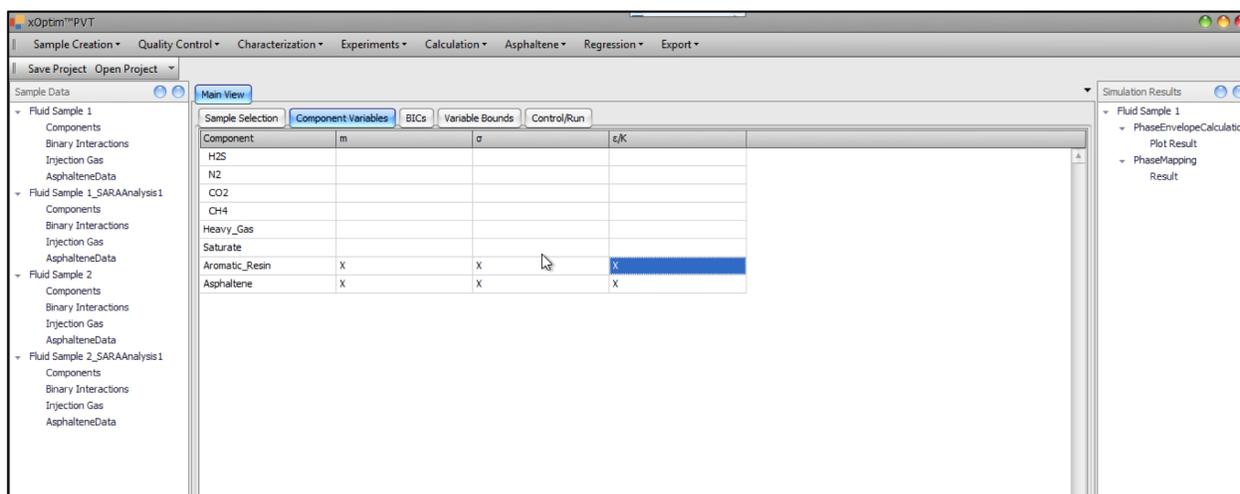
Figure 2—Module of fluid and asphaltene characterization

The developed tool employs an automated regression engine to calibrate PC-SAFT parameters against experimental data. The user selects target data from the integrated PVT database, including bubble-point pressure, upper and lower asphaltene onset pressures, or precipitated asphaltene mass, Figure 3. The regression process optimizes (m , σ , ϵ/k) for the defined components, and/or binary interaction parameters (BIPs) between different components, Figure 3. The optimization algorithm minimizes a weighted objective function combining absolute relative deviations in P_b , onset P_{onset} , and precipitation mass. Once calibrated, the model can simulate asphaltene behavior under arbitrary pressure–temperature (P–T) paths, including isothermal depletion and gas injection, among other scenarios. The output includes Onset pressures, Precipitated asphaltene mass as a function of pressure, Phase envelope with asphaltene dropout boundary, Chemical potential and Fugacity profiles for stability analysis.

While the designed analyzer does not internally compute permeability reduction, the precipitation mass profile serves as a direct quantitative input for external formation damage models. This end-to-end workflow, fully embedded within a comprehensive PVT platform, enables engineers to move seamlessly from lab data to actionable flow assurance insights, significantly reducing turnaround time and modeling uncertainty.



(a)



(b)

Figure 3—PC-SAFT model regression module; (a) Type of experimental data selection for model calibration, (b) Regression parameters selection

Experimental Data

The availability of High-Pressure and High-Temperature (HPHT) experimental data that concurrently specify crude oil composition, asphaltene onset pressure (AOP), and gravimetrically determined asphaltene precipitation is limited in the published literature. The following two asphaltenic crude oil samples, designated Crudeoil-1 and Crudeoil-2, were selected to evaluate the performance of the developed asphaltene precipitation module as well as other well-established commercial software.

The properties of Black Oil Reservoir Fluid 1 are summarized in Table 1. Jamaluddin et al. (2002) examined the trade-off between enhanced oil recovery and aggravated asphaltene instability induced by nitrogen injection. The compositional data for Oil 1 are provided in Table 2.

Table 1—Characteristics of crudeoil-1

Parameter	Value
Bubble Point Pressure at 255°F [psia]	3045
Reservoir Pressure [psia]	3256
Reservoir Temperature [°F]	296
GOR [SCF/STB]	900
API [deg]	32
SARA Analysis [%, w/w of STO]	
Saturates	57.4
Aromatics	30.8
Resins	10.4
Asphaltenes	1.4

Table 2—Crudeoil-1 composition

Component	Reservoir Fluid [mole%]
N ₂	0.49
CO ₂	11.33
H ₂ S	3.20
C1	27.23
C2	9.37
C3	6.68
iC4	0.81
nC4	3.17
iC5	1.23
nC5	1.98
C6	2.50
C7	2.89
C8	3.16
C9	2.77
C10	2.34
C11	1.91
C12+	18.96
MW (g/mol)	102.04
MW of C12+ (g/mol)	337.94
Density of C12+ (g/cm ³)	0.906

Table 3 shows the composition of crudeoil-2. For this fluid sample, only the asphaltene precipitated mass and bubble point are available, shown in Table 4. Therefore, in this case, the models are tuned based on the precipitated mass and then tested for predicting the bubble point.

Table 3—Crudeoil-2 composition

Component	Reservoir Fluid [mole%]
H ₂ S	1.87
N ₂	0.31
CO ₂	3.37
C1	43.586
C2	8.579
C3	6.269
iC4	1.64
nC4	4.89
iC5	2.2
nC5	2.49
C6	1.91
C7	0.89
C8	3.01
C9	2.05
C10	1.84
C11	1.39
C12+	13.709
MW of C12+ [g/mol]	355.452
Density of C12+ [g/cm ³]	0.874

Table 4—Characteristics of crudeoil-2

P _b at Temperature of 400°F [psia]	3997
SARA Analysis (% w/w of STO)	
Saturates	52.49
Aromatics	41.04
Resins	5.48
Asphaltenes	0.99
Asphaltene Precipitation Data	
Pressure [psia]	Observed Mass [wt.%]
5000	0.379668
4500	0.454697
4000	0.492078
3000	0.342419
2000	0.240119

Results and Discussion

Crudeoil-1 was characterized using SARA analysis to support pseudo-component definition in the PC-SAFT framework. The characterized sample, along with the PC-SAFT parameters after characterization, are shown in [Table 5](#).

Table 5—Characterized crudeoil-1 for asphaltene phase behavior modeling using PC-SAFT

Component	Mole [%]	m	σ [°A]	ε/k [K]
N2	0.4712	1.694	3.021	227
CO2	11.3300	1.205	3.313	91
H2S	3.1606	2.073	2.785	169
CH4	27.2000	1.000	3.704	150.03
Heavy Gas	20.8635	1.980	3.636	213.0485
Saturate	28.1525	5.167	3.901	249.7054
Aromatic + Resin	8.7579	8.234	4.174	367.6121
Asphaltene	0.0642	33.507	4.296	383.8957

The PC-SAFT models implemented in the developed software, commercial software-1, and commercial software-2 were independently calibrated using the same experimental dataset for Crudeoil-1: specifically, the bubble-point pressure (P_b) and upper asphaltene onset pressure (P_{onset}) measured across a range of temperatures (190–300°F). This multi-temperature calibration ensures that the tuned models capture not only pressure-dependent but also thermal effects on asphaltene stability, which is critical for field applications involving variable reservoir or injection temperatures. Parameters (m , σ , ε/k) of aromatics+resin and asphaltene were used as regression parameters for tuning the PC-SAFT model in all software. After tuning, the predictive performance of each model was evaluated by computing the average absolute relative deviation (AARD, %) between predicted and experimental values for both P_b and P_{onset} . The results of the P_b and P_{onset} values obtained using different software are indicated in Tables 6 and 7, respectively.

Table 6—Comparison between the matching results (bubble point pressure) of commercial software (crudeoil-1)

Temperature (°F)	Bubble-Observed (psia)	Bubble Point New Software (psia)	Bubble Point Software-1 (psia)	Bubble Point Software-2 (psia)
190	2500	2595	2556	2604
230	2700	2773	2738	2775
260	2900	2890.3	2834	2888.4
300	3000	3005.59	2961	3066

Table 7—Comparison between the matching results (upper onset pressure) of commercial software (crudeoil-1)

Temperature [°F]	Upper Onset, Observed [psia]	Upper Onset, New Software [psia]	Upper Onset, Software-1 [psia]	Upper Onset, Software-2 [psia]
190	5400	5479.99	5208.4	5401.3
230	4050	3908.2	3915.67	3913.57
260	3650	3732.47	3795.4	3787
300	3800	3885.73	3932.17	3893

The newly designed tool achieves the lowest overall error, with AARDs of 2.37% and 1.76% for onset and bubble-point pressures, respectively. Notably, while Software-2 matches the developed analyzer closely in onset prediction (2.39% vs. 2.37%), its bubble-point error is 35% higher (2.38% vs. 1.76%). Software-1, although slightly better than Software-2 in bubble-point prediction (1.81%), exhibits the largest deviation in onset pressure (3.58%). Figure 4 illustrates the calibrated phase behavior models, showing the predicted asphaltene onset curves (onset pressure vs. temperature) and bubble-point curves alongside experimental

data points. The tuned models are the best-matched models found for different software. All three models capture the general trend of onset and bubble-point pressures with increasing temperature. However, the designed tool's curves exhibit the tightest envelope around experimental markers. The close agreement between the developed software and experiment, consistently below 2.5% AARD across temperatures, confirms that its PC-SAFT implementation, coupled with an intelligent calibration workflow, delivers thermodynamically consistent and field-reliable predictions.

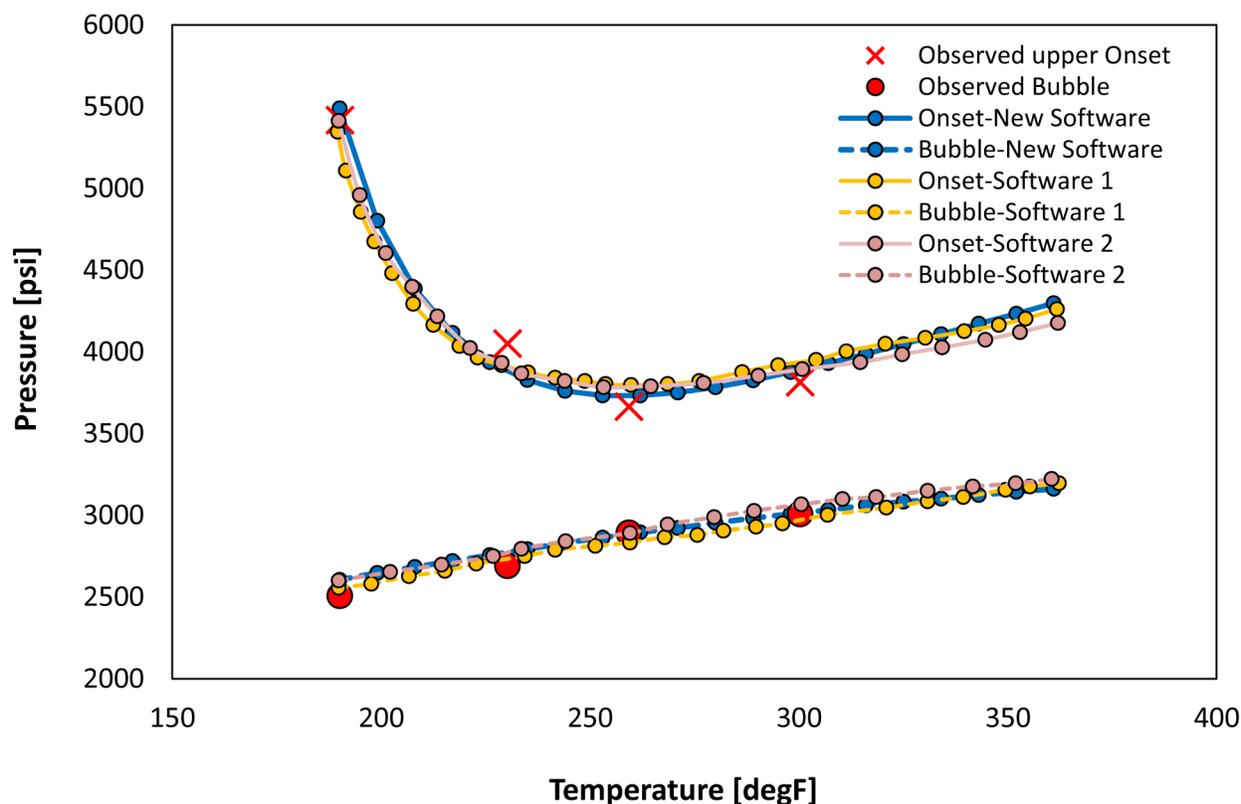


Figure 4—Results of the tuned PC-SAFT models obtained by different software (crudeoil-1)

Following model calibration, the tuned PC-SAFT models in the new software, as well as commercial software-1 and commercial software-2, were used to predict the impact of nitrogen (N_2) injection on the phase behavior of Crudeoil-1. Specifically, the models simulated how increasing N_2 mole fraction (0–20 mol%) affects both the asphaltene onset pressure and bubble-point pressure at a temperature of 180°F. These predictions are critical for evaluating flow assurance risks during gas injection EOR processes.

The accuracy of each simulator was quantified using the average absolute relative deviation (AARD%) between predicted and experimental pressures across the N_2 concentration range. As shown in Figure 5, the developed strategy used in the new analyzing tool achieved exceptional agreement with laboratory data, with AARDs of 2.13% for P_{onset} and 1.32% for P_b . In contrast, commercial software-1 yielded significantly higher deviations of 6.73% and 5.07%, respectively, while commercial software-2 exhibited the largest errors, with AARDs of 10.11% for onset pressure and 10.93% for bubble-point pressure.

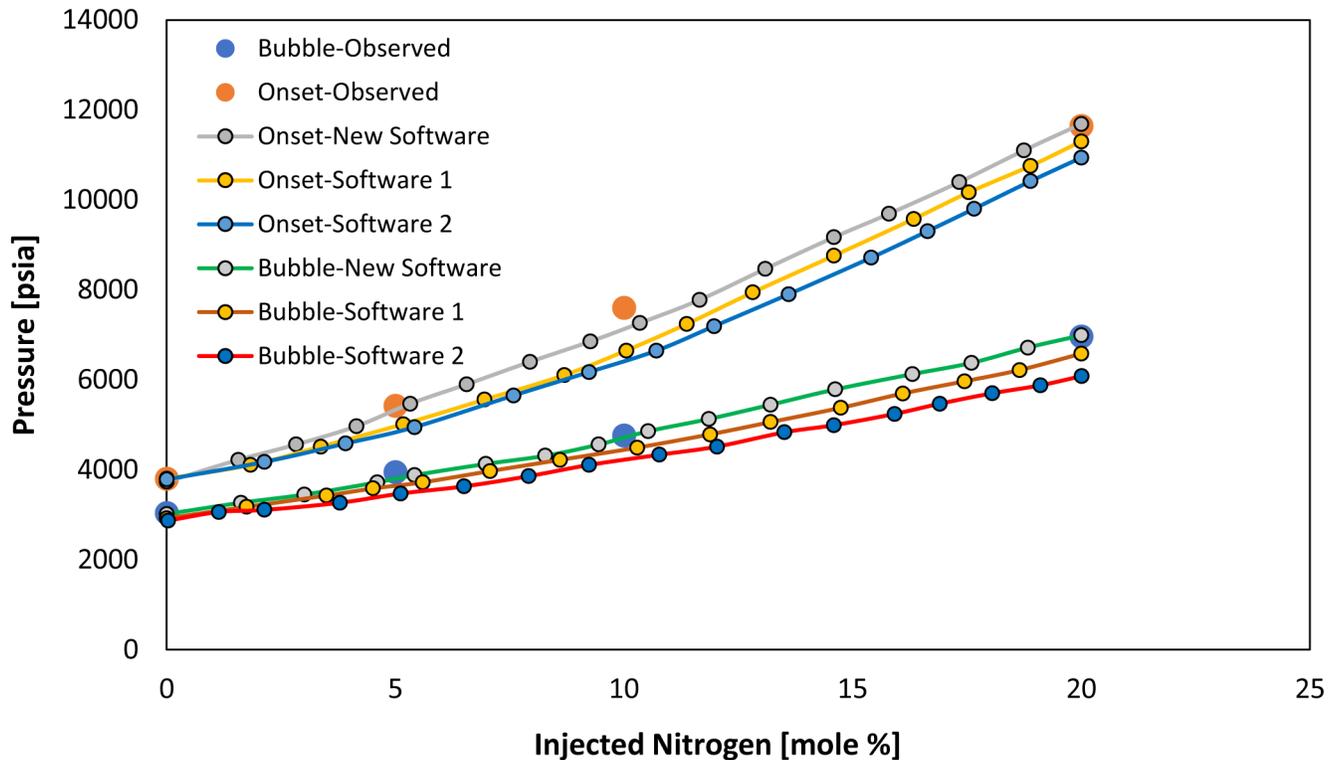


Figure 5—Comparison of different commercial software in predicting the effect of N# injection on bubble-point pressure and asphaltene upper onset pressure for Crudeoil-1

A key observation from Figure 5 is that both commercial simulators (software-1 and 2) systematically underpredict the asphaltene onset and bubble-point pressures as N₂ concentration increases. This consistent negative bias indicates that these tools underestimate the destabilizing effect of nitrogen on the crude oil, predicting that asphaltene precipitation and gas evolution occur at lower pressures than those observed experimentally. Such underprediction of phase instability poses a significant operational risk: it may lead engineers to assume safe production conditions exist below the true onset threshold, resulting in unanticipated asphaltene deposition in the near-wellbore region. Contrary to conservative design, this non-conservative error can cause severe formation damage, productivity loss, and costly remediation, highlighting the critical need for high-fidelity modeling tools like the newly developed analyzer, which accurately captures the N₂-induced shift in phase behavior.

Crudeoil-2 was also characterized using SARA analysis. The characterized sample, as well as initial PC-SAFT parameters after characterization, are shown in Table 8.

Table 8—Characterized crudeoil-2 for asphaltene phase behavior modeling using PC-SAFT

Component	Mole [%]	m	σ [°A]	ε/k [K]
N2	1.8233	1.694	3.021	227
CO2	0.3091	1.205	3.313	91
H2S	3.3274	2.073	2.785	169
CH4	43.3904	1.000	3.704	150.03
Heavy Gas	23.5155	2.066	3.657	216.2812
Saturate	20.5261	4.989	3.896	249.1007
Aromatic + Resin	7.0734	8.712	4.184	369.2721
Asphaltene	0.0347	33.507	4.296	383.8957

For Crudeoil-2, the PC-SAFT models in the designed software, commercial software-1, and commercial software-2 were calibrated against experimental asphaltene precipitation mass measured during isothermal pressure depletion at 400°F. Parameters (m , σ , ε/k) of aromatics+resin and asphaltene were used as regression parameters for tuning the PC-SAFT model in all software. Unlike Crudeoil-1 (calibrated on onset and bubble-point pressures), this case represents a more challenging scenario where the model must reproduce the entire quantitative precipitation profile, not just the onset threshold. Accurate matching of precipitated mass is essential for a reliable formation damage assessment, as the magnitude of solid deposition directly influences permeability reduction.

As shown in Figure 6, the tuned model utilizing the newly developed module exhibits excellent agreement with experimental precipitation data across the entire pressure range. The predicted curve closely follows the measured trend. Additionally, the other commercial software (software-1 and 2) could also successfully capture the trend of precipitation amounts at different pressures. The obtained models are the best-matched PC-SAFT models found for various software.

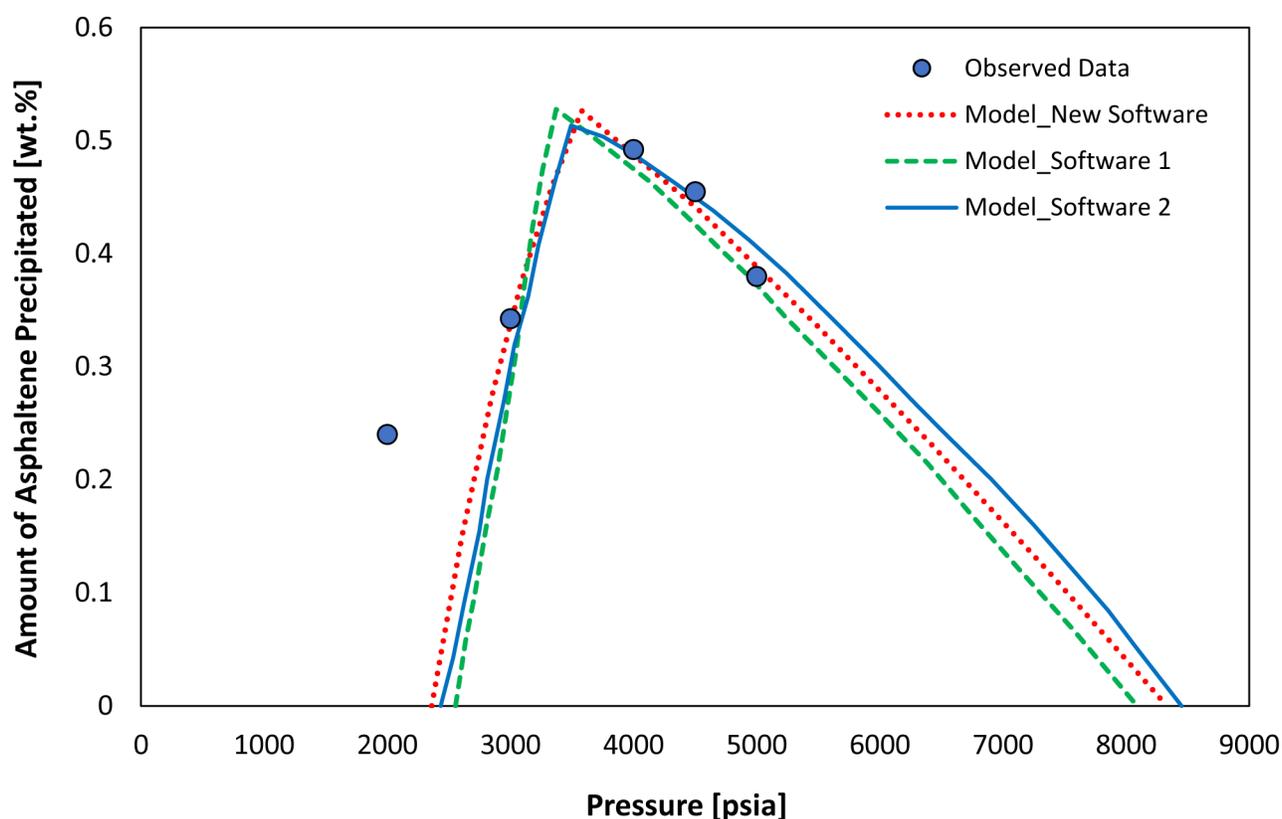


Figure 6—Comparison of the new tool and commercial simulators in matching experimental asphaltene precipitation data for Crudeoil-2

Following calibration, all three models were used to predict the bubble-point pressure at a temperature of 400°F, a condition relevant to high-temperature reservoirs or thermal recovery scenarios. This constitutes a true predictive test, as no bubble-point data at 400°F were used in the regression. The results, summarized in Table 9, demonstrate a clear advantage for the developed tool.

Table 9—Performance comparison of PC-SAFT models (tuned in different software) in predicting bubble-point pressure (crudeoil-2)

	Observed	New Software	Software-1	Software-2
Bubble Point Pressure (psia)	3997	3873	3699	3457
ARD [%]	-	3.10	7.46	13.51

This progressive degradation in accuracy, from the introduced tool to Software-2, highlights a key limitation of conventional tuning approaches. When models are optimized solely for heavy-end behavior (precipitation), they often lose fidelity in light-end or vapor–liquid equilibrium (VLE) predictions, especially under extrapolated conditions such as high temperatures. The proposed analyzer avoids this pitfall through its balanced regression framework, which enforces thermodynamic consistency between the asphaltene solid/liquid phases as well as the bulk oil–gas equilibrium.

Furthermore, Figure 7 presents the complete phase envelope generated by the tuned PCSAFT model in the presented module, including: the vapor–liquid saturation curve, the upper asphaltene onset curve (onset of precipitation upon pressure depletion), and the lower asphaltene onset curve (re-dissolution boundary upon pressurization).

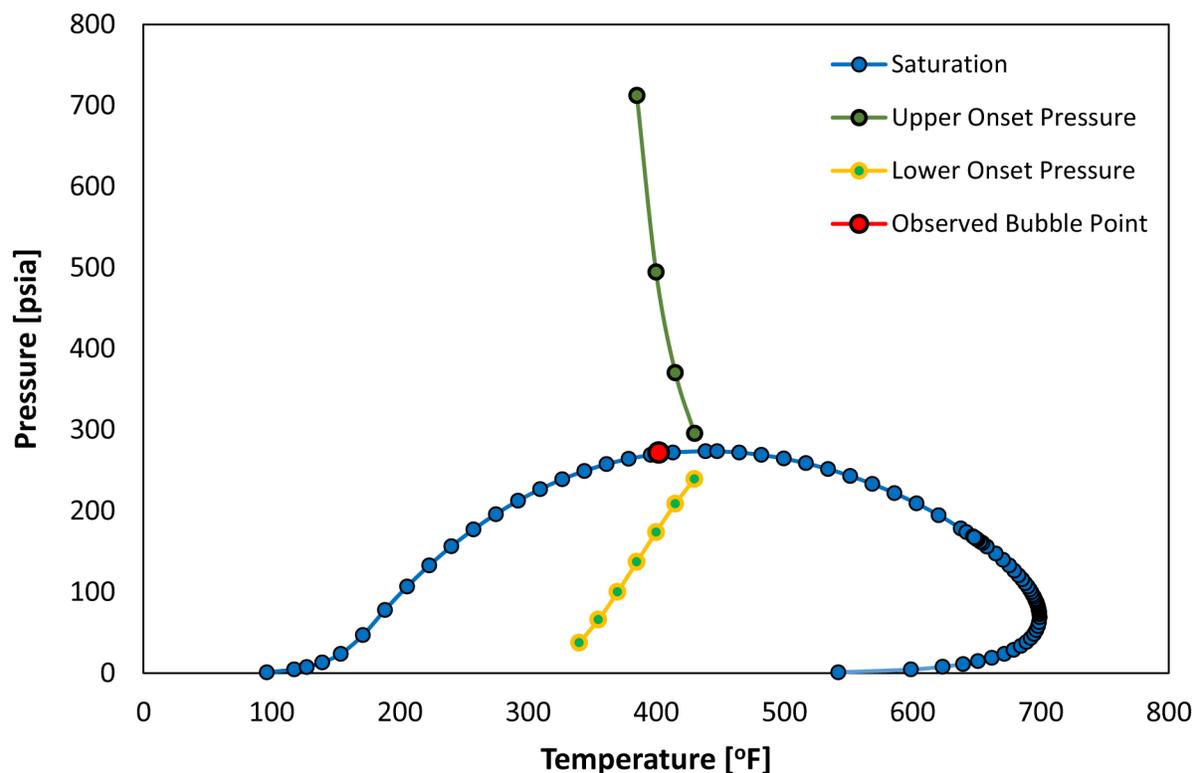


Figure 7—Phase envelope of Crudeoil-2 generated using the calibrated PC-SAFT model by the newly developed software tool

The ability of the developed tool to simultaneously honor quantitative precipitation data and accurately predict VLE at high temperature underscores its dual capability as both a flow assurance tool and a general PVT simulator. In field applications, this means engineers can rely on a single, consistent fluid model for (1) designing production strategies that avoid the asphaltene instability zone, (2) forecasting well performance under thermal or compositional changes, and (3) estimating deposition risk without switching between specialized software. In contrast, the larger errors from commercial tools could lead to significant miscalculations in reservoir simulation, separator design, or gas handling capacity, compounding operational risks in high-temperature developments.

New Tool Predictions for Formation Damage Identification

While the developed tool does not internally compute permeability reduction or deposition kinetics, its high-fidelity prediction of asphaltene phase behavior provides the essential thermodynamic foundation for a quantitative analysis of formation damage. Formation damage due to asphaltene deposition is not solely a

function of whether precipitation occurs, but critically depends on how much solid forms, at what pressure/temperature, and how close to the wellbore these conditions exist during production. The designed analyzer directly addresses these factors through three key capabilities:

Accurate Onset Pressure Prediction (Early Risk Detection). As demonstrated for Crudeoil-1, the presented tool predicts asphaltene onset pressure with an AARD of 2.13% under N₂ injection, significantly outperforming commercial tools. This precision enables engineers to define a reliable stability envelope and identify the critical drawdown pressure below which precipitation initiates. Operating above this threshold, especially in the near-wellbore region where pressure gradients are steepest, can prevent damage from occurring.

Quantitative Precipitation Profiles (Severity Assessment). For Crudeoil-2, the presented tool accurately matched experimental precipitated asphaltene mass across the full depletion path. The magnitude of precipitated solids is a primary input to empirical or mechanistic formation damage models (e.g., based on core-flood data or filtration theory). An overprediction may trigger unnecessary chemical inhibition, while an underprediction risks unmitigated deposition. The designed software's fidelity ensures that damage severity is neither exaggerated nor overlooked.

Robust Extrapolation to Field Conditions (Proactive Mitigation). The accurate prediction of bubble-point pressure and reliable phase envelopes, including upper/lower asphaltene boundaries, demonstrates the proposed tool's capability to operate under realistic reservoir conditions, such as thermal EOR or deep-hot reservoirs. This enables engineers to map the spatial extent of the asphaltene instability zone using reservoir simulation pressure profiles, design inhibitor squeeze treatments targeted to high-risk intervals, and optimize gas injection rates to balance recovery and stability.

Thus, while the developed module focuses on the thermodynamic driver of damage, it provides the quantitative, high-resolution input required by downstream engineering models to identify, quantify, and mitigate formation damage risk, transforming asphaltene management from a reactive to a proactive, data-driven discipline.

Conclusions

1. A new asphaltene-precipitation module was developed and validated within a next-generation PVT software using an optimized PC-SAFT EOS and efficient numerical algorithms.
2. Accuracy significantly exceeded two commercial simulators, with lower AARD/ARD values for predicting onset pressure, bubble-point pressure, and precipitation mass for two asphaltenic crude oils.
 - Crudeoil-1: The tool predicted asphaltene onset and bubble-point pressures with AARDs of 2.13% & 1.32%, far outperforming Commercial Software-1 (6.73% & 5.07%) and Software-2 (10.11% & 10.93%).
 - Crudeoil-2: The module closely matched precipitation mass and predicted the 400°F bubble-point pressure with 3.1% ARD, again superior to commercial alternatives (7.46%, 13.51%).
3. Performance gains arise from physically consistent parameterization, robust phase-stability analysis, and balanced regression that reduce numerical noise and overfitting.
4. The software provides high-fidelity precipitation profiles and phase envelopes, enabling reliable thermodynamic input for formation-damage assessment.
5. While it does not calculate permeability reduction internally, its predictions can be directly coupled with empirical or mechanistic formation-damage models to support risk evaluation and mitigation.
6. Overall, the tool offers a fast, accurate, and field-applicable solution that links PVT analysis with flow-assurance engineering. The module transforms asphaltene modeling into a proactive design tool,

helping operators prevent formation damage, enhance productivity, reduce risk, and improve project economics.

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