Journal of Polymers and the Environment (2026) 34:270
https://doi.org/10.1007/s10924-026-03974-5

ORIGINAL PAPER

A Developed Filtrate Regression Model for Polymers in Water-based Drilling Fluids: Application in Gas Reservoirs

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Received: 30 June 2026 / Accepted: 14 September 2026
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Abstract

High-pressure and high-temperature conditions in the gas fields of Southern Zagros, Iran, create significant challenges for water-based drilling fluids, including excessive filtrate loss and rheological instability. Properly controlled water-based drilling fluids are required to minimize filtrate invasion into high-pressure high-temperature formations, such as the deep Kangan and Dalan gas reservoirs (85–105 °C) in Southern Zagros. This study investigates the effects of three widely used synthetic polymers, polyanionic cellulose, partially hydrolyzed polyacrylamide, and carboxymethyl cellulose, on filtration control at polymer concentrations of 0.5–1.5 g/L. A generalized linear model-based regression approach was developed to predict filtrate volume by representing water-based drilling fluids as a two-phase system consisting of a continuous aqueous phase and a dispersed polymer phase. The interaction effects between these phases were incorporated through experimental variables, including polymer type, molecular weight, pH, and operational conditions. The developed model was applied to 27 experimental runs covering temperature ranges of 85–110 °C, polymer concentrations of 0.5–1.5 g/L, and pH values of 4–9. The results demonstrated the superior filtration control performance of PAC, reducing filtrate volume by 40–60% at temperatures below 105 °C under Southern Zagros conditions with 100,000–200,000 ppm salinity. The optimized PAC formulation achieved filtrate volumes of 8–10 mL/30 min based on favorable pH conditions and polymer structural characteristics. The final model showed a predicted R-square value of 76.26%, an R-square of 83.24%, and an error value of 0.0719, demonstrating its suitability for estimating filtrate behavior under HPHT and high-salinity condition. MW as a structural parameter incorporated in the model equation controlled filtrate volume. Increasing polymer MW reduced filtrate volume by enhancing polymer–water interactions, promoting a more stable hydration layer, and decreasing mud cake permeability.

Keywords Water-based drilling fluids · Polymer-based filtration control · Molecular weight effect · Generalized linear model · High-pressure high-temperature gas reservoirs · Southern Zagros

Abbreviations

WBDF	Water-Based Drilling Fluid
HPHT	High-Pressure High-Temperature
PAC	Polyanionic Cellulose
PHPA	Partially Hydrolyzed Polyacrylamide
CMC	Carboxymethyl Cellulose
GLM	Generalized Linear Model
DOE	Design of Experiments
MW	Molecular Weight
DS	Degree of Substitution
VIF	Variance Inflation Factor
API	American Petroleum Institute
HTHP	High-Temperature High-Pressure
R^2	Coefficient of Determination
Adj	R^2-Adjusted Coefficient of Determination
Pred	R^2-Predicted Coefficient of Determination
MDa	Megadalton
Cpoly	Polymer Concentration
β	Regression Coefficient
α	Significance Level

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Published online: 11 October 2026

V	Filtration Volume / Filtrate Volume
Kangan	Kangan Formation
Dalan	Dalan Formation
SPs	Synthetic polymers

Introduction

In recent years, the design and optimization of engineered fluids in complex reservoirs has become an important topic in petroleum engineering. In a way, it has faced many problems for chemical and petroleum engineers in well operations who mainly work with different fluids. Recent studies have demonstrated that the performance of injection and drilling fluids is not only dependent on their chemical composition, but also influenced by multiple interactions between fluid properties, formation characteristics, temperature and pressure conditions, and fracture structures [1]. in their investigation of alkali-free ternary composite fluids concluded that the transport mechanism, formation damage, and oil displacement efficiency are strongly affected by the interaction between fluid components and the porous medium. These findings highlight the importance of investigating phase behavior and chemical interactions in complex fluid systems, which is also of particular importance in WBDFs with high salinity and HPHT conditions.

On the other hand, real conditions of deep gas reservoirs, especially fractured carbonate reservoirs, require models that can take into account the simultaneous effects of operating parameters and formation characteristics [2]. developed a semi-analytical model for horizontal fractured wells and found that the flow behavior in fractured environments and the stimulated zone of the reservoir cannot be fully described by simple ideal flow models. This indicates the need to develop predictive models that, in addition to laboratory data, also consider the effect of structural and operational variables affecting fluid performance. In drilling fluids, such an approach can help to better understand the relationship between polymer type, MW, chemical conditions of the environment, and filtration loss.

Controlling fluid migration and creating a low-permeability seal layer is one of the most important goals of using polymers in drilling fluids (especially, in WBDFs) and leak control operations [3]. in their study of gas leakage mechanisms in the drainage zone of wells showed that the sealing process and reducing flow paths are strongly dependent on the structural characteristics of the porous medium and the distribution of seal materials. Although this study was conducted in the context of gas drainage wells, its main concept, namely the relationship between material structure, formation of a protective layer, and reducing fluid transport, is directly related to the performance of filtration control polymers in drilling mud. Therefore, quantitatively investigating the effect of molecular parameters of polymers, such as MW and DS, can be effective in designing more stable WBDFs under HPHT conditions.

In addition to fluid chemical properties, modeling of mass transfer, heat transfer, and hydrodynamic behavior of fluids under real operating conditions plays an important role in predicting the performance of engineering systems [4]. concluded that geometric changes and operating conditions can significantly affect the behavior of liquid film, mass transfer, and performance of fluid systems. These results emphasize that predictive models must be able to consider the interactions between different variables. Despite numerous studies in the field of fluid flow and performance modeling, there is still a scientific gap in the development of experimental-mechanistic models to predict the filtration of polymeric WBDFs under simultaneous HPHT and high salinity conditions, especially for fractured carbonate gas reservoirs in the southern Zagros, Iran.

Recent studies in the field of reservoir development have also shown that engineering decision-making in complex formations requires the integration of geological information, formation characteristics, and fluid behavior [5]. investigated the geochemical evolution and microbial controls in coalbed methane reservoirs and showed that the characteristics of the reservoir formations play a decisive role in the performance of fluid systems and production processes. Accordingly, in the present study, an attempt has been made to develop a GLM-based modeling framework to relate polymer type, MW, pH, and operating conditions to filtration volume using HPHT laboratory data. The main innovation of this research is the combination of polymer structural information with a predictive regression model to design a suitable WBDF in high temperature and salinity, and fractured carbonate formations of the southern Zagros.

Gas reservoirs in the Iranian sedimentation region of Southern Zagros, especially South Pars, Kangan and Dalan fields, are mainly stored in carbonate formations that are carbonate-evaporate sequences. Dolomitization, dual porosity and shale layers have led to layer heterogeneity, layer thickness distribution and permeability variability. Subsequently, this type of structural layering has created challenges such as fluid loss and wellbore instability during drilling operations. In gas environments, especially carbonate, in the design of water-based muds, it is very necessary to consider parameters such as filtration control, rheological stability in HTHP conditions, and prevention of the drilling string sticking at points where drilling mud cake has formed. Water-based muds may not perform well in filtration control due to ionic interactions with minerals (especially at high salinity), and the sensitivity of some polymers to divalent ions in in-situ or injection fluid at HTHP conditions. Therefore, it

is very important to determine the rheological properties of polymer muds before using them in drilling fluids.

These three polymers are widely used for filtration control and rheology modification in water-based muds in this gas sedimentary region: PAC, PHPA, and CMC. PAC and modified PHPA polymers perform well at high temperatures (about 100–110 °C) and in the presence of moderate to high salinities (20,000–200,000). However, continuous laboratory tests with field conditions (HPHT, wide pH range, and high salinity) should be conducted in the Southern Zagros sedimentary basin in Iran (such as Kangan and Dalan reservoirs) to obtain a pattern of polymer consumption. A common practical measure to measure the efficiency of filtration control by additives or polymers is the API filtrate value as the volume filtered in 30 min (mL/30 min). Reducing the filtrate to achieve low drilling mud cake thickness is the main goal of formulations. In laboratory studies, controlling parameters such as changing the polymer concentration, polymer type, and other additives directly affect the filtration results. Many recent studies have emphasized the appropriate selection of polymers to improve drilling fluid rheology, and significantly reduce filtration.

To investigate the behavior of drilling fluid flow in channels, heat transfer, pressure drop prediction, and particle deposition, CFD (computational fluid dynamics) modeling methods can be used using non-Newtonian rheology models such as Bingham, Herschel–Bulkley and Carreau. CFD in the problem of filter penetration and mud cake formation may have limitations, which are usually better achieved by combining mechanical models with experimental filtration models. In addition, other methods such as RSM (response surface methodology) or GLM (general linear model) in Minitab are available, where the experimental design is performed by these methods for multiple runs. In this study, the GLM method in Minitab provided interpretable outputs (regression equations and optimal levels) for response variables via 27-run dataset.

PAC, PHPA and CMC Polymers in WBDFs

In recent years, several studies have focused on the development of engineered fluids and predictive models for complex reservoir conditions, especially in carbonate, fractured, and high-temperature-pressure environments [6]. by investigating an innovative polyfraction nanoemulsion to increase oil recovery in carbonate reservoirs demonstrated that the precise design of phase composition and control of interactions between phases play an important role in improving the performance of engineered fluids. This concept is directly related to the behavior of WBDFs modified with polymers, where the interaction of the aqueous phase and the polymer phase affects the control of filtration and rheological stability.

Additionally [7], in a study on surfactant-based solutions for fluid evacuation from gas wells emphasized the importance of understanding fluid behavior in real well conditions, especially in deep gas wells. This proves that the performance of fluids used in gaseous porous media should be evaluated not only in standard laboratory conditions, but also in the real ranges of pressure, temperature, salinity and formation conditions.

On the other hand, the development of numerical models for predicting the behavior of complex formations (e.g., Dalan and Kangan formations in South Zagros, especially in South Pars fields) has become very important [8]. presented an improved model for simulating hydraulic fracture growth in low-permeability formations, showing that consideration of real formation characteristics and operating conditions is necessary to accurately predict the behavior of subsurface systems. This is consistent with the carbonate gas reservoirs of South Zagros, which have natural fractures and extreme changes in rock properties.

In addition [9], investigated the behavior of proppant base fluids in different rock samples and concluded that the characteristics of the porous media, fracture structure and fluid-rock interaction can significantly affect the performance of fluids in subsurface environments. These findings reinforce the importance of investigating the interaction of polymers applied in drilling fluids with the gaseous formation environment and HPHT conditions.

In general, the first application of polymer-based drilling fluids dates back to the 1950s [10]. Early formulations for these fluids included bentonite, vinyl acetate-maleic acid copolymer, and soda ash [11]. Synthetic and natural polymers are used to create these formulations. Synthetic polymers (SPs) are primarily derived from petroleum derivatives [12]. Unlike natural polymers, SPs mostly with smaller molecules [13] have unlimited design flexibility [14]. The size and chemical composition of SPs can be designed for subsurface purposes [12]. All these polymers are classified as linear or branched or network chains [15]. Linear molecules include natural rubber, elastomers and high-elasticity polymers [16]. These synthetic molecules include CMC, PHPA and hydroxyethyl cellulose [17, 18], and their weighting agents constitute about 70–80% of the filter cake material [19].

SPs are mainly used as viscosifiers in WBDFs with the high carrying capacity of solids [20]. SPs control filtration by reducing filter cake permeability [12], and improve rheology with high yield strength and with low plastic viscosity [21]. SPs ensure sufficient gel strength for drilling cuttings suspension [22]. High electrolyte content negatively affects the rheology and filtration of drilling fluid [23]. Salt-resistant

monomers in SPs reduce this problem [24]. Among SPs, PHPA minimizes the effect of equivalent cycling density (ECD) [25]. SPs provide favorable rheology with lower ECD (M-I SWACO, 2009) [26], and are more effective in the upper parts of the well [27]. PAC polymer is salt-resistant above 104 mg/L, and has a temperature tolerance of up to 149 °C [28]. PAC polymer forms a low-permeability filter cake [29], improves fluid loss control [30]. PHPA polymer encapsulates the shale layer [31], prevents the disintegration of drilling fluids through anionic adsorption [32], with a thermal tolerance of less than 120 °C. SPs, such as PHPA, act as wellbore wall stabilizers and fluid lubricants [33]. For example, PHPA polymer combined with KCl reduces shale dispersion, mixed with KCl causes shale inhibition [34], and consequently improve the fluid loss control properties [35]. CMC polymer performs well against salt less 104 mg/L [28], and tolerates temperatures very less than those in PAC and PHPA [36]. Carboxymethyl substitution increases thermal stability, and reduces biodegradation in saline systems [37]. In general, polymers with higher MW increase thermal stability, and improve rheology and filtration [23]. Moreover, quadri-polymer fluids without bentonite can also transport drilling cuttings [38].

WBDFs require additives to preserve rheological stability (PV = 15–30 cP, YP = 5–15 lb/100 ft²), and control filtrate loss below 15 mL/30 min [39, 40]. Synthetic polymers such as PAC (MW = 100,000–500,000 Da), PHPA (MW = 5–15 M Da), and CMC (MW = 90,000–700,000 Da) in WBDFs, interact with aqueous phase, form viscoelastic gels, and reduce filtration [41].

Among the various additives used in WBDFs, PAC, PHPA, and CMC are widely applied polymers for filtration control and rheological modification due to their water-soluble structures and ability to interact with clay particles. PAC is commonly used as an efficient filtration-control agent, while PHPA provides encapsulation and shale stabilization properties. CMC is also frequently used as a viscosifier and filtration reducer in water-based drilling systems. However, their performance under combined HPHT and high-salinity conditions depends strongly on polymer molecular characteristics, ionic tolerance, and reservoir conditions.

The selection of polymeric additives plays a critical role in controlling the rheological and filtration behavior of water-based drilling fluids, particularly under challenging drilling conditions [42]. demonstrated that the incorporation of a biopolymer-based additive can improve the performance of water-based mud by modifying the polymer–fluid interactions and enhancing the stability of drilling fluid properties. Their modeling findings supported the concept that polymer structure and concentration are key parameters governing the interaction between the dispersed polymer phase and the aqueous phase. In the present study, similar polymer-dependent behavior was observed, where polymer type and MW significantly influenced filtrate control under HPHT and high-salinity conditions.

Furthermore [43], in a comparative study on the rheological properties of drilling fluids under HPHT conditions concluded that changes in temperature and operating conditions can directly affect the stability of the polymer structure, viscosity and performance of the drilling fluid. The results of this study emphasize that the selection of appropriate polymer additives should be based on the simultaneous interaction between the structural properties of the polymer, environmental conditions and fluid control requirements. This finding is consistent with the results of the present study, as the developed model shows that the type of polymer, MW and chemical conditions of the environment (especially pH) are the main factors determining the filtration behavior under HPHT and high salinity conditions.

Previous studies have extensively investigated the rheological properties of polymer-based water-based drilling fluids under conventional API laboratory conditions, mainly aiming at reducing filtration, increasing viscosity, and stabilizing shale. Several researchers have confirmed the effectiveness of PAC, PHPA, and CMC in improving filtration control and rheological behavior of their WBDFs. However, polymer performance can change significantly due to thermal degradation, ionic interactions, and polymer-mineral interactions under extreme reservoir conditions. For example, previous studies have concluded that the polymer molecular structure, degree of hydrolysis, and resistance to divalent ions are key parameters controlling filtration performance at high temperature conditions [37, 39, 40, 42]. Other studies have also emphasized the importance of polymer selection to maintain rheological stability and minimize filtration aggression in high-salinity drilling environments. However, most previous research has been conducted under limited laboratory conditions and has not simultaneously focused on the combined effects of polymer type, concentration, pH, temperature, and extreme salinity typical of deep carbonate gas reservoirs. Therefore, the main innovation of the present study is the development of a GLM-based predictive model using 27 experimental runs to optimize the performance of PAC, PHPA, and CMC under real HPHT conditions in the southern Zagros gas fields.

Figure 1 illustrates a schematic diagram of the formation of filter cake on the well wall, in which the solid components of the drilling fluid are formed on the wall to the varied thicknesses due to the penetration of the liquid phase into the formation. This diagram shows how the fluid penetrates into the layers around the well wall, the sedimentation of solid fluid particles, and the flow of the drilling fluid. With the start of mud circulation and the creation of a pressure difference between the well and the formation,

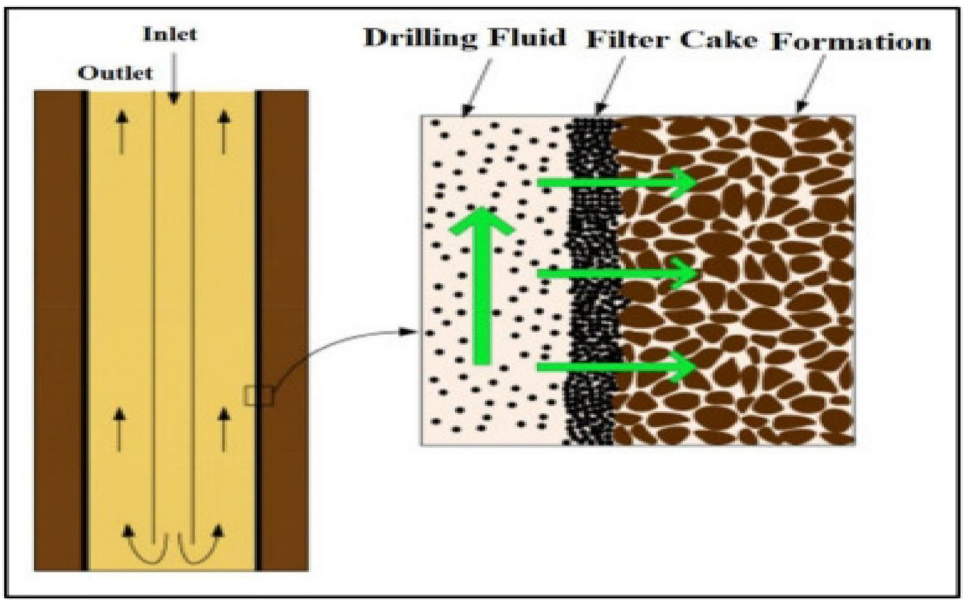


Fig. 1 A schematic diagram of filter cake formation on the well wall [44]

suspended solid particles (such as barite, bentonite, polymers, and additives) in the non-Newtonian drilling mud fluid are trapped in the space between the well wall and the formation, and a compact layer of filter cake is gradually formed. Subsequently, the permeability and filtration rate decrease. This dynamic balance between fluid penetration and particle sedimentation continues until the effective pressure and fluid flow rate stabilize.

The thickness and quality of the filter cake depend on the type and concentration of polymers (such as PAC, PHPA, and CMC), temperature, salinity, acidity and formation characteristics. To prevent any sticking of the pipe inside the well and fluid loss, an ideal filter cake should be thin, cohesive and with low permeability throughout the drilling fluid circulation period. In HPHT conditions and gas-bearing layers, the thermal stability of the fluid and the mechanical characteristics of the layer around the well wall are studied before any injection to prevent any increase in fluid loss and well instability.

First, the main goal of this study was not simply to confirm the superiority of PAC over PHPA and CMC, but rather to develop a generalized regression model to predict the volume of filtrate under real HPHT conditions of gas reservoirs in the Southern Zagros. Such a range of salinity and temperature has not been systematically investigated simultaneously in previous studies.

Second, the innovation of this study was in the use of a two-phase approach (aqueous phase and solid polymer phase) in modeling the water-based mud system, which allows for the simultaneous analysis of the interaction of concentration, pH, temperature, and MW. This approach goes beyond simple experimental comparison of polymer performance and helps to the extraction of quantitative relationships that can support preliminary field design and drilling fluid formulation.

Third, although the number of experiments was 27 runs, the design of the experiments was carried out in such a way that an appropriate statistical coverage of the range of variables was provided. As such, the statistical indices of the model indicated its acceptable predictive power under operational conditions. Moreover, the low model error value indicated the stability of the model.

Fourth, the paper showed that at temperatures below 105 °C and in the presence of high salinity, synergistic polymer interactions can reduce fluid loss by about 50%, which is not just a confirmation of a qualitative trend. In contract, it provides a quantitative framework for prediction and optimization in fractured carbonate reservoirs of the Southern Zagros basin in the Persian Gulf.

Fifth, many previous studies have investigated the performance of polymers under standard API laboratory conditions, while this study modeled the real conditions of deep reservoirs in the gas formations of Southern Zagros. These reservoirs are very challenging in terms of pressure, temperature, and salinity. Therefore, the capability of the developed model to reproduce HPHT conditions representative of southern Zagros gas reservoirs and provide a predictive framework for formulation optimization represents the main distinguishing feature of the present work.

In this study, the term “Two-phase” refers to the physical nature of the system under study; that is, the WBDFs are considered as a system consisting of a liquid phase (brine) and a dispersed polymer phase. In the proposed model, the behavior of this two-phase system is described through an empirical GLM model and not through the solution of mass conservation or multiphase transport equations.

Characteristics of Southern Zagros Reservoir

The valuable idea of the esteemed referee is appreciated. Although the conditions of the South Zagros gas reservoirs were mentioned in different parts of the paper, we agree that the geological and operational characteristics of these reservoirs should be presented more coherently in the Introduction section. Therefore, a new paragraph was added to the Introduction section, which explains the key characteristics of the Kangan and Dalan gas reservoirs of the South Zagros, including the carbonate nature of the formation, the presence of fractures, high pressure and temperature conditions, high salinity of the formation water (100,000–200,000 ppm), and the challenges associated with filtration control and stability of the water-based drilling fluid. This revision makes the connection between the actual reservoir conditions and the necessity of developing the proposed model clearer.

The deep South Zagros gas reservoirs in Iran, especially the Kangan and Dalan formations, are mainly composed of carbonate rocks with medium to low porosity and natural fracture systems. The presence of fractures and heterogeneity of the reservoir rock can increase the penetration of drilling fluid into the formation and reduce filtration control. In addition, the high temperature and salinity conditions in these reservoirs affect the stability of polymers used in water-based drilling fluids and can cause a decrease in viscosity, change the rheological behavior and increase the volume of filtered fluid. Therefore, the design of a suitable WBDF for these environments requires the simultaneous evaluation of the effect of polymer type, polymer molecular characteristics, pH and HPHT conditions. In this study, laboratory ranges were selected based on the conditions reported for the Kangan and Dalan formations to evaluate the performance of PAC, PHPA and CMC polymers in an environment with high salinity (100,000–200,000 ppm) and reservoir temperatures associated with the southern Zagros (85–110 °C).

The Southern Zagros gas basin represents one of the most important gas-producing regions in Iran and contributes significantly to the gas supply from the giant carbonate gas reservoirs. This gaseous basin includes the Kangan and Dalan formations, which are part of the geological system associated with the South Pars gas field, one of the world's largest gas accumulations. In these deep carbonate reservoirs, drilling and production operations are performed under challenging conditions characterized by high formation pressure, deep burial depth, high salinity formation water, and temperature variations typically ranging from approximately 85 to 110 °C depending on reservoir depth and operational conditions.

Although these temperatures may not fall within the extreme HPHT classification used for ultra-high-temperature wells, they represent severe operating conditions for water-based drilling fluids due to the combined effects of high salinity (100,000–200,000 ppm), divalent ions, polymer sensitivity, thermal degradation, and changes in rheological and filtration behavior. In particular, polymer-based filtration control agents may experience significant performance changes even within this temperature range when exposed to high-temperature and high-salinity reservoir conditions such as Southern Zagros deep gas formations.

Objectives, Research Gap and Novelty

The primary objective of this study is to develop a statistically interpretable predictive model for estimating filtrate volume in WBDFs under HPHT and high-salinity conditions representative of the deep gas reservoirs of the Southern Zagros Basin. The model simultaneously evaluates the effects of polymer type, polymer concentration, pH, MW, and operating conditions using a GLM. Rather than developing classical two-phase flow equations, the objective is to statistically represent the behavior of the two-phase WBDF system (continuous aqueous phase and dispersed polymer phase) through experimentally measurable variables that govern filtration performance.

Most previous studies on WBDFs have primarily focused on comparing polymer performance under standard API laboratory conditions or within relatively limited temperature and salinity ranges. Consequently, quantitative predictive models that integrate polymer structural properties with operational variables under realistic HPHT reservoir conditions remain scarce.

The novelty of the present work lies in the development of a GLM-based predictive framework that combines polymer type, MW, pH, and operating variables within a unified statistical model for HPHT drilling fluids. Unlike conventional regression models that treat polymer type solely as a categorical variable, the proposed model incorporates MW as a quantitative physical descriptor of the dispersed polymer phase. This parameter represents an important structural characteristic governing polymer–water interactions, hydration behavior, and filter-cake formation. Consequently, the model captures not only the influence of polymer identity but also the contribution of polymer molecular structure to filtration control. Incorporating MW into the final regression equation also provides a more physically meaningful representation of the indirect influence of temperature on polymer performance, thereby improving the predictive capability of the model under HPHT conditions without introducing unnecessary model complexity. The resulting model therefore offers a practical engineering tool for polymer selection and filtration optimization in high-salinity gas reservoirs while preserving statistical interpretability.

Research Method

To develop formulations and optimize parameters within practical limits, empirical models were used to identify the sensitivity of important factors (polymer concentration, polymer type, pH, temperature), and estimated the empirical relationship between inputs and responses (fluid filtrate). The method in the Minitab provided interpretable outputs (regression equations, optimal levels) for these variables.

The experimental design approach used in this study was a GLM-based multivariable gradient design and was not performed as a full factorial, semi-factorial, or classic RSM (response surface methodology) design. The reason for choosing this method was the multivariable nature of HPHT drilling fluids and the operational constraints of the laboratory. In this study, polymer type was considered as a categorical factor and pH, temperature and polymer concentration were considered as continuous variables.

A 27-run matrix was designed to cover the real operating range of deep gas reservoirs in the Southern Zagros. Three experiments with base fluid without polymer (runs 1, 7 and 28) were also conducted to compare the performance and determine the improvement due to polymer addition. To assess the repeatability, critical boundary conditions were tested several times. The difference between the repeated results was less than ±0.3 mL, indicating a low uncertainty of the filtration measurement.

The DOE matrix was constructed based on a multivariable gradient design within a GLM framework [33, 45]. In this case, the base fluid without any polymer additives was tested under the same salinity and HPHT conditions, which produced a filtration volume of 27–29 mL/30 min. The performance of each of the polymers PAC, PHPA, and CMC has been compared to this reference case.

The Southern Zagros Basin, including the Kangan and Dalan formations, present challenging drilling conditions due to the combined effects of elevated temperature, high salinity formation water, and fractured carbonate structures. Reported reservoir characteristics indicate that formation water salinity in these gas-bearing intervals can reach approximately 100,000–200,000 ppm, while reservoir temperatures are commonly within the range of 85–110 °C. Under such conditions, polymer-based WBDFs may experience reduced hydration efficiency, viscosity degradation, and altered filtration behavior due to thermal effects and interactions with dissolved ions, particularly divalent cations. Therefore, reproducing the actual operational window of Southern Zagros gas reservoirs provides a more realistic framework for evaluating polymer performance and developing predictive models for HPHT drilling fluid optimization.

Instead of altering one parameter at a time, temperature (85–110 °C), polymer concentration (0.5–1.5 g/L), and pH (5.5–7) were varied simultaneously to capture potential interaction effects under high-salinity conditions. The ranges represent realistic operational windows encountered in deep Southern Zagros gas reservoirs. The gradient approach allows evaluation of both linear trends and boundary effects while maintaining a manageable number of 27 runs, thereby ensuring statistical efficiency without compromising coverage of critical conditions.

The structural parameters of MW, degree of substitution (DS), and hydrolysis degree were obtained from supplier technical datasheets: PAC with MW≈0.3 MDa (DS>0.9), PHPA with MW≈8 MDa (20–30% hydrolysis), and CMC with MW≈0.25 MDa. These parameters were applied in the interpretation of filtration behavior and incorporated into the presented regression model.

The formulations of WBDFs were prepared with bentonite (5–10 wt% as the primary viscosifier) in base fluid of deionized water, NaCl adjusted to the target salinity level (100,000–200,000 ppm), and the polymer additive according to the DOE matrix, incorporating three polymers of PAC, PHPA and CMC at concentrations 0.5–1.5 g/L. Experimental design was conducted by a GLM method in Minitab with 27 runs, temperature range representative of southern Zagros HPHT reservoirs (85–110 °C), pH (4–9), and polymer concentration (0.5–1.5 g/L), simulating HPHT conditions of Southern Zagros (salinity fixed at 100,000–200,000 ppm).

Due to the fractured layers in these reservoirs, the porosity was considered 8–12%. The filtrate volume in all runs was less than 15 mL/30 min in HTHP according to API RP 13B-2, but the base fluid without additives (in 3 different runs) produced 27–29 mL of filtrate in this study. In a suitable filtrate volume, polymers (PAC, PHPA, and CMC) should form a low permeability mud cake (0.01 mD). The thermal stability criterion in this study was the filtrate volume, not the permeability of the mud cake.

Filtration tests controlled the guideline of API RP 13B-1/13B-2 [45], measuring filtrate volume at conditions of 100 psi (LTLP) and 500 psi (HTHP) for 30 min, with HPHT tests at 105 °C simulate HPHT conditions of Southern Zagros. Two-phase modeling treated WBDFs as a liquid-liquid two-phase system, where solid phase of polymer (dispersed in WBDFs) interacted with aqueous phase via hydrogen bonding and electrostatic repulsion. This modeling approach carried out using general linear regression in Minitab 17, with categorical factor for polymer type (PAC polymer as reference) and continuous factors of pH and temperature. Stepwise selection (alpha=0.10) and Box-Cox transformation option ($\lambda \approx 0.5$) were utilized for non-linearity. Model residuals were checked for

normality (p-value ≤ 0.007) and for avoiding multicollinearity (VIF ≤ 2.06).

In model, 27 experimental runs designed via a multivariable GLM-based factorial framework covers temperature (85–110 °C), pH (4–9), polymer concentration (0.5–1.5 g/L), and polymer type. The selected salinity range (100,000–200,000 ppm) represents the formation water conditions of reservoirs in Southern Zagros. In this reservoir conditions, high total dissolved solids and bivalent ion concentrations are most important challenges for polymer stability. This ultra-high salinity window was intentionally selected as a criterion to evaluate polymer performance under worst-case downhole conditions rather than moderate laboratory environments. This design enabled simultaneous evaluation of categorical and continuous variables while minimizing experimental redundancy. Each of 27 runs was conducted at least once. Critical boundary conditions were tested in duplicate to assess repeatability. The deviation between repeated measurements remained within ± 0.3 mL and reported filtrate values corresponded to averaged results where repetition was applied.

After incorporating polymer-specific structural parameters, including MW, degree of substitution (DS), and hydrolysis degree, the additional contribution of temperature (temperature as a continuous predictor in the GLM) became statistically insignificant within the investigated limit operating range. Although temperature was included as a DOE factor, polymer molecular characteristics (MW, DS, and hydrolysis degree) were also considered because the thermal response of water-based polymers is strongly related to molecular degradation and chain structure. Physically, temperature affects filtration performance mainly through polymer chain degradation, MW reduction, and changes in hydration behavior. Since the molecular characteristics of PAC, PHPA, and CMC were explicitly considered in the interpretation and modeling framework, part of the temperature-induced variation was captured through polymer-specific parameters.

To further investigate this issue, additional models including temperature interaction terms (Temperature × Polymer) and nonlinear temperature effects were examined. However, these terms did not provide statistically significant improvement in model performance ($p > 0.10$). Moreover, adding temperature to the model complicated the R^2 slightly but made the Predicted R^2 worse and created a collinearity problem. Therefore, temperature was removed from the final regression equation.

Model Validation

To assess the reliability of the developed model and reduce the possibility of overfitting, several statistical and analytical control steps were performed. First, insignificant variables were removed using stepwise regression with a significance level of $\alpha = 0.10$. Accordingly, the temperature factor was removed from the final model due to its statistical insignificance. The collinearity between independent variables was examined using the variance inflation factor (VIF ≤ 2.06), which showed that the remaining variables in the model were not strongly correlated and the model structure had appropriate statistical stability. In addition, Box–Cox transformation, examination of the distribution of residuals, and model error analysis were performed to ensure the appropriateness of the regression structure.

The predictive performance of the model was evaluated using statistical indices including R^2, adjusted R^2, and predicted R^2. The overall R^2 value of the model was 83.24%, the adjusted R^2 value was 81.05%, and the predicted R^2 value was 76.26%. The limited difference between the overall R^2 and the predicted R^2 indicated that there was no significant loss in predictive ability after reducing the number of model variables. This indicates that the final model with fewer effective variables (polymer type, pH, and MW) has a simpler structure and better physical interpretability than the initial model.

In addition to statistical indicators, sensitivity analysis of input variables was performed using matrix plots, main effects plots, plots of filtration volume changes versus temperature and pH, and the average temperature trend at different pH conditions for PAC, PHPA, and CMC polymers. The results of graphical analyses showed that polymer type, pH, and molecular weight are the most important factors controlling filtration behavior. Specifically, the PAC polymer showed the lowest volume of filtered liquid under the HPHT conditions studied, which is consistent with the positive effect of MW, DS, and ability to form a stable hydrated layer on filtration control.

Sensitivity analysis also revealed that the effect of temperature in the tested range (85–110 °C) was weaker than the effect of polymer type and environmental chemical conditions (especially pH). Although increasing temperature can physically reduce viscosity, change polymer hydration behavior, and reduce the stability of the filtration control layer, its independent effect was not statistically significant in the studied temperature range. Therefore, the removal of temperature from the final model is not due to ignoring the thermal effect of polymers, but rather a result of the statistical selection process of variables in the GLM framework.

In order to examine the reproducibility of the experimental data, critical boundary conditions were tested repeatedly. The difference between repeated measurements remained less than ± 0.3 mL, indicating good stability and reproducibility of the laboratory method. Finally, comparison of the predicted model values with experimental results

Table 1 Experimental matrix and filtration response of polymer-based WBDFs under high temperature and salinity conditions for modeling filtrate volume using 27 runs

Filtrate (mL/30min)	pH	T (°C)	Cpolyer (g/L)	Polyer	Run
27	6.5	85	0	Base fluid	1
10	6.5	105	1	PHPA	2
11	6.5	100	1	CMC	3
12	6	90	1.5	CMC	4
11.5	5.5	95	0.5	CMC	5
28	6.5	100	0	Base fluid	7
11	6	100	1	PHPA	6
9.5	7	110	1.2	PAC	8
12	5.5	95	0.8	CMC	9
11	6.5	100	1	CMC	10
10.5	6	90	1.5	PAC	11
9	7	105	1	PAC	12
10	6.5	110	1.2	PHPA	13
11.5	5.5	95	0.8	CMC	14
11	6.5	100	1	CMC	15
10.5	6	105	1.5	PHPA	16
9	6	95	1	PHPA	17
9.5	7	110	1.2	PAC	18
10.5	6.5	105	1.5	PHPA	19
12	5.5	90	0.8	CMC	20
11.7	6.5	100	1	CMC	21
9	7	110	1.5	PAC	22
12.5	5.5	95	0.5	CMC	23
10.5	6	105	1.2	PHPA	24
9.5	7	100	1	PAC	25
11	6.5	100	1	CMC	26
9.5	7	110	1.5	PAC	27
29	6.5	110	0	Base fluid	28
9	6.5	105	1.2	PAC	29
11.5	6	95	0.8	CMC	30

determined that the developed model has an acceptable ability to predict the filtration volume within the range of HPHT and high salinity conditions studied in the Southern Zagros gas formations.

However, since the model was developed based on laboratory data of 27 runs, external validation with larger independent field or laboratory data could be performed in future studies to increase the generalizability of the model.

Discussion and Results

Experimental Matrix

To improve the transparency and reproducibility of the experimental procedure, the complete experimental matrix consisting of all 27 GLM-designed runs is presented in Table 1. Each run specifies the polymer type, polymer concentration, test temperature, pH, and the corresponding filtrate volume measured after 30 min according to API RP 13B-2. The experimental variables were simultaneously varied to investigate both the main effects and possible interactions among polymer type, concentration, temperature, and pH under representative HPHT conditions of the southern Zagros gas reservoirs.

Table 2 Comparison of the performance of water-based and polymer-based fluids in reducing filtration

Scenario	Description	Filtrate (mL/30 min)	Reduction vs. Base (%)
Base mud	WBDF(no polymer)	27–29	0
PAC (optimum)	1.0–1.5 g/L, pH 6–7, 105–110 °C	9.0–9.5	66–69
PHPA (optimum)	1.0–1.5 g/L, pH 6–6.5,95–105 °C	9.0–10.5	62–67
CMC (optimum)	0.8–1.0 g/L, pH 5.5–6.5,90–100 °C	11.0–12.0	57–61

To establish a reference for evaluating polymer performance, a polymer-free WBDF containing bentonite but no polymer additive was considered as the base case. Under identical HTHP filtration conditions, the base fluid produced 27–29 mL of filtrate within 30 min. The effectiveness of PAC, PHPA, and CMC formulations was therefore assessed relative to this baseline condition. The temperature ranges in the base fluid (85, 100 and 105 °C) covers the entire temperature range of the study. These temperature ranges shows that even without polymer, the temperature increment can heighten the filtration.

The analysis was rewritten based on the reference mud to clearly elucidate the filtration reduction process by each polymer. Salinity was maintained within the representative Southern Zagros reservoir range of 100,000-200,000 ppm for all experiments. The polymer-free base fluid yielded 27–29 mL/30 min filtrate under identical HTHP conditions.

According to explanations above, a total of 27 experimental formulations were designed using a multivariable gradient-based experimental approach within the GLM framework. Unlike one-factor-at-a-time experiments, this approach allowed simultaneous evaluation of polymer type, polymer concentration, temperature, and pH effects, including possible interaction effects under high-salinity HPHT conditions. For comparison purposes, three polymer-free WBDF formulations (runs 1, 7, and 28) were considered as base cases. These reference fluids contained the same water phase, bentonite concentration, and salinity conditions but without polymer additives. Table 2 summarizes a comparison between the reference scenario and the 27 implementations, which makes the interpretation of the results more consistent.

In the present study, the main objective was to develop an empirical-statistical model to predict the volume of fluid

filtered under HPHT and high salinity conditions in water-based drilling fluids using polymers.

According to API RP 13B-1/13B-2, filtration volume was chosen as the main operational index to evaluate the filtration that controls performance of polymers, because this parameter is directly used in the design and control of drilling fluids in field operations.

Although direct measurements of mud cake permeability can provide valuable mechanical information, in this study, laboratory measurements of mud cake thickness, microscopic structure, and permeability were not performed for all 27 runs of the experimental design. Therefore, developing an independent model to predict mud cake permeability outside the range of available data could have resulted in unreliable extrapolations.

However, the indirect effect of polymer properties on mud cake behavior is considered in the present model. Parameters such as MW, polymer type (PAC, PHPA, and CMC), pH, and polymer concentration affect the ability to form a hydrated layer, polymer adsorption on clay particles, reducing fluid flow paths, and thus reducing filtration volume. Therefore, the decrease in filtration volume observed in the developed model indicates the formation of a mud cake with a denser structure and higher hydraulic resistance, although the permeability of the mud cake was not directly measured.

The PAC polymer's efficacy in 27-run dataset was revealed in low pH values (4–6) and higher temperature (< 105 °C), reducing filtrate volume to 8–10 mL/30 min at 1.0–1.2 g/L polymer concentrations. This volume was 60% lower than it in WBDFs (27–29 mL) with 150,000 ppm in the reservoir layers of Southern Zagros. In PHPA, the values of pH (6.5–7.0) was higher, the temperature range was similar (85–105 °C), and the filtrate volume was obtained 9–11 mL at 0.5–1.0 g/L polymer concentrations. CMC polymer had better performance in acidic pH (5.5–6.5) and lower temperature (< 90 °C), reducing filtrate volume to 10–12 mL at 0.8–1.5 g/L polymer concentrations, with a less efficacy than PAC and PHPA polymers (up to 20–30% at high temperatures). In the following subsections, the three equations are introduced in order: base filtrate regression equation, expanded filtrate regression equation, and the simplified form of expanded filtrate regression equation.

Table 3 Base regression model of filtrate (V) under HPHT conditions of gas reservoirs (T = 85–110 °C, salinity = 100,000–200,000 ppm, and pH = 5.5–7)

Polymer type	Prediction equation
PAC	Filtrate, mL = $(3.809 - 0.1084 \times pH)^2$
PHPA	Filtrate, mL = $(3.909 - 0.1084 \times pH)^2$
CMC	Filtrate, mL = $(4.050–0.1084 \times pH)^2$
PAC, PHPA, CMC	V, mL = $(3.909–0.1084\ pH + 0.1403\ I(CMC) - 0.0995\ I(PAC) - 0.0409\ I(PHPA))^2$
	Analysis of Variance for Transformed Response
	Source DF Adj SS Adj MS F-Value P-Value
	pH 1 0.04583 0.045829 8.88 0.007
	Polymer type 2 0.20352 0.101758 19.71 0.000
	Error 23 0.11876 0.005164
	Lack-of-fit 15 0.09367 0.006244 1.99 0.164
	Pure error 8 0.02510 0.003137
	Total 26 0.70845
	Coefficients for Transformed Response
	Term Coef SE Coef T-Value P-Value VIF
	Constant 3.909 0.231 16.90 0.000
	pH -0.1084 0.0364 -2.98 0.007 1.83
	Polymer type
	CMC 0.1403 0.0224 6.27 0.000 1.75
	PAC -0.0995 0.0266 -3.73 0.001 2.06
	S R-sq R-sq(adj) R-sq(pred)
	0.0718581 83.24% 81.05% 76.26%

Basic Filtrate Regression Equation

In the HPHT conditions of Southern Zagros reservoirs (85–105 °C), temperature alterations are not significantly different from pH alteration (4–9). Therefore, when the polymer and pH are optimal, only the pH variable is observed in the model response due to the almost similar effect of temperature on filtrate reduction and even less than pH. For this reason, the resulting regression equation for all three types of polymers PAC, PHPA and CMC in the very complex HPHT conditions at depths above 3000 m was obtained as a function of pH only. Moreover, due to the correlation of temperature with pH at higher values (in HPHT reservoir conditions), one of the parameters in the model may appear redundant. In the two polymers PAC and CMC with different pH values in Table 3, it is observed that the PAC polymer performs better at high temperature (T < 95 °C with pH < 6) than the CMC polymer (T < 90 °C). In the limited temperature range (85–110 °C) and in the presence of high NaCl, bentonite, alkaline conditions and stable polymers, the independent effect of temperature after considering the type of polymer and pH was not statistically significant. That is, temperature has an effect, but its effect shows itself through changing the behavior of the polymer, changing the ionization of active groups, and changing the polymer-clay interaction. Therefore, this behavior of temperature with other variables changes the structure of the equations.

In the present study, salinity was not entered into the model as an experimental design variable, but was applied as a fixed boundary condition in all experiments. The reason for choosing this approach was that the main objective of this study was to investigate and model the effect of polymer type, pH, polymer concentration, and polymer structural feature (molecular weight) on filtration control in the harsh conditions of the Southern Zagros gas reservoirs. The salinity range of 100,000–200,000 ppm was selected based on the conditions reported for the Kangan and Dalan formations in the southern Zagros and was considered as

a high-salinity environment to evaluate the performance of polymers in conditions close to the reality of the reservoir. Therefore, salinity was considered as a controlled factor in this study to eliminate side effects and focus on the response of polymers under a fixed critical condition.

The adjusted R-square obtained from two-phase regression model was 81.05% (p-value≤0.007). The model coefficients were: β pH = −0.1084, indicating 1.3–1.5 mL reduction in filtrate volume per unit pH increase. This value was optimal at pH values of 6.5–7.0, (PHPA is reference). According to Table 3, compared to PHPA, the PAC polymer reduced filtrate by 0.0995 (up to 0.8–1.0 mL lower filtrate volume), while CMC type increased filtrate by 0.1403 (with higher filtrate volume of 1.1–1.3 mL). Temperature factor (85–110 °C), due to non-significant effect ($p>0.10$), was excluded from the model by Stepwise selection (α=0.10), although three polymer (PAC, CMC) above 95 °C had weak performance. This confirmed that pH and polymer type can control fluid filtrate under HPHT conditions in Southern Zagros reservoirs.

Therefore, base regression equation of filtrate (mL) is as Eq. (1):

$$V = [3.909 - 0.1084\,pH + 0.1403\,I(CMC) - 0.0995\,I(PAC) - 0.0409\,I(PHPA)]^2 \quad (1)$$

The value obtained for R-square=83.24% indicates that more than 83% of the filtrate variation is explained by pH and polymer type (PAC, PHPA, CMC), and the model has high accuracy (error=0.0719). Under HTHP conditions (500 psi, 85–110 °C) considered for the model, PAC reduces the filtrate to less than 9.3 ml/30 min in this range (see an example in Table 4). The predicted filtrate range (9.3–10.8 mL) falls within the operationally relevant filtration range reported for HPHT gas reservoir drilling fluids.

Table 5 presents an example of the model response. If pH=6.5, then according to equation, the filtrate in polymers PAC, PHPA and CMC are 9.63, 20.26 and 11.18, respectively. PAC is optimal to the filtration control in pH=6.5.The controlled filtrate volume for polymers, depending on pH, may change.

Note: The insignificant statistical contribution of temperature in the final model does not indicate that temperature has no effect on polymer performance. Instead, within the investigated HPHT range (85–110 °C), temperature-induced changes were strongly associated with polymer chemistry and molecular characteristics. High MW polymers such as PHPA exhibited better filtration control at elevated temperatures due to their higher chain length, whereas PAC performance was governed mainly by hydration capacity and substitution degree.

Table 4 Interpretation of the model response obtained for filtrate

Criterion	Explanation
R-sq(adj)=81.05%	The model can explain more than 81% of the filtrate variation perfectly with the pH and polymer type data.
R-sq(pred)=76.26%	With 76% the model can be used accurately for the field data.
VIF<2.06	The model coefficients are reliable due to no multicollinearity.
p-value<0.007	All effects are highly significant.
S=0.0719	The prediction error of filtrate is very low.
Box-Cox (λ=0.5)	Transformation of √Filtrate ensures normality of errors.
Regression equation derived	V = (3.909–0.1084 pH + 0.1403 I(CMC) - 0.0995 I(PAC) - 0.0409 I(PHPA))^2. The variable of I, dummy or indicator variable, transfers categorical variable to numerical model.

Table 5 Typical example of model in pH=6.5 to the filtrate estimation

Polymer type	I(CMC)	I(PAC)	(√Filtrate)	Filtrate (mL)
PHPA (Reference)	0	0	3.909−0.1084×6.5=3.2034	(3.2034)² = 10.26
PAC	0	1	3.2034−0.0995=3.1039	(3.1039)² = 9.63
CMC	1	0	3.2034+0.1403=3.3437	(3.3437)² = 11.18

Basic filtrate regression equation (PHPA as the reference category): V = [3.909−0.1084 × pH+0.1403 × I(CMC)−0.0995 × I(PAC)]²

In the calculations, the MW variable was centered on its mean value (2.85 MDa) to reduce numerical instability and multicollinearity during regression analysis.

Although MW and polymer type are related, they represent different physical effects. Polymer type accounts for chemical functionality (e.g., charge density, substitution degree, and hydration mechanism), while MW represents chain-length effects influencing filtration behavior. Because temperature effects in HPHT polymer systems are mainly associated with molecular degradation and viscosity loss, MW was incorporated into the final model to capture polymer-chain-related thermal effects.

Developed Filtrate Regression Equation

To investigate the effect of polymer MW as a factor in reducing filtrate in the derived basic filtrate regression equation above, the MW of each polymer in terms of MDa was added to the data. The average MW of the polymers PAC, PHPA and CMC were 300,000, 8,000,000 and 250,000 Dalton respectively, with an estimated average of 2,850,000 (2.85MDa). Then MWcentered = MWpolymer -MWave was added to the model predictors (in terms of MDa). The regression model was run again in the software using the

same GLM method. The coefficient βMW = - 0.012×106 Da^{-1} was extracted from the model to make the effect of million Daltons (MDa) as the true range of polymers meaningful. The negative effect of the coefficient indicates a decrease in filtrate (model response) with increasing polymer MW, where longer chains play a greater role in increasing viscosity, and forming a larger network to trap other particles added to the drilling fluid. The expanded filtrate regression equation is obtained according to Eq. (2):

$$V = [3.909 - 0.1084 \times pH + 0.1403 \times I(CMC) - 0.0995 \times I(PAC) - 0.012 \times 10^{6} Da^{?1} MW_{centered}]^2 \quad (2)$$

The units of $MW_{centered}$ and V are MDa and mL, respectively. After simplifying coefficients, the expanded filtrate regression equation is written as Eq. (3)**:**

$$V = [4 - 0.1pH - 0.1(PAC) + 0.14(CMC) - 0.012(MW - 2.85)]^2 \quad (3)$$

The unit of MW is MDa. PAC polymer performed well in controlling filtrate due to the strong dummy effect (-0.0995) obtained from the model. Although PHPA polymer had a weak dummy effect, it compensated for this by having a higher MW to trap finer particles of the fluid by forming a network, and so that its filtrate at the same pH did not differ much from that of PAC polymer (Table 6).

The relationship between structural parameters of polymers, including MW, degree of substitution (DS), degree of hydrolysis, and filtration control mechanisms, including polymer adsorption, hydration layer formation, mud cake permeability reduction, and polymer-mineral interaction, is of great importance. For this purpose, in addition to the type of polymer as a categorical variable, the MW of the polymers was also entered as a quantitative parameter in the final model. This model's development and modification approach implicates not only based on the names of the polymers, but also consider the effect of the polymer's structural characteristics on the filtration behavior. The negative coefficient related to MW in the final equation of the model shows that the increase in MW of the polymer, within the investigated temperature range, causes a decrease in the volume of the filtered liquid. This behavior is physically consistent with the increased ability of higher MW polymer chains to create polymer bridging, increasing particle surface coverage, and reducing flow paths (permeability reduction) in the mud cake.

Moreover, the chemical effects of polymers were included in the interpretation of the results:

- • PAC with MW of about 0.3 MDa and DS higher than 0.9, due to active carboxylate groups, has a high ability to hydrate and create a hydrophilic protective layer around bentonite particles. This hydrated layer reduces free water migration and reduces filtrate in HPHT conditions.
- • PHPA with a MW of about 8 MDa and a degree of hydrolysis of 20–30%, due to its very long chain, has a high ability to create bridging, but its greater sensitivity to divalent ions at high salinity can cause a decrease in surface adsorption efficiency and performance loss.
- • CMC with a MW of about 0.25 MDa, although it has hydrophilic groups, has a limited ability to form a stable polymer network under high temperature and salinity conditions due to its lower MW and chain stability.

Although mud cake permeability was not directly measured in this study, the decrease in filtrate observed in the HTHP experiments indicates the formation of a mud cake structure with more restricted flow paths. Therefore, the presented model is not a completely empirical model without a physical basis, but a mechanistically informed empirical model that relates the effective chemical parameters of the polymer to the macroscopic filtration response.

Therefore, temperature was initially entered as an independent variable, but was removed in the stepwise selection process due to relative collinearity with some interactions and reduced statistical significance at the 95% confidence level. While temperature exhibited a positive trend on filtrate volume (approximately 0.3–0.5 mL increase per 10 °C), its statistical contribution was less compared to pH within the evaluated range. Therefore, temperature was excluded from the final reduced model without implying physical insignificance. The results of both cases (with and without temperature) were reported and indicators such as VIF, residual plots, normality, independence, and homogeneity of variance tests were presented in the research. Confidence

Table 6 A example to the expanded filtrate regression equation of polymers at pH = 6.5

Polymer type	MW (MDa)	$MW_{centered}$ (MDa)	Dummy effect (relative to PHPA)	(√Filtrate)	Filtrate (mL)
PHPA (Reference)	8	5.15	0	3.909 − 0.1084 × 6.5–0.012 × 5.15 = 3.1416	9.87
PAC	0.3	2.55	0.0995	3.909 − 0.1084 × 6.5 -0.0995 × 1- 0.012 × 0.3 = 3.1345	9.82 (best)
CMC	0.25	2.6	0.1403	3.909 − 0.1084 × 6.5 + 0.1403 × 1- 0.012 × 2.6 = = 3.3749	11.39

$V = [3.909 - 0.1084 \times pH + 0.1403 \times I(CMC) - 0.0995 \times I(PAC) - 0.012 \times 10^{6}\ Da^{-1}\ MW_{centered}]^2$; $MW_{centered} = MW_{polymer} - MW_{ave}$

intervals for model coefficients and interaction effects have been also mentioned in the statistical data.

For assessing model adequacy, multiple statistical solutions were applied. The adjusted R^2 (81.05%) and predicted R^2 (76.26%) indicated acceptable internal predictive capability. Variance inflation factors (VIF ≤ 2.06) confirmed absence of severe multicollinearity in the model. The non-significant lack-of-fit test ($p = 0.164$) demonstrated an appropriate model structure. Although temperature was initially included in the input data, stepwise selection ($\alpha = 0.10$) identified pH and polymer type as statistically dominant factors within the studied range.

PAC polymer with a degree of substitution (DS) higher than 0.9 due to the increase in carboxymethyl groups showed greater hydrophilicity and ionic stability at high salinities and led to a decrease in filtrate volume to about 9–9.5 ml at 110 °C, while CMC with a lower DS had a poorer performance (up to 12.5 ml). Likewise, PHPA polymer with a degree of hydrolysis of 20–30%, due to the increase in negative chain charge and the creation of a viscoelastic structure, was able to limit the filtrate volume to about 10–10.5 ml under HPHT conditions. In the developed regression model, the effect of MW and chemical structure was reflected as a quantitative negative coefficient ($\beta MW < 0$), indicating that increasing chain length and ionic charge density improved cake formation and reduced permeability. In terms of field application, the predicted range of the model (about 8.5–11.5 ml) is consistent with filtration levels generally targeted for carbonate gas reservoir drilling operations under HPHT conditions.

Overall Behavior of Variables Versus Filtrate in Model

The figures were used to display the comparative trends and the overall behavior of the variables within the GLM framework. Since the final model was calibrated based on the entire dataset and its validity was assessed through statistical indices such as r-square, lack-of-fit test and VIF values, the data dispersion is implicitly reflected in the model structure of filtration and the standard error of the estimate. Moreover, for critical conditions, the runs were performed in duplicate and the deviation of measurements was within the acceptable laboratory range (about ± 0.3 mL), which indicates the stability of the data and good reproducibility of the results. Since the amount of dispersion was insignificant as compared to the total variation range (8.5 to 12.5 mL), the research focused on clarifying the statistical method and explaining the criteria for model adequacy. Thus, the statistical accuracy of the filtration results as the model response is reported through modeling indices and the graphical coherence of the figures is also maintained.

The general regression model with √filtrate transformation ($\lambda = 0.5$) and adjusted R-square = 81.05% proved the main controlling factors of filtrate (pH and polymer type). To further analyze the two-phase filtration behavior and simulate the fluid flow through the mud cake (thin layer formed on the well wall by mud filtration), matrix, 3D surface, empirical CFD and trend analysis plots were used to model the fluid behavior under HTHP reservoir conditions of Southern Zagros. These plots visually and quantitatively analyze the relationship between the input variables and the response variable (filtrate) for 27 laboratory runs.

Figure 2 illustrates an overview of the pairwise relationships between input variables and filtrate (mL) to identify correlation patterns. In this graph, the horizontal axis shows polymer concentration (0.5–1.5 g/L), temperature (85–110 °C), and pH (4–9) for data points from 27 scattered laboratory runs. Increasing polymer concentration (particularly PAC at 1.0 g/L) reduces filtrate from 12 to 8 mL/30 min (about 33%), which is consistent with the HTHP API standard (less than 25 mL) according to the research text. At the same time, higher pH values (6.5–7.0) are negatively correlated with filtrate reduction, indicating that each unit increase in pH can reduce filtrate by about 1.3–1.5 mL. The effect of this correlation has been observed at salinity conditions of 100,000 to 200,000 ppm in reservoirs of Southern Zagros. Temperature (85–110 °C) alone has a limited effect on filtrate, but when combined with polymer concentration, it can synergistically reduce filtrate by up to 15% at 105 °C. Moreover, in the scatter of the data in this filtrate matrix plot, where runs are usually associated with the lowest polymer concentration (0.5 g/L) and the maximum filtrate volume, the importance of additives in controlling lost circulation advances with increasing polymer concentration. This percentage was supported by the general regression model with an adjusted R-square of 81.05. Controlling the filtrate to less than 12 mL/30 min is one of the main objectives in this research. Figure 2 is useful for optimizing the WBDFs under HPHT conditions of the Southern Zagros reservoirs. Finally, the matrix plot of filtrate in Fig. 2 exhibits that the polymer concentration of 1 g/L and pH of 6.5 at a reservoir temperature of above 90 °C is the optimal combination for controlling the less filtrate (8–9 mL).

Figure 3 illustrates the variation of filtrate volume with temperature for PAC, PHPA, and CMC polymers under HTHP conditions (500 psi and 30 min filtration time). This figure was used to evaluate the thermal response of the polymer systems within the investigated temperature range of 85–110 °C. The results indicate that all polymer systems maintained acceptable filtration control; however, the magnitude of temperature sensitivity was different depending on polymer structure and chemical characteristics.

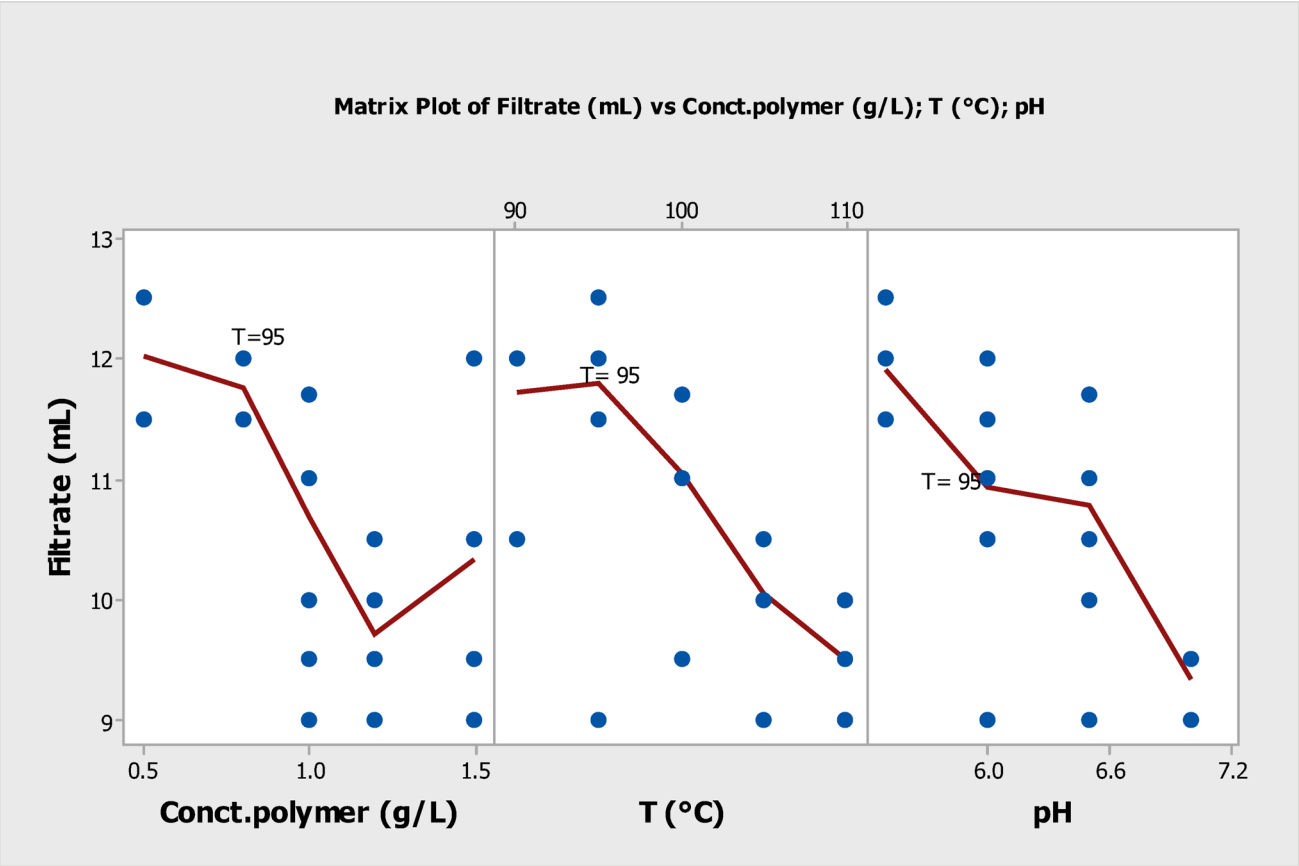


Fig. 2 The matrix relationships between the experimental input variables (polymer concentration, temperature, and pH) and filtrate volume obtained from the 27 HTHP laboratory runs

For the PAC system, the filtrate volume remained relatively stable with increasing temperature. The filtrate increased from approximately 8.5 mL at 85 °C to about 9.0–9.5 mL at 110 °C, corresponding to a limited increase of nearly 5–10%. This relatively low sensitivity indicates that PAC preserved its filtration-control capability at elevated temperatures within the studied range. The stable behavior of PAC can be attributed to its anionic cellulose backbone and high DS (> 0.9), which improves polymer hydration and maintains an effective filtration barrier under high-salinity conditions.

The PHPA system showed an intermediate temperature response, with filtrate values increasing from approximately 9.0 mL at 85 °C to 10–10.5 mL at 110 °C. The observed increase of about 10–15% suggests a higher sensitivity to thermal effects compared with PAC. Nevertheless, PHPA maintained satisfactory filtration performance due to its high molecular weight (≈8 MDa) and partial hydrolysis degree (20–30%), which contribute to polymer chain extension and viscosity retention under saline conditions.

In contrast, CMC exhibited the highest sensitivity to temperature variation among the investigated polymers. The filtrate volume increased from approximately 10 mL at 85 °C to 11.5–12 mL at temperatures approaching 100–110 °C. This behavior indicates a reduction in filtration-control efficiency at higher temperatures, which may be related to lower thermal resistance of the CMC molecular structure compared with PAC and PHPA.

Overall, Fig. 3 demonstrates that although temperature affects polymer performance through thermal degradation and changes in polymer hydration behavior, PAC provides the most stable filtration response over the investigated temperature range. The limited variation caused by temperature compared with the stronger influence of polymer chemistry and solution conditions explains why temperature showed a lower statistical contribution in the final GLM model.

These findings may provide useful guidance for preliminary optimization of water-based fluids in HPHT carbonate gas reservoirs with similar temperature and salinity conditions. For example, in the South Pars field in the Southern Zagros sedimentary basin, where drilling fluid loss increases by about 15–20% with increasing temperature. However, at temperatures up to 90 °C, choosing polymer PAC with a concentration of 1.0 g/L (with pH < 6) can keep the filtrate volume below 9 mL.

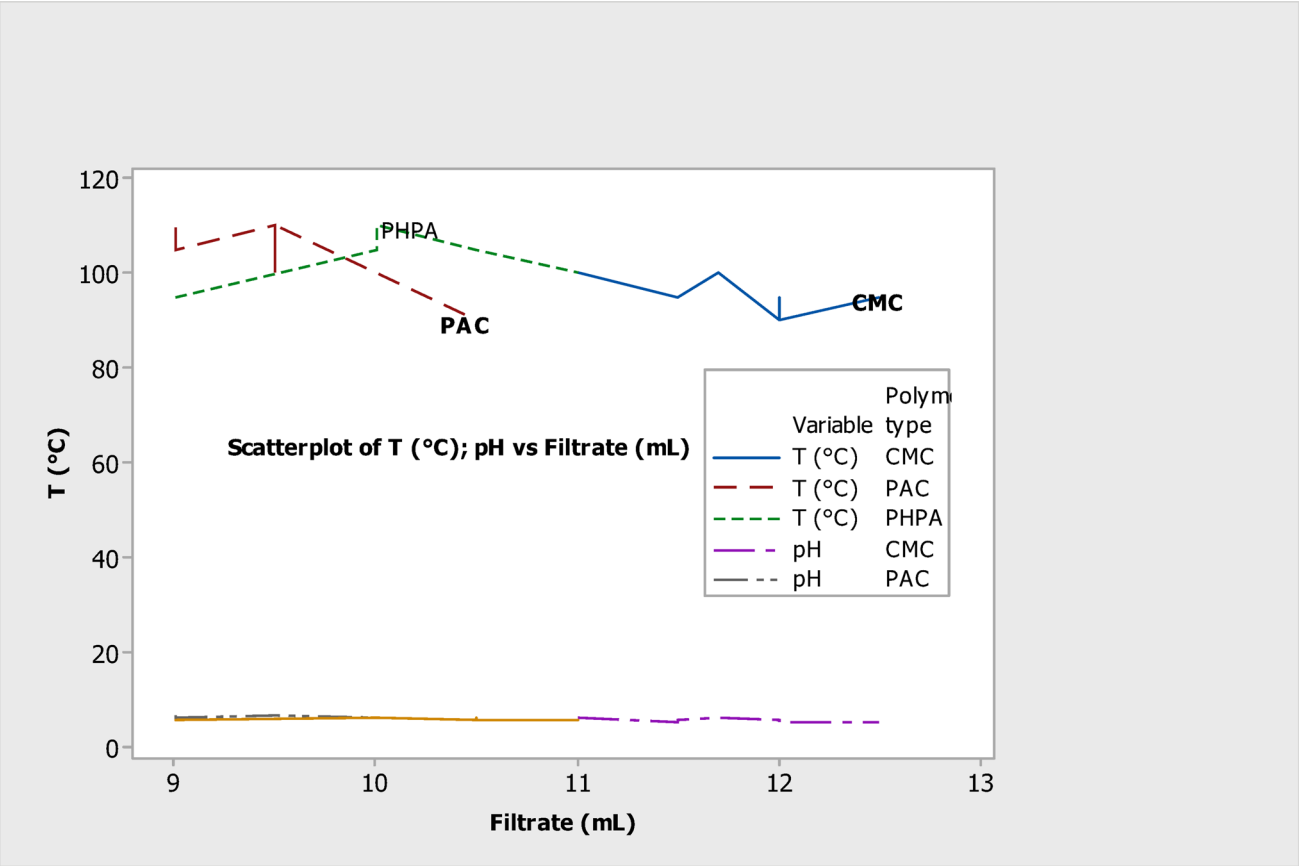


Fig. 3 Matrix plot showing the relationships between input variables and filtrate volume

The empirical CFD plot in Minitab is a numerical CFD alternative that simulates two-phase (liquid-polymer) behavior with a 3D surface. This empirical CFD simulation predicts the two-phase filtration behavior based on trend analysis of 27 laboratory runs. Figure 4 illustrates the trend of filtration change with increasing temperature, the operating range of PAC, and the effect of PAC in reducing the temperature effect. Figure 4 exhibits an empirical CFD plot of the predicted trend based on the GLM regression model in Minitab. PAC polymer tolerates the temperature increases better due to its molecular structure and high DS, and the increase in filtration remains limited.

The response trend shows that PAC maintains relatively stable filtration control when temperature increases from 85 to 110 °C. The predicted filtrate volume increases only slightly from approximately 8.0–8.5 mL/30 min at lower temperatures to about 9.0–9.5 mL/30 min at the upper temperature limit. This limited variation indicates that PAC has higher thermal tolerance compared with the other investigated polymers under the studied high-salinity conditions.

The relatively low sensitivity of PAC performance to temperature variation can be attributed to its chemical structure, particularly the presence of anionic carboxymethyl groups and a high DS. In addition, the molecular weight of PAC incorporated into the developed regression model represents an important structural factor affecting polymer efficiency by influencing chain interaction and filter cake development.

Although temperature is physically known to affect polymer stability and fluid viscosity, the statistical analysis of the present dataset showed that its effect within the investigated range (85–110 °C) was less significant than polymer type and pH. Therefore, temperature was not retained as an independent term in the final GLM equation after stepwise selection. However, the response trend shown in Fig. 4 confirms that temperature variation still influences filtration behavior, but this effect is moderated when an appropriate polymer system, such as PAC, is applied.

The predicted response obtained from the GLM model indicates that PAC provides a stable filtration performance under HPHT conditions representative of Southern Zagros gas reservoirs. The results demonstrate that combining polymer characteristics, including polymer type and molecular weight, with operational parameters such as pH provides a more reliable approach for predicting filtration behavior than considering temperature alone. Empirical CFD model with adjusted R-square = 81.05% confirms that PAC

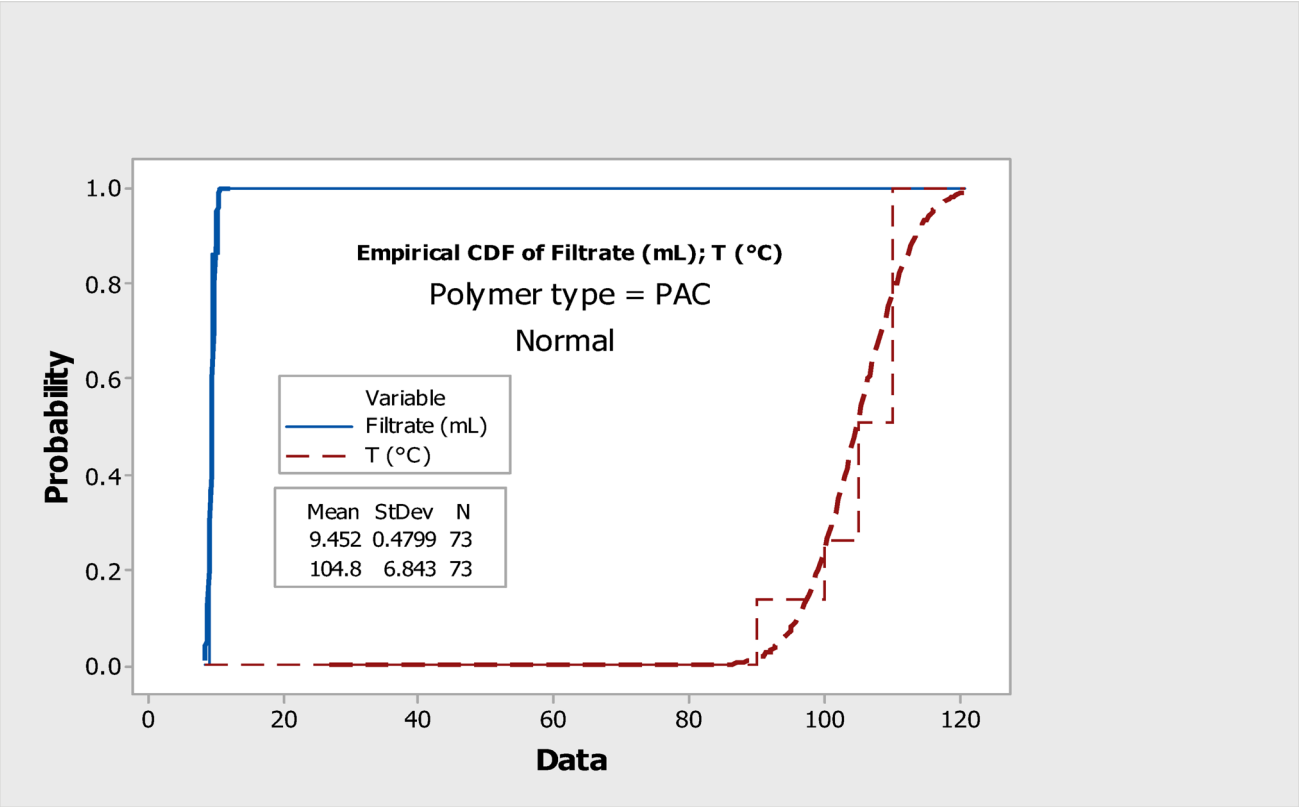


Fig. 4 Response trend of filtrate volume versus temperature for PAC polymer obtained from the GLM-based regression model

polymer forms a mud cake with a low permeability (0.01 mD), and controls invasion of Darcy flow.

Within the experimental dataset, an approximate increase of 0.3–0.5 mL in filtrate volume per 10 °C temperature increase was observed in some formulations; however, this trend was not included as an independent predictive relationship in the final regression model.

However, this temperature effect represents an experimental trend rather than an independent predictive factor in the final GLM equation, because temperature was statistically insignificant after stepwise regression ($p > 0.10$). Among the investigated polymers, PAC exhibited the lowest slope of filtrate increase with temperature, indicating better thermal stability and stronger filtration control compared with PHPA and CMC. This stabilizing effect was more pronounced at temperatures below 100 °C and acidic conditions (pH < 6), where PAC maintained a more effective hydrated polymer layer and lower filtrate volume.

Figure 5 presents the main effects plot of polymer type and temperature on the average filtrate volume obtained from the 27 experimental runs. This analysis was performed to evaluate the independent contribution of each factor to filtration control and to identify the dominant variables affecting the response behavior.

The results demonstrate that polymer type is the dominant factor controlling filtrate volume. Among the investigated polymers, PAC exhibited the lowest average filtrate volume of approximately 8.5 mL/30 min, followed by PHPA with an average value of about 9.7 mL/30 min, whereas CMC showed the highest filtrate volume of approximately 11 mL/30 min. Therefore, PAC improved filtration control by approximately 10–15% compared with PHPA and 20–25% compared with CMC under the investigated conditions.

The superior performance of PAC can be related to its molecular characteristics, including its relatively stable cellulose backbone, with high DS. In contrast, the lower filtration-control efficiency of CMC at elevated temperatures may be associated with reduced structural stability of its polymer chains, while PHPA maintained intermediate performance due to its high molecular weight and partial hydrolysis characteristics.

The temperature main effect indicates that increasing temperature from 85 to 110 °C resulted in a relatively small increase in average filtrate volume compared with the effect of polymer type. This observation suggests that, within the investigated temperature window, polymer selection has a stronger influence on filtration behavior than temperature variation alone. The statistical model also confirmed the

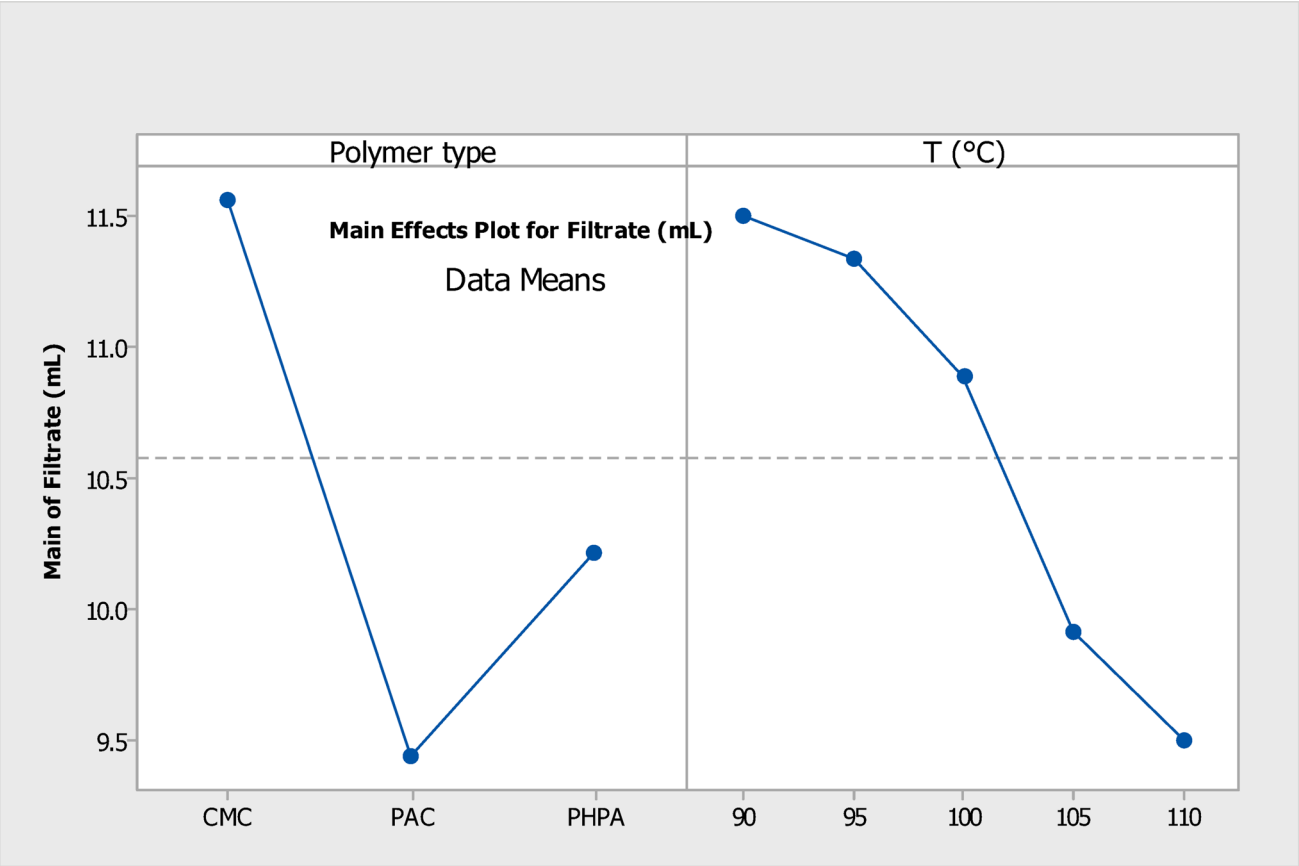


Fig. 5 Main effects plot of polymer type and temperature on filtrate volume

dominant role of polymer identity in controlling filtration response.

Overall, Fig. 5 highlights that selecting an appropriate polymer system is the primary strategy for improving filtration control in HPHT water-based drilling fluids. The results support the incorporation of polymer characteristics, including polymer type and molecular weight, into the developed predictive model for estimating filtrate behavior under high-temperature and high-salinity conditions.

Figure 6 presents the matrix plot of filtrate volume against the main experimental variables, including temperature, polymer concentration, and pH, for PAC, PHPA, and CMC systems. The results show that polymer concentration and pH have stronger relationships with filtration control compared with temperature variation. Increasing polymer concentration within the investigated range (0.5–1.5 g/L) generally reduced filtrate volume, while suitable pH conditions improved polymer efficiency. The scatter distribution also confirms the superior filtration performance of PAC compared with PHPA and CMC under comparable operating conditions. In other words, where the runs are accompanied by very low polymer concentrations (runs 1, 7 and 28 with high filtrates) the points appear as outliers, indicating the importance of polymers in controlling the fluid loss.

Although temperature influences polymer behavior, the matrix plot indicates that its effect is less pronounced within the studied range of 85–110 °C. This observation is consistent with the GLM results, where polymer type, pH, and MW were identified as the dominant factors affecting filtrate prediction. Overall, Fig. 6 supports the statistical interpretation of the developed model by illustrating the combined effects of operational and polymer-related parameters on filtration behavior under high-salinity HPHT conditions.

Figure 7 illustrates the variation of mean filtrate volume for PAC, PHPA, and CMC polymers. In Fig. 7, the horizontal axis represents the polymer type, while the vertical axis represents temperature (0–120 °C). The individual lines correspond to different pH conditions (5.5–7.0) and illustrate the temperature-dependent behavior of PAC, PHPA, and CMC polymers within the investigated HPHT range (85–110 °C).

This analysis was performed to evaluate the influence of the chemical environment on polymer performance and to support the pH effect identified in the developed GLM regression model.

The results indicate that pH has a significant influence on filtration behavior, particularly through its interaction with polymer structure and hydration characteristics. For PAC,

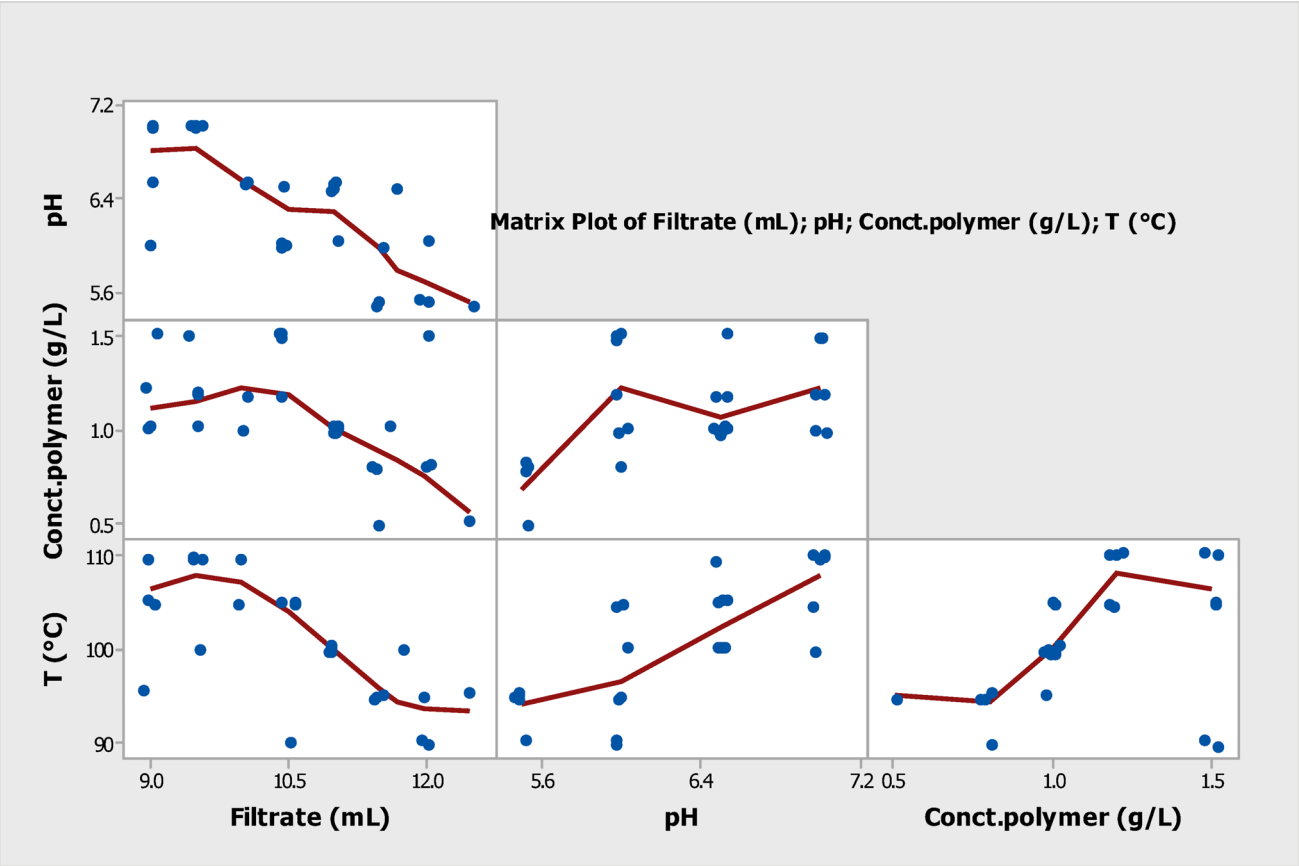


Fig. 6 Matrix plot of filtrate volume versus experimental variables for PAC, PHPA, and CMC

the lowest filtrate volume was obtained in the slightly acidic to neutral range (approximately pH 6–7), where the polymer maintained stable filtration control with an average filtrate volume of about 8.5 mL/30 min, due to a high DS.

PHPA showed stable performance over a wider pH range (approximately 6–7), with an average filtrate volume of about 9–10 mL/30 min. Its filtration-control behavior can be associated with its high molecular weight and partial hydrolysis degree (20–30%), which contribute to polymer chain extension and improved interaction with the aqueous phase. However, its performance becomes more sensitive at lower pH conditions due to changes in polymer ionization and chain behavior.

The PAC polymer exhibits stable performance over a wide pH range (6–7), particularly at pH values around 6 or lower. This behavior is likely attributed to the presence of anionic groups in its structure, which enhance polymer–water interactions and contribute to the lowest mean filtrate volume (8.5 mL) predicted by the developed model. The filtrate volume obtained with PAC is approximately 20–25% lower than that of CMC (11 mL) and 10–15% lower than that of PHPA (9.7 mL).

The pH trend for PAC shows a relatively gentle slope, indicating a limited change in filtration behavior with pH variation. An increase in pH from 6.5 to 7 results in a reduction of filtrate volume by approximately 1.3–1.5 mL, which is consistent with the coefficient obtained from the regression model ($\beta pH = -0.1084$). As discussed previously, higher pH values (6.5–7.0) are associated with improved filtration control.

Overall, PHPA demonstrates effective filtration control within the pH range of 5.5–7.0. According to the graph, its optimum performance occurs between pH 6 and 6.5; however, at pH values below 6, its filtration-control efficiency decreases by up to 10%, possibly due to reduced hydrolysis behavior compared with PAC.

CMC shows the highest sensitivity to pH variation, which may be related to polymer flocculation under acidic conditions. It performs relatively well within the pH range of 5.5–6.5 (particularly 5.5–6), especially at lower temperatures compared with the other two polymers. However, within this range, its filtration-control performance remains lower than PAC by approximately 20%.

In general, Fig. 7 highlights the average effect of pH on polymer performance and indicates that a pH value around 6.5 provides suitable filtration control for the investigated polymer systems. This observation is consistent with the chemical conditions reported for the Southern Zagros

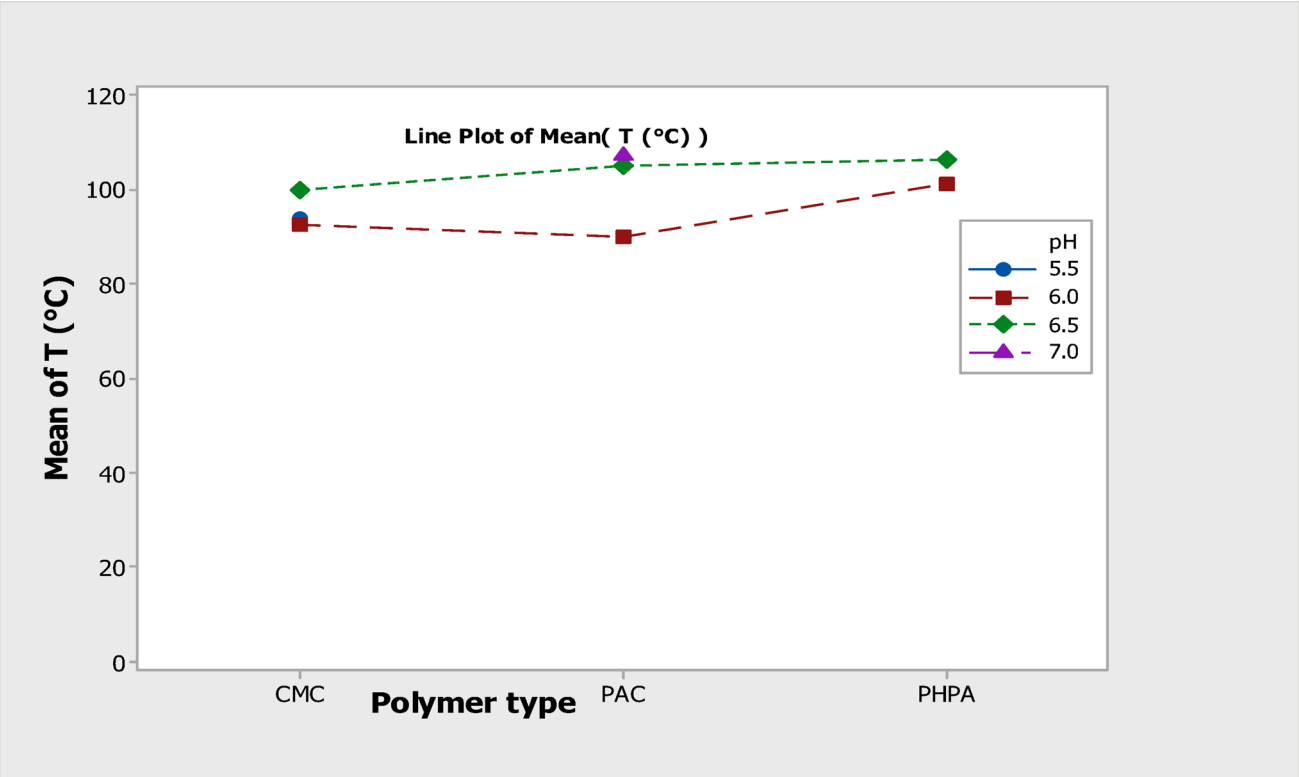


Fig. 7 Effect of pH on the filtrate volume of PAC, PHPA, and CMC polymers under HTHP conditions

sedimentary basin in Iran, particularly the Dalan and Kangan gas reservoirs, where the pH range is approximately 5.5–7.0.

The observed pH-dependent behavior is consistent with the developed regression model, in which pH was identified as one of the significant parameters controlling filtrate prediction. The negative coefficient of pH in the model confirms that appropriate adjustment of the chemical environment improves filtration control. Therefore, Fig. 7 demonstrates that optimizing pH together with polymer selection and molecular weight is essential for designing WBDF systems suitable for HPHT and high-salinity gas reservoirs.

In Figs. 2, 3, 4, 5, 6 and 7 above, Fig. 2 was utilized to show the pairwise relationships between input variables and filtration volume and to identify general trends in the experimental data. Figure 3 was used solely to examine the behavior of filtration changes with temperature for the three polymers. Figure 4, Empirical CFD, was presented as an empirical trend analysis based on the GLM model. Figure 5 was applied to show the main effects of polymer type and temperature, as it directly illustrates the relative importance of the model factors. Figures 6 and 7 were also presented to provide only supplementary information on the interaction effects of variables and pH–polymer behavior.

The quantitative sensitivity analysis between MW and filtrate and the physical relationship between polymer chain length and cake permeability reduction were highlighted in Eqs. 2 and 3. Likewise, Table 7 presents the quantitative effect coefficients of MW and other parameters.

Table 7 Summary of statistical–physical interpretation of polymers

Variable	Statistical data	Physical effect
pH	$p<0.001$	pH often determines the ionization and hydration value of polymer.
Polymer type	$p<0.001$	Polymers depend on structural properties (e.g., PAC is superior at saline and HPHT places).
MW	$\beta = -0.012$	Polymers with high MW and longer chains reduce cake permeability.
Temperature	$p>0.10$	Temperature as thermal thinning has less effect
Lack-of-fit	$p=0.164$	A reliable range of model.

Under extreme HPHT conditions (110 °C and 1.5 g/L), PAC demonstrated filtrate volume between 9.0 and 9.5 mL, while CMC exhibited higher value up to 12.5 mL under comparable salinity levels. These boundary-condition results confirmed the superior thermal–salinity stability of PAC.

In the two-phase modeling approach, liquid–liquid interactions in WBDFs are considered, where the dispersed polymer phase (0.5–1.5 g/L) forms hydrated networks through interactions with the continuous aqueous phase. These interactions enhance the stability of the filter cake formed on the

wellbore wall, reduce its permeability (0.01–0.05 mD), and decrease filtrate volume by 40–60% under the high-salinity conditions (100,000–200,000 ppm) of the Southern Zagros gas reservoirs.

PAC's high DS (> 0.9) contributed to improved salt tolerance under the investigated high-salinity laboratory conditions (100,000–200,000 ppm), resulting in approximately 20% lower filtrate volume than CMC at pH values of 5.5–7.

Its result is forming thinner membrane (filter cakes with thickness up to1 mm) that adjusts equivalent circulating density (ECD) up to 0.2–0.4 ppg at HTHP conditions (depths > 3,000 m). The hydrolysis of PHPA (20–30%) facilitates the encapsulation of water-sensitive shale layer in Southern Zagros at higher temperatures (85–105 °C). The efficacy of PHPA drops 15–25% in pH less than 6 due to lower ionization. In contract, CMC's thermal stability (T < 90 °C) is less relative to PHPA and PAC, and its performance at high temperatures (T > 90 °C) is up to 30% weaker compared to PHPA (forming a harder mud cake). Nevertheless, CMC is more cost-effective and with more biodegradability property at offshore operations in the Southern Iran.

According to API RP 13B-1/13B-2, filtration volume was chosen as the main operational index to evaluate the filtration that controls performance of polymers, because this parameter is directly used in the design and control of drilling fluids in field operations. Although direct measurements of mud cake permeability can provide valuable mechanical information, in this study, laboratory measurements of mud cake thickness, microscopic structure, and permeability were not performed for all 27 runs of the experimental design. Therefore, developing an independent model to predict mud cake permeability outside the range of available data could have resulted in unreliable extrapolations.

Conclusions

The present study, focusing on the Iranian gas reservoirs of Southern Zagros, presented an innovative model using Minitab software that, models the two-phase filtration behavior of WBDFs with the addition of affordable and readily available polymers in Iran. It provides a practical methodology for screening and optimizing polymer selection under laboratory-simulated HPHT and high-salinity conditions.

This method, via experimental data from 27 runs, was conducted under HTHP conditions (500 psi (34.5 bar) and 85–110 °C), with pH values of 5.5–7.0 and salinity of 100,000–200,000 ppm. The result was a model with R-square of 83.24%, adjusted R-square of 81.05%, predicted R-square of 76.26%, and an error of 0.0719. The model demonstrated that the PAC polymer at a concentration of 1.0 g/L and pH values of 5.5–7.0 (especially, pH < 6) can reduce the filtrate to below 9.3 mL/30 min. The performance of PAC and PHPA polymer in controlling fluid loss was 60–70% better than the water-based fluid without polymer, and at least 25% better than polymer CMC under HTHP conditions.

In this study, by combining generalized regression, Box-Cox transformation ($\lambda = 0.5$), and the matrix and 3D plots, it was predicted that every 10 °C increment in temperature increases the filtrate by 0.3–0.5 mL, but PAC reduces this effect by 10–15%. This model confirmed the thermal stability of PAC, PHPA, and CMC in the high salinity of Iranian reservoirs of Southern Zagros (especially 200,000–100,000 salinity), with complete dependence on the pH values. In addition to pH, MW was considered as one of the factors in measuring fluid viscosity and stability. The developed filtrate regression equation estimated the filtrate amount for polymers depending on MW as an influencing factor on the equilibrium of chemical structure and chain size of polymers.

The final results showed that the MW of the polymer, as an effective structural parameter, plays a decisive role in predicting the filtration behavior of WBDFs under HPHT conditions. By developing the regression model, the effect of MW was entered as an independent term in the prediction equation and, together with pH and polymer type, was able to describe the changes in the volume of filtered liquid with higher accuracy. The MW coefficient in the developed model showed that increasing the MW of the polymer reduces filtration by strengthening the polymer network, increasing the thickness of the hydrated layer, and reducing the permeability of the mud cake. This finding indicates that combining the chemical parameters of the polymer (MW, polymer type, and ionic properties) with operational variables provides a more accurate framework for designing WBDFs in HPHT reservoirs in the southern Zagros.

Limitations

The proposed regression model was established using laboratory-generated data under controlled HPHT conditions representative of southern Zagros gas reservoirs. Although the temperature, salinity, and pH ranges selected were chosen to reproduce realistic reservoir environments, the model does not accurately account for formation heterogeneity, transient wellbore pressure fluctuations, cuttings transport, drilling hydraulics, circulation losses, or other operational factors encountered during field drilling.

Salinity was maintained constant within the range of 100,000–200,000 ppm to represent the high-salinity conditions of Southern Zagros gas reservoirs. The developed

model is valid for predicting filtration behavior in the investigated salinity range, and to generalize it to different salinity conditions, it will be necessary to conduct additional experiments with salinity as an independent variable.

The paper emphasizes that the developed model is designed to reproduce the behavior of WBDFs in the range of laboratory conditions corresponding to the gas reservoirs of the southern Zagros (temperature 85–110 °C, salinity 100,000–200,000 ppm, and standard HPHT pressures according to API) and can be used as a prediction and initial screening tool for polymer selection and formulation optimization before field tests. As a result, the model should be considered primarily as a laboratory-based predictive tool for formulation optimization, not a fully validated field simulator. Future studies should consider independent laboratory data sets and field measurements to further evaluate the robustness of the model under actual drilling operations.

Adding MW improved the model performance, but this effect should be interpreted along with other structural properties of the polymers. Therefore, it is suggested that in future research the study on multiple grades of a polymer with different MWs could allow for the isolation of the independent effect of MW from polymer type.

Author contributions MK Methodology, Resources, Validation, Conceptualization, Investigation, Writing–original draft, Formal analysis. MSJ Supervision, Methodology, Writing–review&editing, Validation, Resources. BM Project Administrator, Methodology, Data curation, Writing–review&editing, Validation, Software, Resources.

Funding This research did not receive funding.

Data Availability The authors declare that the data supporting the findings of this study are available within the manuscript.

Declarations

Competing interests The authors declare they have no competing financial interests.

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