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A systematic design approach for bulk gel treatments based on gel volume-concentration ratio in field projects

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ABSTRACT

Controlling excessive water production in mature oil fields has always been a desired objective of the oil and gas industry. This objective calls for planning of more effective water-control gel treatments with optimized designs to obtain more attractive outcomes. Unfortunately, planning such effective treatments remains a dilemma for reservoir engineers due to the lack of methodical design tools in the industry.

This paper presents a novel systematic design approach for polyacrylamide-based bulk gel treatments by classifying their field projects according to the gel volume-concentration ratio (VCR) into three design types. In terms of one another, the approach estimates either the gel volume or the gel concentration based on the average gel VCR of each design and formation type. First, field data was collected from SPE papers and reports of US Department of Energy for 65 gel projects conducted between 1985 and 2020. Stacked histograms were then used to examine distributions of field projects according to the gel VCR and the formation type. A comprehensive review of channeling strength indicators in field gel projects was performed to identify the classification criterion and design types of gel treatments. Based on the mean-per-group concept, the average gel VCR was assessed for each design type and formation type to build the design approach. Approximations for the overall gel concentration and correlations for extremum designs were established and included in the approach.

The study showed that the gel VCR is a superior design criterion for in-situ forming bulk gel treatments. It aggregates gel treatments into three project groups and ranks them according to the channeling strength. The three project groups have clear separating VCR intervals (<1, 1–3, >3 bbl/ppm) and each of them is mostly dominated by one formation type. The VCR range of each project group represents one design type of the bulk gel treatments. The channeling type is the criterion of grouping and group-wise ranking of gel projects with respect to the gel VCR. In design type I, VCRs<1 bbl/ppm are used to treat pipe-like channeling usually exhibited by unconsolidated sandstones. More balanced VCRs of 1–3 bbl/ppm are designed for fracture-channeling frequently presented in naturally-fractured formations (design type II). Large gel treatments with VCR>3 bbl/ppm are performed to address matrix-channeling often shown in matrix-rock formations (design type III). Prediction results demonstrated that the VCR approach reasonably estimates volumes and concentrations of both single gel treatments and averaged field projects in training and validation samples. Besides its novelty, the new approach is systematic, accurate, practical, and will facilitate the optimization of future gel treatments to improve their performances and success rate.

1. Introduction

The petroleum industry has always faced the problem of producing and disposing large quantities of injection water because of the severe heterogeneity of oil and gas reservoirs. Thus, several conformance control technologies have increasingly been applied to mitigate excessive water production, notably the polymer gel treatments. However, designing gel treatments represents a fundamental challenge for conformance engineers due to the lack of reliable methodological design approaches.

Polyacrylamide-based bulk gels are probably the most widely applied polymer gel system in conformance improvement treatments (Sydansk and Southwell, 2000; Lantz and Muniz, 2014). These polymer

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Nomenclature

AAPE	Average absolute percentage error, %
C_p	Polymer concentration, ppm
C_{pvwa}	Volume-weighted average polymer concentration, ppm
n	Number of treatment stages in a treatment or of treated wells in a field
N	Total number of sample data points
RD	Relative deviation, %
V_g	Gel volume, bbls
VCP	Volume-concentration product, bbl.ppm
VCR	Volume-concentration ratio, bbl/ppm
WSO	Water-shutoff

gels have practically been proven to be effective solutions for a variety of conformance issues. They are applied to treat both production wells and injection wells as water shutoff and profile control treatments. They improve the reservoir conformance of the improved and enhanced oil recovery floods (IOR/EOR) by plugging the high permeability zones/areas and diverting the injected water into the low permeability zones/areas (Zheng et al., 2021). Bulk gels are injected as a watery gelant solution that in-situ forms a semi-solid 3D network structure within reservoirs. They are formulated using high concentrations (3000–30000 ppm) of hydrolyzed polyacrylamide polymers (HPAM) with either a metallic or an organic crosslinking agent.

For MARCIT℠ gels developed by Marathon Oil Company, HPAM polymers of high molecular weight (MW) are crosslinked using the Chromium (III)-acetate (Sydansk and Smith, 1988). The Cr (III)-acetate-HPAM gel system has successfully been applied in formation temperatures less than 220 °F (Sydansk and Southwell, 2000). For high temperature applications, HPAM polymers of medium MW are crosslinked with an organic agent and a stabilizer. An example of this specialized chemistry is the UNOGEL technology developed by Union Oil Company of California (UNOCAL), which can be applied in a temperature range of 200–300 °F (Norman et al., 2006). Aldhaheri et al. () provided that bulk gels are applied to treat strong channeling (>0.5–1), small volume ($<10^6$ barrels), and oil-swept reservoir conformance problems. A strong channeling indicates a severe injector-producer communication with a correlation coefficient of water injection and water production rates >0.5–1.0.

The difficulty of adequate characterization of conformance problems has resulted in a high degree of technical sophistication for the design of gel treatments (Smith, 1999; Romero et al., 2003; Lantz and Muniz, 2014). Therefore, gel treatments are empirically designed based on the experiences of oilfield operators and/or gel service companies (Avery et al., 1987; Giangiacomo and Vivas, 2000; Sydansk, 2007; Pender, 2013). Practically, the gel concentrations are adopted in a case-finding manner from previous gel case histories applied in analogous reservoir types. In addition, the gel volume, if not left to be decided during the job on the fly, is roughly estimated as a percentage of the volume of problem zone between 5 and 50% for matrix-rock reservoirs (Smith, 1999; Ricks and Portwood, 2000; Portwood and Romero, 2018). Overall, the above experience-analogy practice implies that the current planning practices are merely design thoughts and, in their best cases, they only provide starting points for the designs of gel treatments. In addition, the gel volume and the gel concentration are independently and separately planned while they are completely connected and related to each other in reality.

Despite the long application history of bulk gels, it was noted that the design of gel treatments still represents a dilemma for conformance engineers. The reason is that the treatment design has been qualitatively and unsystematically treated in the previous studies. For example, Avery et al. (1987) listed the reservoir and operational variables that should be taken into considerations in the design of gel treatments. To strengthen the empirical procedure of gel treatment design, Seright (1993) provided summaries of the treatment sizing procedures of eight major oil companies and seven gel vendors. Lantz and Muniz (2014) developed a descriptive treatment design matrix that has considered both the polymer concentration and the gel volume as a heuristic designing tool. Recently, Portwood and Romero (2018) outlined the practical considerations of and lessons learned about the selection, design, implementation, and evaluation of bulk gel treatments based on experiences gained from treating ±700 injection wells over 25 years.

The above discussion evidently highlights that there is an immediate need for developing mathematical design models that effectively and accurately design the volumes and concentrations of gel treatments. This paper introduces a new design approach for bulk gel treatments based on the statistical classification and ordination of field design data of 65 worldwide gel projects applied in conventional oil fields. The paper first discusses how the gelant volumes and concentrations should be planned for effective designing of bulk gel treatments. Then, it will explain how gel projects were classified and grouped, and how design types of gel treatments were identified. The tasks of the data compilation, approach construction and validation, input data approximation, and estimation of extremum designs are discussed in detail. Some performance observations, future enhancement efforts, and importance of the new approach will be presented as well.

2. Field data compilation and analysis

An extensive database was constructed for injection-well gel treatments using the field data of gel projects published in SPE papers and reports of US Department of Energy. The database consists of four major sections that cover all aspects of a conformance project including the field/reservoir information, problem diagnosis, treatment design, and performance evaluation. The dataset totally includes 65 field projects that were implemented in 11 different countries between 1985 and 2020. All gel projects were applied in conventional oil fields except the case of Viewfield Bakken unconventional tight oil formation (Roostapour et al., 2020). Individually, the dataset involves 57 field projects for MARCIT℠ gels and eight case histories for the organically-crosslinked bulk gels. The 65 gel projects comprise 653 gel treatments that were implemented in five different IOR/EOR floods: steam (Aldhaheri et al., 2016a), gas (Al-Anazi et al., 2019), CO_2 (Chou et al., 1994), polymer (Aldhaheri et al., 2017), and water (45). The data of reservoir-fluid properties, job designs, and treatment performances can be found in the work of Aldhaheri et al. (2016–2020) referenced in this study.

During the treatment, bulk gels are placed into reservoirs in a number of injection stages that have different polymer concentrations and gel volumes (i.e., treatment data). Treated injectors in a field also have different concentrations and volumes (well data) and different numbers of injectors are treated in a gel project (field data) based on project outcomes and economics. Therefore, a specialized data reporting approach was used to obtain sufficiently representative field-wide average values for the gel treatment designs from the treatment and well data (Aldhaheri et al., 2018). In this reporting approach, the polymer concentrations were averaged based on the volume of injected gels (i.e., volume-weighted average) expressed as:

$$C_{pvwa} = \frac{\sum_{i=1}^{n} C_{Pi} * V_{gi}}{\sum_{i=1}^{n} V_{gi}} \tag{1}$$

where C_{pvwa} is the field-wide average polymer concentration, C_p is the polymer concentration, V_g is the gel volume, and n is the number of treatment stages in the well data or the number of treated wells in the field data. For the gel volume, the treatment and well data were normally averaged using the arithmetic mean to evaluate the field-wide estimations.

To develop a structured design approach for gel treatments, a review of the available literature explaining the process of the gel treatment was initially performed. The objective was to recognize how should gel treatments be planned and what are the requirements for effective treatment design. Secondly, the average gel volumes and polymer concentrations in field projects were simultaneously processed as a product and ratio and used to examine distributions of gel projects using stacked histograms. Next, the gel projects were classified and the average gel VCR was evaluated for each project group to build the design approach. Furthermore, two approximations for the average input polymer concentration and two correlations for minimum and maximum designs were identified and included in the approach. Finally, the estimated volumes and concentrations were validated against the actual designs using training (48 data points) and validation (23 data points) samples. Scatterplots, coefficient of determination (R^2), the absolute relative deviation (*RD*), and the average absolute percentage error (*AAPE*) given by equations (Albonico and Lockhart, 1997) and (Aldhaheri et al., 2016a) were utilized to verify the performance of the design approach.

$$RD = \frac{\left|V_{gactual} - V_{gpredicted}\right|}{V_{gactual}} * 100 \tag{2}$$

$$AAPE = \frac{\sum_{i=1}^{n} RD}{N} \tag{3}$$

where *N* is the total number of sample data points.

In this study, the polymer concentration and the gel concentration terms were interchangeably used to refer to the gel strength of bulk gels. The term water channeling refers to the problem of water communication between an injector and its offset producers through the high permeability zones. The channeling strength indicates the degree or severity of this interwell connectivity and usually it is assessed by the correlation coefficient of water injection and water production rates of a well-pattern. The design type of a gel treatment represents a range of gel VCRs that is applied to treat certain channeling problems. The half-open interval notation (left endpoint included and right endpoint not included) was used to represent the ranges of design parameters in the stacked histograms. The following abbreviations were used in the tables of this paper to save space: UC = unconsolidated, NF = naturally-fractured, and MR = matrix-rock.

3. Requirements of effective design of gelant treatments

The design of bulk gel treatments involves deciding on several variables that are generally related to the gel concentration, gel volume, and gel injection and placement. In fact, these design variables are strongly connected or interrelated to each other in many ways. Therefore, it is essential at first to recognize how to design the treatment variables in a way that mimics the real process of the gel treatments in the field.

The in-situ forming polymer gels (i.e. gelant-based) tend to have shorter gelation times and provoke faster injection-pressure build-ups as their concentrations increase (Norman et al., 2005; Al-Anazi et al., 2019; Wu et al., 2021), especially when they are formulated with high MW polymers (>7 million Daltons) to treat the injection wells. The rapid gel maturing and pressure building resulting from the fast formation of gel network significantly reduce the volume of gel treatments as they restrict the deep placement of earlier injected gels (Scott et al., 1987; Albonico and Lockhart, 1997; Romero-Zeron et al., 2008). Therefore, the gel volume is balanced with the gel concentration during the treatment by gradually ramping-up the polymer concentration (Avery et al., 1987; Norman et al., 2005; Pender, 2013). This implies that the injectable volume of bulk gels into reservoirs is inversely proportional to the polymer concentration for a constant maximum injection pressure. In addition, for an effective treatment design, the gel volume should be correspondingly designed in terms of the gel concentration, and vice versa. This realization indicates that both the gel volume and the gel concentration should be taken into considerations in the development of design methodologies for bulk gel treatments. Therefore, it was decided to simultaneously evaluate the gel volume and the gel concentration as a gel volume-concentration product (VCP) and gel volume-concentration ratio (VCR).

Before proceeding with the classification of gel field projects, it was first required to answer the following questions: what are the characteristics of a good design criterion for bulk gel treatments? And which gel measure, the VCP or the VCR, will be a potential design criterion? In this context, it was expected that the prospective criterion would be the one that (a) expresses the inverse relationship of the gel volume and the gel concentration and (b) has the ability to differentiate designs of the gel projects in a way that facilitates the design process. Accordingly, the study started by checking the attributes of the gel VCP and VCR, and by examining distributions of the gel projects with respect to them using stacked histograms.

3.1. *Gel volume-concentration product*

Initially, we preferred using the gel VCP as a design criterion for gel treatments because it does reflect the reversal relationship between the gel volume and the gel concentration when used in designing new jobs. In other words, the gel VCP estimates smaller gel volumes for higher polymer concentrations and vice versa ($V_g = VCP/C_p$). However, it has been noted that the utilization of the gel VCP has the following serious drawbacks. First, when the VCP increase/decrease, it is not possible to indicate which parameter is increasing/decreasing, the gel volume, the polymer concentration, or both of them. The reason is that in the form of a product, both the gel volume and the polymer concentration increase in the same direction (to right) as shown in Fig. 1. This means that the VCP lacks the ability to follow and explain the trends of design parameters, which is considered an essential aspect as it helps in identifying the contrasts in the designs between gel projects and/or reservoir types.

Secondly, the gel VCP resulted in unfavorable distributions for gel project with respect to the formation type. Fig. 1 illustrates that reservoirs treated with either high concentrations/small volumes (frequently used to treat unconsolidated formations) or with low concentrations/large volumes (often used to treat matrix-rock formations) have together allocated in the small VCP ranges (<30 million bbl. ppm). On the other side, reservoirs treated with high concentrations/large volumes (frequently used to treat naturally-fractured formations) or with moderate concentrations/extremely large volumes (sometimes used to treat matrix-rock formations) have occupied the large VCP intervals (>40

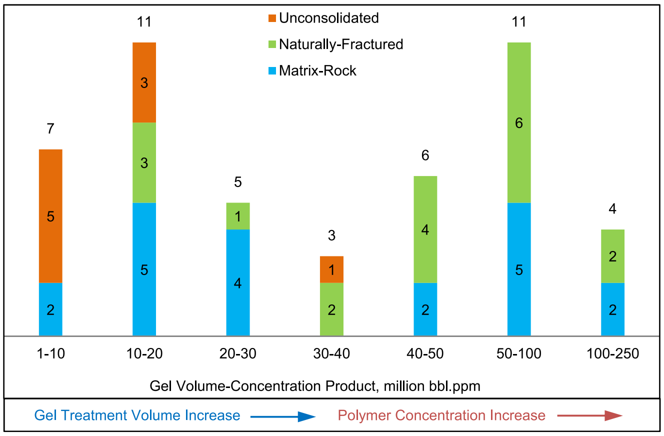


Fig. 1. Distribution of bulk gel projects according to gel volume-concentration product for different formation types.

million bbl. ppm). It is clear that this mixing or grouping of formation types has hindered the ability of the VCP to produce a separable distinct design interval for each reservoir type. Most importantly, it has not been possible to detect the problem property or the treatment aspect that the arrangements of reservoir types shown in Fig. 1 would indicate. In sum, it was noted that the gel VCP has weak tracking, indicating, and discriminating powers for the designs of gel treatments based on the reviewed field data.

3.2. Gel volume-concentration ratio

Several traits have nominated the gel VCR as the basis for developing a design approach for gel treatments. First, the VCR explicitly indicates the change directions of the gel volume and the polymer concentration so it is quite easy to follow or interpret their trends when the gel VCR changes. For example, when the VCR increases, normally, this means that the gel volume is increasing and the polymer concentration is decreasing, and vice versa. In addition, as a ratio (contrast), it is expected that the VCR is able to reflect the differences in the treatment designs between gel projects and/or different conformance problem types. Several other advantages of the gel VCR have been identified that will be presented in next paragraphs and sections as the discussion progresses. However, the gel VCR does not exhibit the inverse correlation of the gel volume and the polymer concentration when it is used in the design of gel treatments. Namely, the VCR estimates a larger gel volume as the polymer concentration increases ($V_g = VCR * C_p$) which is opposite to the field observations.

Subsequently, the distributions of gel projects were examined according to the gel VCR together with the reservoir lithology, formation type, and recovery process using stacked histograms. No noticeable grouping trends were detected for the gel projects in the VCR histograms in regard to the reservoir lithology or the recovery process. In contrast, obvious aggregating tendencies were observed for the gel projects in the gel VCR-formation type histogram as shown in Fig. 2. Favorably, this figure shows that the gel VCR has continuous, discrete, equal-length intervals over its whole range (0.06–40 bbl/ppm). In addition, the gel projects have almost uniform and equal frequencies (Aldhaheri et al., 2018, 2019, 2020) over the VCR intervals except the last interval. These characteristics are considered essential features that any integrated efficient design tool should possess to ensure its efficiency.

Concerning the grouping tendency of gel projects, Fig. 2 illustrates that the majority of field projects applied in each formation type tend to occupy two or three VCR intervals. This figure shows that most gel projects applied in unconsolidated (7 out of 9 or 78%), in naturally-fractured (10 out of 18 or 59%), and matrix-rock formations (11 out of 20 or 55%) are aggregated in VCR ranges of <1, 1–3, and >3 bbl/ppm, respectively. This banding behavior of gel projects implies that the gel VCR in field projects is greatly influenced by the formation type (for now). In addition, it reveals that the gel projects can be pooled into three VCR intervals or project groups based on the gel VCR and the formation type. Furthermore, it indicates that there is a general or typical VCR design range for each formation type (e.g., VCR<1 bbl/ppm for unconsolidated formations). To have a better conception of the VCR intervals or project groups, the gel project distributions in Fig. 2 have been reconstructed based on the observed VCR boundaries or cut-offs (i.e., <1, 1–3, >3 bbl/ppm) as shown in Fig. 3. This figure shows that the gel trials indeed tend to assemble in three project groups and each project group is mostly dominated by one formation type. More and more, it appears that the gel VCR is a promising design criterion for the bulk gel treatments.

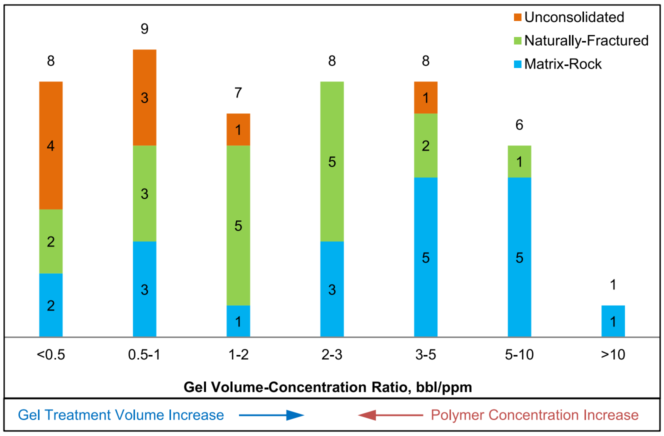


Fig. 2. Distribution bulk gel projects according to gel volume-concentration ratio for different formation types.

4. Design types of bulk gel treatments

At this stage, there was a desire to know what the three project groups represent or in what respect they differ from each other. It was agreed that the starting point is the formation type because, as yet, it seems the most obvious grouping criterion of gel projects with respect to the gel VCR.

In principle, the strength of bulk gels (i.e., concentration) is designed based on the channeling strength of the conformance problems causing water channeling. On the other hand, the injectable gel volume is determined by the designed gel concentration and thus, it, in turn, also depends on the channeling strength. This realization illustrates that the channeling strength is the main driver of the design process of gel treatments. In field, the channeling strength is primarily characterized by the formation type during diagnosing the conformance problems (Aldhaheri et al., 2016b and 2017). Furthermore, the designs and performances of gel treatments are greatly influenced by the formation type (Aldhaheri et al., 2018, 2019, and 2020). These observations illustrate that the formation type in Fig. 3 is actually reflecting the channeling strength and in fact, the channeling strength is the grouping criterion of the gel projects and not the formation type. Moreover, this implies that each gel VCR interval represents the solution (design recipe) for a certain type of channeling problem.

To confirm the above implications, a comprehensive review of gel case histories was performed to study channeling strengths of conformance problems presented in each project group in Fig. 3. The goal was to confirm that all case studies in one VCR interval had the same channeling behavior for all formation types. In this review, 13 diagnosis indicators of the interwell connectivity including the formation type were used to compare the channeling strengths between the three project groups. The comparative analysis illustrated that the channeling type is the dividing or distributing criterion of the gel projects among the

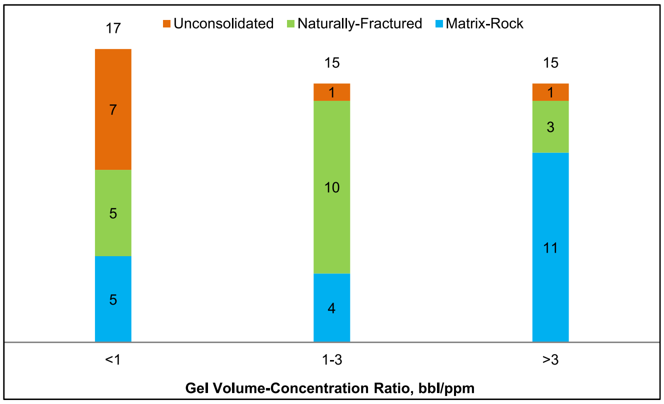


Fig. 3. Reconstructed histogram shows aggregating tendencies of gel projects according to gel VCR and formation type.

three VCR intervals. It was also identified that generally three types of the drive-fluid communication have been treated by the bulk gels including pipe-like, fracture, and matrix-channeling using VCRs of <1, 1–3, and >3 bbl/ppm, respectively. This means that there are three design types (I, II, and III) for gel treatments that each of them addresses one of the above mentioned channeling types. In the following subsections, the design types and their corresponding channeling types are further elaborated.

It is important to remark that each channeling type encompasses a wide channeling strength range and this is why that the dominant formation type in each project group is always accompanied by other two reservoir types. In addition, this accompaniment does not imply that all problems or formations in a given VCR interval had exhibited exactly the same channeling strengths (transit time or communication correlation). Instead, it emphasizes that all problems or formations in a project group had similar channeling behavior or the water channeling was caused by similar problem types.

4.1. Treatment design for pipe-like-channeling

The design type I is used to treat the pipe-like conformance features that cause direct fluid communications between the injectors and the producers. Pipe-like features are so named because they are thin, laterally-long, small-volume, and large-aperture voids that cause a concentrated flow like fluid streams in pipes. Therefore, small gel volumes of high polymer loadings that correspond to VCRs <1 bbl/ppm are generally employed to treat such conformance issues. For this VCR design range, it is clear that the gel strength is the dominant design criterion while the gel volume is of a secondary consideration because of the largeness of the flow channel apertures.

Fig. 3 illustrates that the unconsolidated formations frequently (7 out of 9) exhibit the pipe-like type of the fluid channeling. Our review of gel projects showed that most of these unconsolidated formations are plagued by the sand production problem (Saez et al., 2012; Lantz and Muniz, 2014). The sand production problem is known to induce this channeling type through the development of extended wormholes of large apertures. The review also indicated that matrix-rock and naturally-fractured formations have displayed this channeling type because of the unintentional fracturing (for matrix-rock only) and the long flooding time (11–24 years) that has exacerbated their channeling strengths to reach the ultimate limits. Examples for the conformance features treated by this design type are the void spaces, conduits, wormholes, faults, karsts, direct fractures (hydraulic or induced), and small-volume, extreme permeability streaks with >4000 md permeability and no crossflow. It is important to mention that in addition to the pipe-like channeling, it was noted that the design type I was also used in high temperature applications (steam floods) and in economically-designed gel treatments planned and applied in matrix-rock formations based on available investments.

In regard to the formation type, it is normally expected that unconsolidated and naturally-fractured formations exhibit the pipe-like channeling immediately after the reservoir flooding or with the time. In addition, many direct indications for this channeling type are frequently provided in the gel case histories applied in these formation types. However, for the matrix-rock formations that are known for their small pores, the matter needs strong proofs and the field projects provided few direct indications for this channeling type. Therefore, special attention was paid during this study to make sure that matrix-rock reservoirs really had a pipe-like channeling. In the next paragraphs, field evidences of the pipe-like channeling are provided for two gel projects applied in the matrix-rock formations.

First, in the case study of the Christabelle oil field, the operator ran an interference test by shutting-in the water injection for 14 days to detect the offending injector. The total fluid production began to drop in six days and dropped more than 700 BFPD in the eighth day as shown in Fig. 4 (Lantz and Muniz, 2014). The clear and fast response of the total fluid production rate to the changes in the water injection rate signals a strong water channeling with a pipe-like behavior. The injector was treated by 4000 barrels of bulk gels with concentrations between 3000 and 6000 ppm (4750 ppm on average).

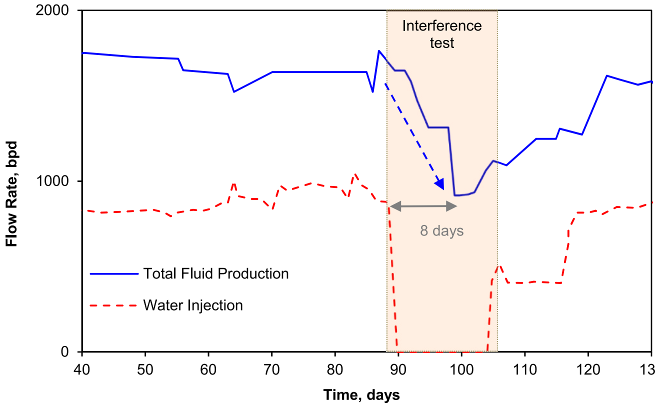


Fig. 4. Interference test utilized in diagnosis of water channeling problem in Christabelle field (Lantz and Muniz, 2014).

For the Eunice Monument South Unit (EMSU), the problematic injectors were quantitatively identified and ranked based on correlation coefficients of the water injection and production rates as shown in Fig. 5 (Chou et al., 1994). This figure clearly shows that each of the treated injection wells had a strong correlation coefficient (0.6–0.8) with only one producer. Such coefficients suggest the existence of direct interwell communication caused by large-pore thief zone. Small volumes (700 barrels) of relatively high-concentration (5000 ppm) bulk gels were used to treat these injectors. Several other indications (injectivity, injection profiles, etc.) and injection/production plots were used to ascertain the direct communication between the injectors and producers (Love et al., 1998) in this field.

4.2. Treatment design for fracture-channeling

As the name implies, this channeling type refers to a strong communication of the drive-fluid in small-volume, highly-conductive reservoir fractures or similar features like the conduits and the voids. Fig. 3 shows that this type of interwell communication is mainly

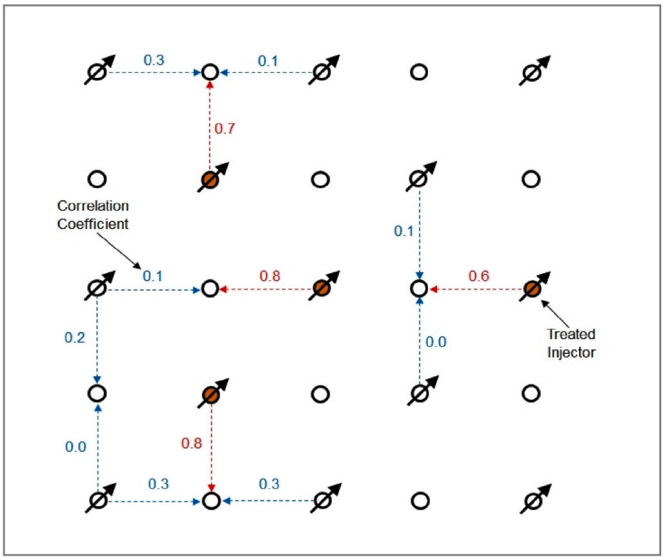


Fig. 5. Interwell communication map of gel-treated injectors in EMSU field showing correlation coefficients of water injection and production rates (Chou et al., 1994).

exhibited by the naturally-fractured formations (10 out of 18); however, it may also be offered by the matrix-rock formations because of the intentional or unintentional fracturing of these formations. For the fracture-channeling, the gel volume is more balanced with the gel concentration than for the pipe-like channeling to completely fill-up and plug the fractures or the voids. In other words, large gel volumes that correspond to VCRs of 1–3 bbl/ppm are utilized to treat these strong conformance problems using the design type II. This design type is used to treat the same conformance features listed for the pipe-like channeling but with smaller aperture sizes or lower channeling strengths. That is, the bulk gels designed with VCRs of 1–3 bbl/ppm are strong enough to prevent the gel extrusion and breakthrough, and they can withstand the high differential pressures that exist in these problem zones. It is important to note that for fracture-type.

4.3. Treatment design for matrix-channeling

In design type III, large-volume gel treatments with VCRs >3 bbl/ppm are performed to address the matrix-type channeling. This channeling is often exhibited by stratified, heterogeneous, high permeability, matrix-rock reservoirs as shown in Fig. 3 (about 73% or 11 out of 15 projects in VCR>3 bbl/ppm interval). For these large-volume conformance problems, the goal is to economically fill-up with bulk gels as much as possible of the flow channel between the injector and the producer, especially when the crossflow is expected. Larger treating volumes would enable the remediation to influence a farther and larger extent of the problem zone and stimulate a deeper water diversion. For this VCR design range, it is clear that the gel volume is the dominant design criterion of gel treatments. In this study, it was noted that this design type has been used to treat other problem types like fracture networks and horizontal injection wells.

It is important to note that the distributions and sequences of channeling types, formation types, and VCR intervals in Fig. 3 are quite consistent with conformance engineering considerations. First, the channeling types are conveniently arranged in terms of increasing channeling strength as matrix, fracture, and pipe-like from right to left. Secondly, for each project group, the dominant formation type is accompanied by other two formation types. This accompaniment supports the notion that any formation type may exhibit all channeling types and the channeling strength of a conformance problem may further increase with time to display a stronger channeling type. Finally, Fig. 3 shows that higher gel concentrations are required when the channeling strength increases so that the gel VCR decreases toward the left side of the figure. These remarks highlight that the VCR is a superior design criterion for the conformance-improvement treatments by bulk gels.

5. Approach development

In view of its many favorable features, the gel VCR has been employed to develop a systematic design approach for bulk gel treatments. In fact, we would have liked to take the advantages of the gel VCR capability in grouping and group-wise ranking of gel projects into three design types (I, II, and III). The basic idea of the approach is to identify the design type of new gel treatments based on the channeling type and the formation type of targeted conformance problems. Then, either the gel volume ($V_g = VCR * C_p$) or the polymer concentration ($C_p = V_g / VCR$) is estimated using the gel VCR of the identified design type. The unsolved problem here is that each design type encompasses a wide VCR range (<1, 1–3, >3 bbl/ppm) while a single VCR value is required to estimate the designs. In addition, an initial guess of the gel concentration is needed in order to predict the gel volume and vice versa.

In a manner similar to the idea of the regression analysis (i.e., modeling the mean of response variable), it was decided to use the average gel VCR in the construction of the approach. However, the gel treatment designs are integrated into three design types that each of them represents one channeling type and contains three formation types (3 × 3) as shown in Fig. 3. This means that there are totally nine channeling-formation categories or classes and the group-wise averaging is required. Therefore, to build the design approach, the average gel VCR was estimated for each of the nine channeling-formation combinations based on the mean-per-group strategy as shown in Table 1. To facilitate the utilization of the VCR approach, spreadsheets titled “VCR Approach for Designing Bulk Gel Treatments” were constructed and made available on the first author’s ResearchGate account (https://www.researchgate.net/profile/Munqith_Aldhaheri). Fig. 6 shows a design example using the VCR approach for the treatment of I-1 injector (horizontal well) in Kuparuk River Unit (Mishra et al., 2016).

The gel VCR approach sizes gel treatments based on their overall average polymer concentration. However, a gel treatment involves a number of injection stages that each has different polymer concentrations and gel volume. Unfortunately, it is not recommended to assess the treatment average gel concentration straightforwardly from the planned polymer loadings for its injection stages. The reason is that the average polymer concentration is gel-volume dependent variable and if evaluated as a simple arithmetic mean, it becomes a poor indicator of the gel concentration (Aldhaheri et al., 2018, 2020). To address this matter, the following approximations for the overall gel concentration were made available in the VCR approach. First, the designer can directly use his/her own guess of the average polymer concentration if a reasonable estimation was made. Table 1 provides summaries of problem types, polymer concentrations, and gel volumes for each of the nine design categories. Thus, an initial guess value can also be adopted from this table if none has been made, yet. The objective is to provide the designer with ideas about the practical ranges of gel treatment designs to guide him/her during the design process.

Secondly, for gel treatments applied in unconsolidated and naturally-fractured reservoirs, it was indicated that the best approximation for the treatment composite concentration is the averaging of polymer concentrations of the treatment middle stages. The treatment middle stages are two or three injection slugs that have the largest gel volumes and in which, the bulk or majority of the treatment is injected. An example for this approximation is shown in Fig. 6 which illustrates that the estimated polymer concentrations are nearly identical to the actual field designs (4000 vs. 3955 ppm) for the case study shown in this figure (Kuparuk River field). Finally, for gel treatments applied in matrix-rock formations, it was identified that the treatment average polymer concentrations in summarized field projects are well-correlated with the maximum polymer concentrations of the last treatment stage ($C_{pavg} = 0.591 * C_{pmax} + 475.2$) with R-squared of 0.71. Therefore, this correlation was used as an approximation for the treatment average polymer concentration for this formation type.

6. Approach validation and results discussion

Using the average gel VCR of each channeling-formation combination, the gel volumes were predicted in terms of the field gel concentrations and vice versa as shown by equations (Aldhaheri et al., 2016b) and (Aldhaheri et al., 2017). The predicted average volumes and concentrations were then validated against the actual field data using the scatterplots shown in Fig. 7 to demonstrate the predictivity of new approach. For the training sample, prediction results showed strong correlations with the actual gel volumes and polymer concentrations with R^2 of 0.93 and 0.68, respectively. These R-squared values indicate that the VCR approach provides reasonable designs for the gel volumes and gel concentrations of profile-control gel treatments.

$$V_g = VCR * C_{pactual} \tag{4}$$

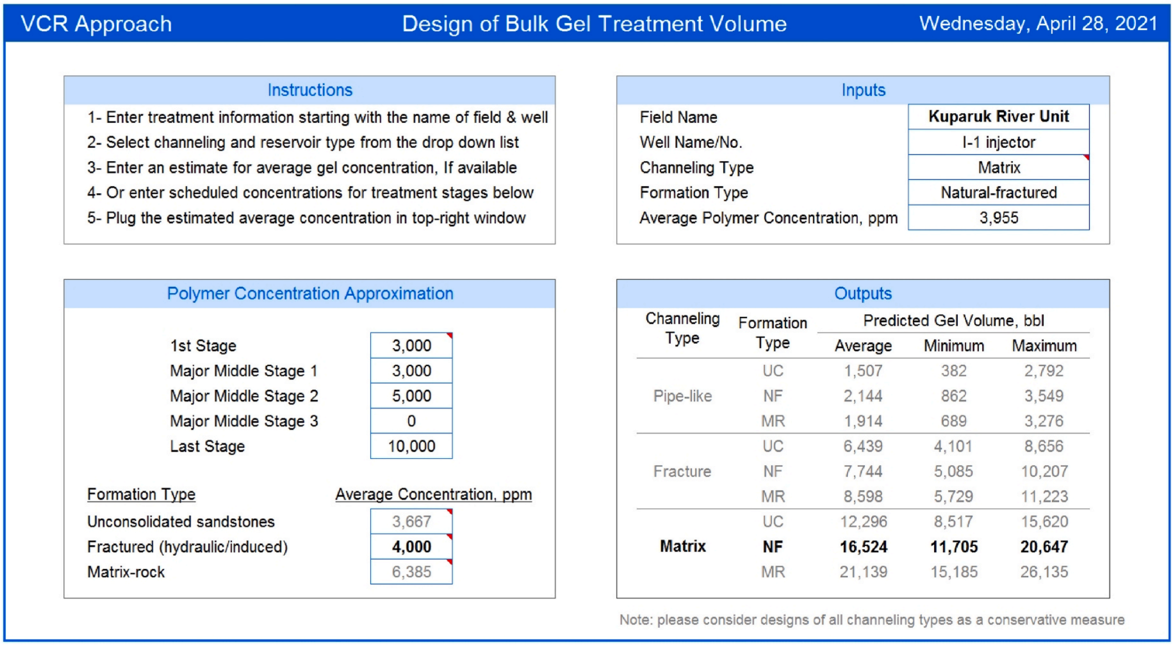
$$C_p = \frac{V_{gactual}}{VCR} \tag{5}$$

However, it is clear that data points in Fig. 7 are not lying very

Table 1
Summary of VCR design approach and field designs of profile-control gel treatments.

Design Type	Channeling Type	Formation Type	Average VCR bbl/ppm	Polymer Concentration, ppm [a]			Gel Volume, bbl [a]			Problem Type
				min	avg	max	min	avg	max	
Type I	Pipe-Like Channeling	UC	0.381	3350	4500	5600	265	1660	3320	Void spaces Wormholes Sand Production Solution channels
		NF	0.638	4250	7200	12,900	1225	2870	6645	Direct fractures Conduits Vug porosity
		MR	0.484	3000	4800	6200	470	2525	4100	Direct fractures >4000 md streaks No crossflow
Type II	Fracture Channeling	UC	1.628	3500	3500	3500	5700	5700	5700	Wormholes
		NF	1.958	4300	5750	7400	6700	11,150	16,300	Natural fractures Conduits
		MR	2.174	3000	3800	4400	4600	5700	6550	Induced fractures No crossflow
Type III	Matrix Channeling	UC	3.109	3500	3500	3500	10,900	10,900	10,900	No severe sand production Diffuse channeling
		NF	4.178	4000	4600	5100	14,700	19,000	21,700	Fracture networks Horizontal wells
		MR	5.345	3000	3500	5200	9500	23,500	60,000	Reservoir strata With crossflow

[a] Field-wide average estimations.



VCR Approach Design of Bulk Gel Treatment Volume Wednesday, April 28, 2021

Instructions

1- Enter treatment information starting with the name of field & well
2- Select channeling and reservoir type from the drop down list
3- Enter an estimate for average gel concentration, If available
4- Or enter scheduled concentrations for treatment stages below
5- Plug the estimated average concentration in top-right window

Inputs

Field Name	**Kuparuk River Unit**
Well Name/No.	I-1 injector
Channeling Type	Matrix
Formation Type	Natural-fractured
Average Polymer Concentration, ppm	3,955

Polymer Concentration Approximation

1st Stage	3,000
Major Middle Stage 1	3,000
Major Middle Stage 2	5,000
Major Middle Stage 3	0
Last Stage	10,000

Formation Type	Average Concentration, ppm
Unconsolidated sandstones	3,667
Fractured (hydraulic/induced)	**4,000**
Matrix-rock	6,385

Outputs

Channeling Type	Formation Type	Predicted Gel Volume, bbl		
		Average	Minimum	Maximum
Pipe-like	UC	1,507	382	2,792
	NF	2,144	862	3,549
	MR	1,914	689	3,276
Fracture	UC	6,439	4,101	8,656
	NF	7,744	5,085	10,207
	MR	8,598	5,729	11,223
Matrix	UC	12,296	8,517	15,620
	NF	**16,524**	**11,705**	**20,647**
	MR	21,139	15,185	26,135

Note: please consider designs of all channeling types as a conservative measure

Fig. 6. A snapshot of VCR approach shows gel volume design results for treatment of I-1 injector in Kuparuk River Unit.

closely to the black unit-slope line (points that overlap this line have equal actual and predicted values, $Y = X$). This data position signals that there are prediction errors beyond the acceptable tolerances (10%, for example). To address this issue, correlations for the minimum and maximum expected gel volumes and polymer concentrations were established and included in the approach as shown in Fig. 6. These relationships of these minimum and maximum designs were drawn based on the trends observed in Fig. 7 and in terms of the predicted values by the gel VCR approach (e.g., $V_{gmax} = 1.189 * V_{gpred} + 1000$). This step integrates the picture of the treatment designs as it provides the designer with a conservative narrow design window/range of known interval limits for the gel concentration and gel volume.

The authors were also curious about the performance of the VCR approach with respect to new out-of-sample data (i.e., validation sample), individual gel treatments with unaveraged designs, and water-shutoff treatments (WSO) applied in production wells. To satisfy this curiosity, the design data of 23 single gel treatments were used to examine the efficiency of the VCR approach in predicting the gel volume including two new injector treatments and five WSO treatments. Table 2 provides the field designs of the 23 single gel treatments and compares the predicted and actual gel volumes using the relative deviation and *AAPE* given by equations (Albonico and Lockhart, 1997) and (Aldhaheri et al., 2016a). This table shows that the VCR approach has accurately forecasted the gel volumes of the two new injector treatments (case No. 2 and 13 in Table 2) with relative deviations between 9.8 and 15.8% (average 12.8%). In addition, quite reasonable sizes were estimated for

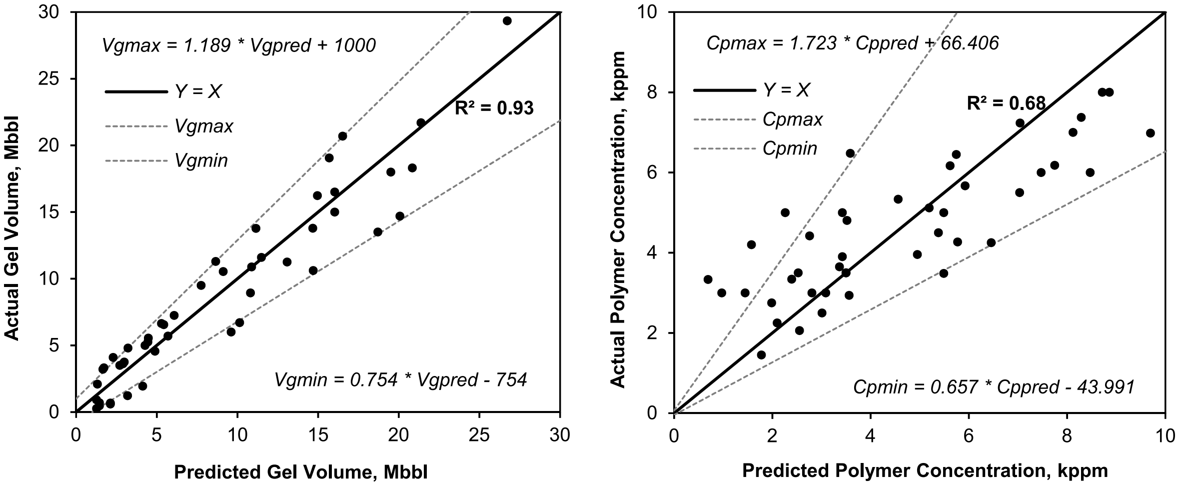


Fig. 7. Scatterplots of actual and predicted average gel volumes and polymer concentrations of training-sample bulk gel treatments.

Table 2
A comparison of actual and predicted gel volumes of validation-sample gel treatments.

Case No.	Channeling Type	Formation Type	Actual Designs		Predicted Gel Volume, bbl			Relative Deviation %	V_g Within Predict Range	Remarks and Reference No.
			C_p, ppm [1]	V_g, bbl	Avg	Min	Max			
1	**Pipe-like**	UC	4760	2000	1814	613	3156	9.3	Yes	Lantz and Muniz, (2014)
2		UC	4564	1501	1739	557	3068	15.8	Yes	New, (Varshney et al., 2018)
3		UC	3480	1840	1326	246	2576	27.9	Yes	Lantz and Muniz, (2014)
4		UC	4530	3333	1726	547	3052	48.2	No	(Saez et al., 2012)[2]
5		NF	3000	2000	1914	689	3276	4.3	Yes	Lantz, (2010)
6		MR	6180	3750	2991	1501	4556	20.2	Yes	Romero et al., (2003)
7		MR	4720	4000	2284	968	3716	42.9	No	Lantz and Muniz, (2014)
8	**Fracture**	NF	4712	8613	9226	6202	11,969	7.1	Yes	New, WSO, (Turner et al., 2010)
9		NF	4592	10,039	8991	6025	11,690	10.4	Yes	New, WSO, (Turner et al., 2010)
10		NF	4767	8059	9334	6284	12,098	15.8	Yes	New, WSO, (Turner et al., 2010)
11		NF	4920	8150	9634	6510	12,455	18.2	Yes	New, WSO, (Lantz, 2010)
12		NF	4493	11,532	8798	5879	11,460	23.7	No	New, WSO, (Turner et al., 2010)
13		NF	4653	10,100	9111	6116	11,834	9.8	Yes	New, (Lantz, 2010)
14		NF	4800	15,000	20,054	14,367	24,845	33.7	Yes	Lantz, (2010)
15		MR	4019	6378	8737	5834	11,388	37	Yes	UNOGEL, (Norman et al., 2006)
16	**Matrix**	NF	6455	28,000	26,970	19,582	33,068	3.7	Yes	20,100 bbl [3], (Lantz, 2012)
17		NF	5870	28,200	24,525	17,738	30,160	13.0	Yes	Lantz and Muniz, (2014)
18		NF	7663	28,025	32,015	23,385	39,066	14.2	Yes	Lantz, (2012)
19		NF	3955	19,739	16,524	11,705	20,647	16.3	Yes	Horizontal well 45,000 bbl [3], (Mishra et al., 2016)
20		NF	4428	14,600	18,500	13,195	22,997	26.7	Yes	15,000 bbl [3], (Montoya Moreno et al., 2014)
21		MR	3000	15,000	16,035	11,336	20,066	6.9	Yes	Norman et al., (2005)
22		MR	3675	15,000	19,643	14,057	24,355	31	Yes	Muruaga et al., (2008)
23		MR	2168	8269	11,588	7983	14,778	40.1	Yes	17,000 bbl [3], (Perez et al., 2012)
Average Absolute Percentage Error (*AAPE*), %								**20.7**		

1- Volume-weighted average, 2- Headed tapering schemes of polymer concentration used, 3- Initial design by gel vendor.

the WSO treatments (case No. 8–12 in Table 2) with relative deviations between 7.1% and 23.7% (average 15.1%). Furthermore, the VCR approach generally has acceptable error values for the practical application with overall *AAPE* of 20.7% for gel volume and 23.2% for polymer concentration. Finally, the actual gel volumes are within the prediction range of the VCR approach (i.e., $V_{gmin} < V_{gactual} < V_{gmax}$) for 20 out of the 23 gel treatments.

The above performance measures noticeably demonstrate that the VCR approach is also capable of predicting reasonable designs for new out-of-sample and single gel treatments not only the field-wide designs. It is thought that this prediction behavior is attributed to the utilization of the designs of approximately 22 individual gel treatments in the development of the VCR approach. For the WSO treatments applied in production-wells, the decision was left to the reader whether to use the VCR approach in the design of these treatments or not. However, it is important to note that the WSO treatments are implemented by the same way as the injection-well treatments but MARCIT℠ gels are formed with polyacrylamide polymers of same or lower molecular weights (4–8 million Daltons) than those utilized for injection wells (5–18 million Daltons). For gel treatments applied in unconventional tight oil reservoirs which are characterized by smaller size and lower strength (Roostapour et al., 2020), the minimum expected gel volumes (V_{gmin}) predicted by the VCR approach were in good agreement with the actual injected volume (e.g., 555 vs. 513 bbl and 488 vs. 465 bbl). Therefore, it is recommended to adopt the minimum expected gel volumes in the design of gel treatments for the unconventional tight oil reservoirs.

7. Features and importance of VCR approach

In spite of its several virtues (listed in conclusions), the VCR approach presents the following drawbacks: (a) it still depends on the field experience in specifying the channeling or design type, (b) it still needs the current experience-analogy design procedure to guess one of two design variables (gel concentration) to be used in estimating the other variable (gel volume), (c) it does not explicitly consider other factors affecting the gel strength and gel volume like reservoir temperature, polymer MW and degree of hydrolysis, tapering scheme, polymer-crosslinker ratio, fluid leak off, and treatment timing, (d) it has not been well verified for production wells and horizontal injection wells, and (e) it may predict treatment designs with large relative deviations (up to 48%) as for cases 4 and 7 in Table 2.

Before delving into these points, it is first useful to know and understand the intention behind developing the gel VCR approach. The objective of this study is to provide reservoir engineers with a practical design tool for bulk gel treatments even if it gives just a simple idea about what the designs will be in the reality. In view of the complexity of the gel treatment design and the complete absence of systematic design methods in the industry, it seems that this objective represents an absolute necessity for the increased application of bulk gel treatments. This necessity can be further illustrated by imagining what would have happened in the following case study if the operator had a design model prior to field application of the gel treatment.

In the case of I-1 injector in the Kuparuk River Unit, the field execution of the gel treatment was the hardest task for the conformance team due to the extreme low temperatures in North Slope of Alaska and the large volume of the designed treatment. The team had intentionally overdesigned the initially estimated treatment size (30,000 barrel) by a factor of 50% to be 45,000 barrel (Mishra et al., 2016). This overestimation was required because this remedy was the first gel treatment in this field and no previous experiences were available at the design time. The freezing of the lines and equipment was expected at the implementation time of the treatment in October 2013. The conformance team was realizing that this treatment is a large-scale job that needs a pumping time of weeks (45,000 bbl at 5000 bpd needs 9 days), which is not a routine in Alaska. Based on this comprehension, the conformance team made several special preparations and measures to address the concerns about pumping the 45,000 barrel of gels. For example, to have a continuous water supply, four 290 bbl water transport trucks were used to fill three 400 bbl upright tanks in the site. In addition, it was decided to supply the gel-mixing water from the nearby injector I-2 by constructing a hardline (spur line). A large heated working and storage area was established using an outdoor frame structure to protect personnel and materials from the weather.

During the field execution of this treatment, the designed polymer concentrations for the treatment stages (3000, 5000, 7000, and 10,000 ppm) were exactly followed. Based on the injection pressure response, the treatment was ended having pumped 19,739 barrel of bulk gels which is just about 44% of the planned treatment size (45,000 barrel). Using the actual average gel concentration (3955 ppm), the VCR approach estimated the volume of this treatment to be 16,525 barrel (*RD* of 16.3%) and in the range of 11,700 and 20,650 barrel as shown in Fig. 6 and Table 2 (case No. 19). In addition, if the design process is started from the scratch (assuming there is no prior knowledge about the treatment) and the designed concentrations for treatment stages are used (average 5000 ppm), the VCR approach estimates the treatment size to 20,890 barrel (*RD* of 5.8%) and in the range of 14,997 and 25,838 barrel. This argument suggests that if these design estimates were available prior to the job execution, definitely, the conformance team would have taken fewer precautions to ensure the treatment execution, saving cost and time and reducing the operational risks in the harsh environment, especially during water transport.

It is noteworthy that efforts are underway on to develop a methodology to determine the channeling or design type of gel treatments based on diagnosis indicators of conformance problems. In addition, field design guidelines and new design strategy for the gel strength and gel volume of bulk gel treatments were recently provided to facilitate the design of gel concentrations (Aldhaheri et al., 2020 and Aldhaheri et al., 2022).

8. Conclusions

A novel data-driven design approach was developed for in-situ polyacrylamide bulk gel treatments by grouping and rating their field designs according to the gel VCR into three design types. The new approach estimates, in terms of one another, either the gel volume or the gel concentration based on the design and formation type. Distributions of field projects and formation types with respect to the gel VCR were comprehensively investigated to indicate the grouping criterion and design types of gel treatments. The mean-per-group strategy was adopted to build the approach by estimating the average VCR for each design type. Two approximations were used to estimate the overall gel concentration from the scheduled polymer concentrations for treatment stages. Correlations for the minimum and maximum designs in terms of predicted values were identified and included in the approach. The predictivity of the proposed approach was demonstrated using training and cross-validation samples that involve both single-treatment and averaged project data of profile-control and water shutoff treatments. R^2 values of 0.93 and 0.68 were observed for gel volumes and polymer concentrations in the training sample. For the validation dataset, an *AAPE* less than 21% and 24% were obtained for the unaveraged gel volumes and concentrations of 23 single treatments including two new injector and five producer remedies.

The analysis showed that the gel VCR is a superior design criterion for in-situ bulk gel treatments where it aggregates gel projects into three project groups that each project group is mostly dominated by one formation type. The channeling type is criterion of the grouping and group-wise ranking of the treatment designs. The VCR range of each project group represents one design type for the bulk gel treatments. Gel treatments are designed with VCRs$<$1 bbl/ppm to treat conformance problems that exhibit pipe-like channeling usually presented in unconsolidated formations and fractured formations with very long injection time (design type I). This design is also used in economically-designed gel treatments applied in matrix-rock formations. For fracture-channeling problems frequently presented in naturally or hydraulically-fractured formations, VCRs of 1–3 bbl/ppm are used (design type II). Large gel treatments with VCR$>$3 bbl/ppm are performed to address matrix-channeling often shown in matrix-rock formations and fracture networks (design type III).

Besides its simplicity and predictivity, the gel VCR approach has the following distinctive features: (a) it is the first systematic design approach for bulk gel treatments, (b) it predicts any of the two most influential design parameters, the gel volume and the gel concentration, (c) it reflects the actual relationship between the gel concentration and the gel volume as it was built using actual field data, (d) it is a practical design approach as it mimics the real treatment process, (e) it is able to predict both the field-wide and single treatment designs, and (f) it is the first design approach available in the public domain. The proposed approach will help conformance engineers in designing gel treatments using a mathematical model and in optimizing the designs of the gel treatments to improve their performances and success rate especially when they are applied in a field for the first time.

Credit author statement

Munqith Aldhaheri: Conceptualization, Methodology, Writing. **Mingzhen Wei**: Reviewing and Editing. **Baojun Bai**: Conceptualization, Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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