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Review article

A comprehensive review on proppant technologies

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ABSTRACT

The main function of traditional proppants is to provide and maintain conductive fractures during well production where proppants should meet closure stress requirement and show resistance to diagenesis under downhole conditions. Many different proppants have been developed in the oil & gas industry, with various types, sizes, shapes, and applications. While most proppants are simply made of silica or ceramics, advanced proppants like ultra-lightweight proppant is also desirable since it reduces proppant settling and requires low viscosity fluids to transport. Additionally, multifunctional proppants may be used as a crude way to detect hydraulic fracture geometry or as matrices to slowly release downhole chemical additives, besides their basic function of maintaining conductive hydraulic fractures. Different from the conventional approach where proppant is pumped downhole in frac fluids, a revolutionary way to generate in-situ spherical proppants has been reported recently. This paper presents a comprehensive review of over 100 papers published in the past several decades on the subject. The objectives of this review study are to provide an overview of current proppant technologies, including different types, compositions, and shapes of proppants, new technologies to pump and organize proppants downhole such as channel fracturing, and also in-situ proppant generation. Finally, the paper sheds light on the current challenges and emphasizes needs for new proppant development for unconventional resources.

1. Introduction

Hydraulic fracturing has been an important technique to enhance production of hydrocarbon fluids from oil and gas bearing formations. The fracturing process involves injecting a fluid at a pressure sufficiently high to break down the rock. Proppant slurries are then pumped into the induced fracture to keep it open so that the hydrocarbon production from the well can be significantly enhanced [1]. The carried proppant is of extreme importance as it provides the long term conductivity of the fracture. This paper will thoroughly review different types of proppant materials and functions which have been developed and used in the oil and gas fields. Each of these materials will have its own operating window in terms of closure stresses [2], resistance to diagenesis [3], specific gravity [4] and cost [5].

In order to carry the proppants to downhole, sophisticated fracturing fluids have been designed and engineered in the entire hydraulic fracturing process. Al-Muntasheri [1] has published a review paper recently on different types of fracturing fluid systems.

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Quantifying proppant performance before a fracturing job can add significant value to the stimulation operation. To quantify proppant performance, specific quality-control procedures outlined by American Petroleum Institute (API) and the International Standards Organization (ISO) must be followed. These standard procedures must be continuously improved owing to the inconsistency between lab results and what was observed in the field. In some cases, conductivity values in the field scenario may be less than 10% of the lab-measured values [6]. Some factors which can cause the underperformance in the field include non-Darcy or multiphase flow, fines plugging, proppant embedment, formation spalling, filter cake build up [7,8], and gel damage [9]. The net effect can result in 98% reduction in conductivity compared to the baseline conductivity [10].

To the best of the authors' knowledge, there is no recent paper that summarizes the experience and advancements in the field of proppants. The objectives of this paper are to: provide an overview of the existing proppant technologies, including the basic types of proppants and advanced proppants, and advancements in proppant technology which have been developed in recent years.

2. Proppant basics

2.1. Size of proppant

The size range of the proppant is very important for hydraulic fracture treatment. Proppant sizes are generally between 8 and 140 mesh (105 μm–2.38 mm). The mesh size is the number of openings across one linear inch of screen. When describing the size of the proppant, the proppant is often referred to as simply the sieve cut. For example, 16/30 mesh is 595 μm–1190 μm; 20/40 mesh is 420 μm–841 μm; 30/50 mesh is 297 μm–595 μm; 40/70 mesh is 210 μm–420 μm; 70/140 mesh is 105 μm–210 μm. Typically, larger particle sizes provide higher fracture conductivity. The traditional fracture treatment will start with smaller particle size proppant and tailor with larger particle size proppant to maximize the near wellbore conductivity.

The dry sieve analysis is the standard way to measure the mesh size. It has been well documented in the API/ISO standard testing procedures. Laser diffraction technique is a new way to measure the particle size distributions. Kumar et al. [11] compared the two particle size measurement techniques. They concluded that the two techniques give comparable particle size readings for granular materials up to around 500 μm; Above this size, sieve analysis is preferred. This agrees with the work from Growcock et al. [12] which suggests that sieve analysis and laser diffraction results begin to deviate with larger particles.

It is common in hybrid completion designs to mix various sizes of proppant based on stimulation design assumptions and criteria. Mixing of various proppant sizes in stimulation treatments has the potential to reduce permeability. For example, application of 100 mesh is likely problematic relative to 20/40 proppant due to the potential for the 100 mesh to invade and occupy pore space. Schmidt et al. [13] investigated how different proppant sizes perform when mixing of different proppant sizes and tail-in mixing. They found that higher concentrations of more conductive proppant have a significant impact on propped fracture conductivity. Larger size LWC (lightweight ceramic) proppant mixed with 40/70 sand significantly improves the conductivity of the overall proppant pack, regardless of concentration. Low concentrations of 40/70 sand mixed with larger size LWC proppants have nearly the same conductivity as high concentrations of 40/80 LWC mixed with larger size LWC. Tail-in mixing experiments in the laboratory show higher conductivities than experiments where proppants are blended.

Hu et al. [14] published a brief overview of different proppant types and amounts used in stimulation designs in the Bakken shale play between 2011 and 2013. The results are based on four case studies that focused on 72 wells in four different fields and the production rates were compared based on the 270 day production data. To assure a fair comparison between the different types of proppants and minimize other effects, the wells were chosen from the same field, similar fracture dates, and by the same operator. The well production data is summarized in Table 1. It was concluded that using a combination of high percentages and large amounts of ceramic proppant has yielded higher production and estimated ultimate recovery (EUR). The use of ceramic proppant not only recovers the additional cost in a short period of time, but also generates higher revenue in the long term.

2.2. Proppant transport

Proppant suspension in the fracturing fluid is very important to deliver proppants to the wellbore and into the created fractures. In the traditional view, that is still dominant in oilfield industry, the most important parameter in fracturing fluid design is viscosity. Viscosity can be measured at a constant shear rate (40 s^{-1} or 100 s^{-1} are typically used) by a viscometer. This is based on the classical Stokes' law, which states that the sedimentation velocity is inversely proportional to the medium viscosity. This has been applied to most of the fracturing fluids design, including guar-based fluids, cellulose-based fluids and recently developed synthetic polyacrylamide based fluids. Later it has been found that the fluid elasticity is another important parameter that controls proppant suspension [15–17]. The viscoelastic surfactant (VES) fluids have been developed based on this view [18,19]. Both the elastic (G') and viscous (G'') modulus can be measured using a dynamic-oscillatory rheometer. These measurements were done using proppant-free fracturing fluids. A new slurry viscometer [20–22] was developed in 2004 that is capable of incorporating proppants and measuring the proppant transport characteristics of the fluid.

In slickwater fracturing in shale reservoirs, the mechanism of proppant transport is different. Since slickwater has only small concentration of polymers (up to 2 gpt), it does not have high viscosity or elasticity required to keep the proppant in suspension. In this case, the proppant settles faster under static conditions, and proppant transport may be dominated by the movement of the proppant bank itself.

Three proppant transport mechanisms in slickwater have been proposed [23,24]. At very low velocity, little or no proppant is moved. At higher velocity, proppant grains roll or slide along the surface of the settled proppant bank (reptation creep). At even higher velocity, proppant grains bounce off the surface back into the flow stream (saltation). Dufek and Bergantz [25] demonstrated that saltation depends on the coefficient of restitution which is defined as the ratio of the velocity with which the object leaves after a collision to the velocity with which it enters the collision. Proppants with a higher coefficient of restitution and a lower friction coefficient than other proppants will be transported deeper into the fracture.

3. Basic types of proppants

Since the first fracturing operation was done with silica sand proppant in 1947, many materials have been used as proppants including walnut hulls, natural sand, glass, resin coated sand,

Table 1
Case study of well production on Bakken shale play with different types of proppant selection [14].

Case study	Group	Average weight of proppant per well (MMlb)	Type of proppant & mesh size	Avg. Cum. Production (BOE)		
				90 days	180 days	270 days
I	A	3.3	mixture of 29% resin coated sand (20/40 and 40/70) and 71% silica sand (20/40 and 40/70)	26,044	44,261	57,498
	B	3.16	mixture of 32% ceramic (20/40) and 68% silica sand (20/40 and 40/70)	29,722	50,790	63,732
II	A	2.5	100% silica sand (20/40 and 40/70)	19,892	33,712	45,954
	B	2.7	mixture of 30% lightweight ceramic (20/40) and 70% silica sand (20/40 and 40/70)	36,538	68,570	92,764
III	A	2.9	mixture of 35% of ceramic (20/40) and 65% silica sand (20/40 and 40/70)	39,226	63,676	81,964
	B	3.85	mixture of 62% ceramic (20/40) and 38% silica sand (40/70)	54,757	82,546	107,931
	C	3.9	100% ceramic proppant (20/40 or 30/50 and 40/70)	61,351	104,170	137,117
IV	A	2.45	100% silica sand (no mesh size information)	23,134	40,244	54,362
	B	2.6	mixture of 32% ceramic (20/40) and 68% silica sand (20/40 and 40/70)	56,251	86,127	109,627

sintered bauxite and kaolin, and fused zirconia [26]. Common sand dredged from the Arkansas River was first introduced as a proppant to hydraulic fracturing in 1947 [27]. Even now, sand and ceramic proppants are the two most common proppants in fracturing processes.

3.1. Sand (frac sand/silica sand)

'Sand', 'Frac sand' or 'silica sand' is composed of processed and graded high-silica content quartz sand. Since Stanolind Oil conducted the first experimental fracturing in the Hugoton field utilizing sand from the Arkansas River in 1947, sand has remained the most commonly used proppant for hydraulic fracturing process because of economic advantages.

Generally, Frac sand is not used as-mined without processing. It is subjected to further processing for optimum performance. The processes include extracting material from silica sand deposits, crushing, washing/cleaning, drying and sizing the sand grains. There are two major types of frac sand, namely white sand and brown sand. Most white sand is mined from geological formations found in the Midwest region of the United States [28]. Because of their light color (due to few impurities), these sands are often known as white sand. Brown sand does not contain as high percentage of silica as the white sand. Its brownish color is due to the higher impurity content, which makes it cheaper and more prone to crushing at lower stress.

Fig. 1 shows the industrial sand and gravel production in the United States from year 2010 to 2014 as reported by U.S. Geological Survey (USGS) in Mineral Commodity Summaries2015[1] released in January 30, 2015. The increase in sand consumption is largely attributable to the recent rapid expansion of shale oil and gas which is heavily dependent on the use of the hydraulic fracturing process. In 2014, about 72% of the US sand and gravel production was used as hydraulic fracturing sand and well packing and cementing sand.

3.2. Ceramic proppant

As sand was not capable to withstand high closure stresses (up to 6000 psi), higher strength ceramic proppants were introduced to the market. Ceramic proppants are manufactured from sintered bauxite, kaolin, magnesium silicate, or blends of bauxite and kaolin. Compared to silica sand, ceramic proppant has higher strength and is more crush resistant especially where closure stresses exceed 8000 to 10,000 psi. Additionally, it is more uniform in size and shape, and has higher sphericity and roundness to yield higher porosity and permeability of the proppant bed. Furthermore, ceramic proppant has the highest thermal and chemical stability, which can minimize diagenesis. All of these properties contribute to its higher conductivity both in short and long term inside a fracture. Being an engineered product with a more complex manufacturing process, ceramic proppant is more costly than uncoated or resin coated sand.

Ceramic proppants can be further divided into three broad classifications based on their density, namely, lightweight ceramics (LWC), intermediate density ceramics (IDC) and high density ceramics (HDC). The alumina content of ceramic

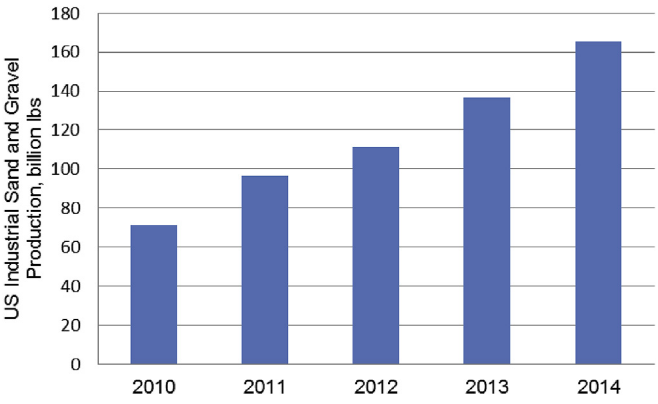

Fig. 1. Industrial sand (typical size range from 0.075 m to 4.75 mm) and silica gravel (typical size range from 4.75 mm to 76.2 mm) production in the United States from year 2010 to 2014 (Data source: USGS Mineral Commodity Summaries 2015).

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[1] USGS Mineral Commodity Summaries 2015. http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcs2015.pdf.

Table 2
Alumina content and specific gravity for different grade of ceramic proppant.

Ceramic proppant	Alumina content (%)	Specific gravity (S. G)	Reference
LWC	45 to 50	2.55 to 2.71	Carbo[a]
IDC	70 to 75	~3.27	Carbo[a]
HDC	80–85	~3.5	Carbo[a]
UHSP	Nearly 100	~3.9	[2]

[a] http://www.carboceramics.com.

proppants correlates well with the pellet strength and the proppant density. The approximate correlation between alumina content and strength is true provided the proppant grains are of high quality and manufactured in a manner which minimizes internal porosity. LWC typically contains 45–50% alumina; IDC contains 70–75% alumina; HDC contains 80–85% alumina (Table 2). However, Palisch et al. [2] have reported that even if the alumina content increased to nearly 100%, the conductivity performance would not improve much more. They coupled a raw material that is very high in alumina content with a new manufacturing process that creates extremely spherical, monosized, fully densified particles. Such proppants are referred to as ultra-high-strength proppant (UHSP) can be rated to 20,000 psi in crushing strength.

4. Modified proppants

4.1. Resin coated proppant (RCP)

Since frac sand is easily friable, and creates fines when it is over-stressed, resin coated sand was developed to enhance the conductivity of frac sand. The same coating technology has been applied to glass beads and ceramic proppants as well. All these proppants belong to resin coated proppant (RCP) category. The main advantage of using resin to coat proppant is that the resin coating can trap pieces of broken grain within the coating, thereby preventing proppant flowback to wellbore. They also could connect individual proppant grains together to prevent the proppant flowback. In this way, they are commonly used in tail-in fracturing process [29]. RCP can also be used as a way to prevent sand production in areas of soft formations where sand control is needed [29,30]. The main disadvantage of the resin coating is that since the coating material is made of polymers, they tend to have low softening temperatures or low degradation temperatures compared to inorganic materials.

Proppants are either pre-coated with resin in a production facility and taken to location, or coated at the well site by liquid resin coating (LRC) systems [30–32]. The resin coat can be pre-cured or curable. In general, uncured resin systems have poor mechanical properties. However, good properties are obtained by reacting the linear resin with suitable curatives to form three-dimensional crosslinked thermoset structures. This process is commonly referred to as curing. Pre-cured, resin-coated sand is processed by applying or “coating” the resin on to silica sand. No further curing will take place downhole. For curable resin-coated proppant, the well is shut-in after fracturing to allow curing. The curing process results in a consolidated proppant bed with a coating of cured resin surrounding each proppant grain. The performance of the proppant depends on the properties of the cured resin material. The chemical crosslinks that form during the cure of the resin materials do not allow the cured material to melt or flow when re-heated. However, cured/crosslinked resins do undergo a very slight softening at elevated temperatures at a point known as the Glass Transition Temperature (T_g). When the temperature is above the T_g, the mobility of the polymer chains increases significantly and the cured resin changes from a rigid/glassy state to more of a rubbery/compliant state. In this case, the resin system becomes soft and the strength decreases. So T_g has been used as a valuable parameter to determine the upper performance limit of the resin.

The most commonly used resins used to coat proppants are epoxy resins, furan, polyesters, vinyl esters, and polyurethane. The types of polymers and their properties are listed in Table 3 (modified from Zoveidavianpoor et al. [33]). Epoxy resin is the main type of polymer which is used for proppant coating, mainly because it has very good mechanical strength, excellent heat resistance and chemical resistance. Furan resin is another type of polymer used for proppant coating. Furan has great resistance to heat and water. However, furan does not provide enough mechanical strength. Polyurethane is another type of polymer which can be used for coating proppant. It can provide great mechanical strength, good heat resistance and chemical resistance when the application temperature is below 250 °F [34].

Resin systems are typically made from a reactive base polymer and a curing agent/hardener. For example, epoxy resins are made from an epoxide resin and an amine hardener. The properties of the cured resin depend on the nature of the hardener and also the stoichiometry (molar ratio) of the resin and hardener. Dewprashad et al. [35] has reported that the best results were achieved when stoichiometric reactant amounts near 1:1 are used. The properties are also dependent on the curing time and temperature. Dewprashad et al. [35] introduced an apparatus (consolidation chamber) to measure the Young's modulus of consolidated core of resin-coated proppant as a function of temperature. The plots generated from this test such as Fig. 2 (source: Dewprashad et al. [35]) were used to determine the glass transition temperature of the resin coating, making it a useful tool for RCP selection. In this plot, the young's Modulus

Table 3
Coating polymers and their properties (modified from Zoveidavianpoor et al. [33]).

Polymers	Application temp (°F)	Strength	Heat resistance	Chemical resistance
Epoxy Resin	250–400	Good	Excellent	Good
Furan Resin	375	Poor	Moderate	Good
Polyester	212–300	Fair	Fair	Moderate
Urea Aldehyde	250–400	Good	Excellent	Good
Polyurethane	210–250	Good	Good	Moderate
Phenol-aldehyde	250–400	Good	Excellent	Good
Vinyl Esters	212–300	Fair	Fair	Moderate
Furfural Alcohol and Furfural	250–400	Good	Excellent	Good

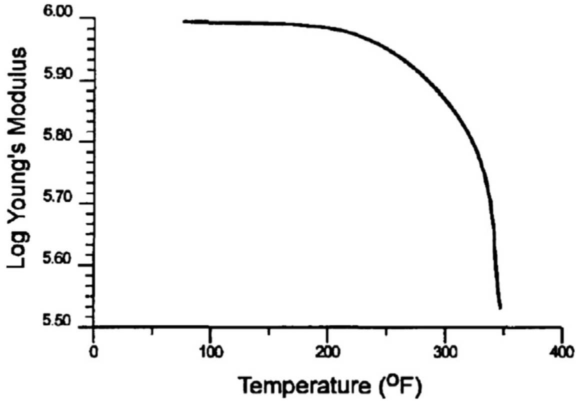

Fig. 2. Resin with a glass transition of 300 °F (source: Dewprashad et al. [35]).

decreases sharply at 300 °F, suggesting this particular cured resin system has T_g around this temperature.

4.2. Lightweight proppant

The specific gravity (S.G) of sand is approximately 2.65 and the manufactured ceramic proppants have S.G as high as 3.9. Both of these are significantly heavier than the water (S.G of 1.0) or brine solutions (S.G of about 1.2) which are typical base fluids used to carry the proppant to the formation. As a result, there are three major trade-offs in using high density proppants. First, using higher density materials means smaller fracture volume for a fixed weight of proppant. Second, higher density material means higher cost. Third, a higher density material will have faster settling rate in the carrier fluids. To prevent settling, the common practice is to use high viscosity fracturing fluids to keep the proppant material suspended to allow it to penetrate further into the fractures.

Ultra-lightweight proppant is preferred in some applications since it reduces proppant settling, requires low fluid viscosity to transport and allows for increased propped length. Shale reservoirs are often fractured with low viscosity slickwater which generates long fractures and causes minimal formation damage compared to crosslinked fluids. Due to the low viscosity of the slickwater, a high density proppant cannot be carried efficiently. As such, very high pumping rates are employed to transport the proppant into the fracture by velocity rather than the fluid viscosity and elasticity. Alternatively, a proppant with lower density can be more useful in situations where high pump rates or carrier fluids with low viscosities are needed.

Several techniques have been used to reduce specific gravity of the proppant. Table 4 compares specific gravities of different types of lightweight proppants. The S.G for lightweight proppant ranges from 0.8 to 2.59.

One way to make lightweight proppant is to select a proppant material which has a lower specific gravity. Walnut shells, pits and husks were the earlier types of lightweight proppant used in the field. Even though such materials would penetrate deeper into the formation, their low structural strength limits their applicability to formations with relatively low closure pressures. Additionally, small particle fragments resulting from crushing of such materials reduce the conductive space available for fluid flow by reducing the fracture network.

Table 4
Comparison of specific gravity of different types of lightweight proppants.

Proppant	Specific gravity (S.G)	Reference
Walnut Shells	~1.25	Parker et al. [4]
Resin-impregnated and coated, chemically modified walnut hull	1.25	Rickards et al. [36]
Plastics	1.1 to 1.4	Parker et al. [4]
Thermoplastic Alloy	1.08	Parker et al. [4]
Nanofiller reinforced thermoset polymer	N/A	Bicerano [37,38]
Porous Ceramics	1.8 to 2.4	Parker et al. [4]
Resin-coated porous ceramic proppant	1.75	Rickards et al. [36]
Low density material coated porous ceramic or silica sand	N/A	Rediger et al. [39]
Advanced Ceramic Proppant	2.0 to 2.9	Mack and Coker [40]
Hollow glass spheres	0.8 to 1.4	Parker et al. [4]
Hollow spheres and hollow, closed-ended elongated particles (glass, ceramic, metals, metal oxides)	0.8 to 1.75	Parse and Jette [41,42]
Inorganic materials coated low cost silica sand	2.55 to 2.59	Bestaoui-Spurr [43]

Rickards et al. [36] have reported a resin-impregnated and coated, chemically modified walnut hull as ultra-lightweight (ULW) particles. The material has a specific gravity of 1.25 and bulk density of 0.85 g/cm^3. It can withstand up to 6000 psi closure stress at 175 °F. As temperature increases, the maximum closure stress limitation for this material declines. The closure limit at 225 °F is 4000 psi.

Parker et al. [4] have investigated a new type of thermoplastic alloy (TPA) that is composed of a crystalline phase for excellent chemical stability and an amorphous phase for excellent dimensional strength and heat resistance. The specific gravity of this type of proppant is 1.08, which is very close to that of an aqueous fracturing fluid. The low-density TPA proppant has a better potential to achieve a widely dispersed arrangement than the conventional proppants. A monolayer proppant concept has been proposed for TPA particles since it seems to provide much more porosity than tightly packed proppant beds. In a laboratory test, a test cell load of 6000 psi and a TPA proppant concentration sufficient to only partially cover the formation face (0.1 lbm/ft^2) was employed. The effective stress on the particles supporting the load was greater than 11,000 psi. The fracture porosity was about 74% at the start of the test and ended at about 46%. The upper temperature limit for this type of proppant is 250 °F.

Since the fines generated from proppant crushing could cause fracture conductivity loss, deformable proppant was proposed by Brannon et al. [44] as ultra-lightweight (ULW) propping agent. The deformable ULW proppant has an apparent specific gravity less than or equal to 1.25. The deformable proppants could be selected from natural products such as nut shells, seed shells and fruit pits. Alternatively, they can be deformable resin systems such as furan, furfuryl alcohol, phenolic resins, epoxy resins and thermoset polymers. The selection of the proppant is dependent upon the mechanical properties of the formation rock. The maximum elastic modulus of the deformable proppant is less than the minimum modulus of the formation rock being fractured. This method is particularly applicable in fracturing of subterranean reservoirs such as those comprised primary of coal, chalk, limestone, dolomite, shale, etc.

Because of the limited strength of the deformable proppants, Bicerano [37,38] invented a new way to improve their mechanical strength by reinforcing impact-modified ultra-lightweight thermoset polymer with nanofillers. The thermoset polymer matrix used is either styrene-divinylbenzene copolymer or a styrene-ethylvinylbenzene-divinylbenzene terpolymer. An impact modifier and a nanofiller are blended into the polymer.

Rickards et al. [36] have reported another type of ULW proppant which is resin-coated porous ceramic proppant (ULW-1.75). The resin coating prevents the fluid invasion into the proppant in order to maintain the reduced density. The porosity averages 50%, yielding a bulk density of 1.10–1.15 g/cm^3 and a specific gravity of 1.75. The performance limit of this ULW proppant is 8000 psi closure stress at 275 °F.

Another method of reducing the specific gravity of proppant while retaining structural strength is to coat a strong higher density proppant with a lower density material. Rediger et al. [39] invented a composite proppant comprising a core proppant substrate such as a porous ceramic or a silica sand that is coated with a particulate material having a density less than the apparent density of the proppant substrate to increase the buoyancy of the composite proppant. The amount of coating was in the 0.1%–20% range by weight of the composite proppant. Coated particles can be better suspended in the fracturing fluid.

One method of reducing the specific gravity of proppants is to incorporate voids into a proppant that has inherently high crush strengths. Mack and Coker [23,40] introduced a unique family of advanced ceramic proppants which are based on formulated mixed-metal oxides. These advanced ceramic proppants have a higher strength/weight ratio than conventional ceramic proppants. The improved process of making advanced proppants involved spraying a formulated mixed-metal oxide slurry shell over the hollow template. The formulation, spraying process and sintering method are designed to eliminate the creation of porosity and flaws. It also minimizes the variation of pore size in the shell. The proppant pack conductivity of advanced ceramic proppant is higher than the conductivity of conventional proppants and sand in industry-standard tests.

Parse and Jette [41,42] developed ULW proppants made from hollow spheres and hollow, closed-ended elongated particles, having a uniform and continuous wall composed of single or multiple component materials from glass, ceramic, metals, metal oxides, or a combination such that the particle has a neutral buoyancy or substantively neutral buoyancy while retaining structural integrity against hydrostatic or contact loading. The materials can have a density of about 0.8 g/cm^3 to 1.75 g/cm^3.

While some coatings are meant to harden the exterior of the proppant thereby contributing to strength, coated proppants ultimately behave as basic sand particles. Bestaoui-Spurr [43] proposed an approach to increase the strength of the low-cost silica sand by coating them with inorganic polymers. The physical properties of the inorganic polymers are largely determined by their composition. The coating was made of a solid inorganic network having an amorphous three-dimensional structure that significantly increased the compressive strength of silica proppant. The resulting coated proppant materials have specific gravities of 2.55–2.59 g/cm^3, and are tolerant to high closure stresses (over 10,000 psi). The sieve distribution of the generated fines in crush test suggests that the mechanism of decreasing fines generation compared to uncoated samples is due to a strength increase, not to a stress distribution as observed in the case of resin-coated proppant, where the polymer diffuses the stress, resulting in larger broken particles that are retained within the polymer coating.

Although there are ways to make lightweight proppant, strength will be a critical way to determine at what pressure these proppant can be used. Fig. 3 (source: Palisch et al. [2]) shows the stress at which a conductivity of ~1750 mD-ft is maintained for different types of proppants. It aligns well with the common concept that higher density materials can typically withstand higher stress in order to maintain the same conductivity.

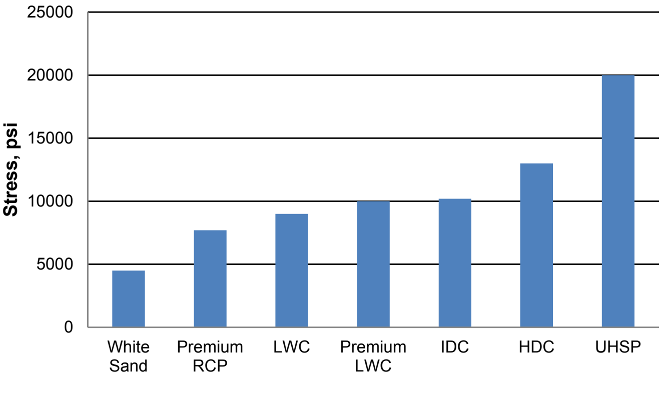

Fig. 3. Stress at which ~1750 mD-ft is maintained for different types of proppants (Source: Palisch et al. [2]).

5. Advancements in proppant technologies

5.1. Multifunctional proppants

As mentioned earlier, the primary function for proppant is to maintain a conductive fracture during well production. Beyond that, it can serve as a matrix to deliver chemicals deep into the reservoirs. Multifunctional proppants such as traceable proppants and proppants filled with chemical additives or costed with chemicals have been used in the field for long-term well performance.

5.1.1. Traceable proppant

After hydraulic fracturing treatment, it is highly desirable to obtain detailed information about the stimulation treatment, such as location and geometry of created hydraulic fractures. It is also important to determine if the hydraulic fracture has extended to unwanted zones such as water zones. Acoustic, nuclear or temperature logs are the common ways used for induced fracture detection in the near wellbore region; tiltmeter or microseismic measurements are used for estimation of the induced hydraulic fracture location and fracture dimensions in the far-field region.

The most common nuclear method involves the use of radioactive materials. Radioactive tracers can be detected by gamma ray logging tools. The radioactive tracers can be made by coating sand with radioactive materials, mixing with pulverized natural radioactive materials, impregnating radioactive ion exchange resins or ground plastic into proppants. When mixed with regular proppant during the fracturing process, these radioactive materials will emit gamma rays. Then gamma ray detectors, which have been in use in the oil industry since early 1940's, are used to log after the hydraulic fracturing process. The gamma rays from the radioactive tracers are detected, recorded and analyzed either in real time during wireline logging run [45], or recorded into memory and processed later after the tracers are retrieved [46]. This technique is typically very effective and can be used to trace signals from multiple tracers. However, since the radioactive material has relatively short half-lives, the proppants have to be employed shortly after being generated. It resolves the concerns of the handling, transportation, storage and environmental concerns of handling a radioactive material.

McDaniel et al. [47] has patented an advanced technique which involves non-activated radiation-susceptible materials capable of being activated by a neutron source. These materials can be incorporated into the resin coating of the proppant or into the composite composition of the proppants to be pumped downhole the same way as the radioactive tracers. Then a logging tool which contains a pulsed or continuous neutron source and gamma ray detector is moved past the intervals containing the traceable proppant. The gamma rays emitted from the neutron activated tracers are then detected by the sensor in the tool when it passes through a zone containing the activated material. The advantage of this technique is that it resolves the concerns of the handling, transportation, storage and environmental concerns of handling a radioactive material. However, the neutron source will not only activate the tracers; it can also activate other nuclei presented in the formation. A correction for the gamma rays from naturally occurring materials needs to be considered when processing the data. Also, since nuclei with long half-lives require a long time to activate, it will slow down the logging speed. The depth of the investigation of this method is relatively short since the source neutrons and emitted gamma rays are attenuated as they travel though the formation.

Duenckel et al. [48] reported a technique which can detect the fracture geometry without using radioactive elements. This is accomplished by incorporating a high thermal neutron capture compound (HTNCC) at low concentrations into each ceramic proppant grain during manufacturing process. The concentration of the HTNCC is sufficiently low such that the proppant properties are not affected. The HTNCC-containing proppant can be pumped downhole and into the induced fractures. Because these high thermal neutron capture compounds absorb neutrons, changes to neutron levels can be detected using conventional compensated neutron logs (CNL) or pulsed neutron capture (PNC) tools. The proppant containing zone is scanned using after-frac compensated neutron logs and the results are compared with the corresponding before-frac logs. The location of the detectable proppants was determined from analysis of before-frac and after-frac compensated neutron logs [48–52].

Han et al. [53] has shown log examples which illustrate the effective detection of HTNCC tagged proppant placement within fractures and cement. Monte Carlo modeling indicates the possibility of using HTNCC tagged pack material in gravel packs and frac packs. This technological advancement will expand the portfolio of traditional radioactive tracers while diminishing the downsides of using radioactive tracers such as undesirable environmental, regulatory, and safety issues [54].

5.1.2. Slow-released solid scale inhibitor

Mineral scale build-up is one of the major concerns in maintaining productivity over the lifetime of a well. It can decrease permeability of the formation, plug tubulars, reduce the well productivity and shorten the lifetime of the production equipment [55]. To prevent scale formation, chemical inhibitors are commonly used in production wells. Chemical scale inhibitors are efficient at ppm (parts per million) levels. When these chemicals are applied in solution form, typically as a squeeze treatment or as a frac fluid component, there is not much control over their long term, in situ release rate. In order to provide long term inhibition of scale deposition, slow release of these chemical inhibitors is needed. The use of porous ceramic proppant as carrier to deliver chemicals downhole was introduced in the early 1990's, and a number of field applications of the technology have been documented [56,57]. Scale inhibitors were the first types of chemicals to be used with this technology. The chemical infused ceramic proppant can be mixed with regular proppants and pumped downhole. After the well is put on production, produced water samples are collected to monitor the concentration of the inhibitor.

Gupta and Kirk [58] extended incorporation of scale inhibitors onto a high surface area water-insoluble adsorbent to inhibit the formation of inorganic scales in a subterranean formation or wellbore. The composite may be introduced into an oil or gas well with a carrier fluid. The scale inhibitor was infused into the high surface area adsorbent and the concentration of the scale can be controlled by releasing rate of the scale inhibitors into the formation. Prolonged chemical inhibition is the desired outcome of placing a solid inhibitor during the fracturing process. A “solid inhibitor” [59–61] refers to an inert, proppant-sized, solid particle adsorbed with chemical inhibitors using this technology. This technology has been introduced to over 2000 wells in 5 years since May 2005. Szymczak et al. [59] presented the initial findings on the scale inhibitor residues from wells treated after a year. The same wells were reported for up to three years [62] and five years [60]. The longevity metric of the original placement showed the scale inhibitor were still effective after 3.5 years of production.

Brown et al. [63] have studied the long-term release rate and mechanism for solid scale phosphonate type inhibitors in laboratory on solid inhibitors loading from 0.05% to 10% by weight of proppant. They have shown that when solid inhibitor loading is less than 5wt%, the return concentration of the inhibitor in the fracture is a function of the surface area of solid matrix exposed to the return fluid. The release rate of inhibitor is probably dominated by the desorption rate of inhibitor from the solid substrate. When the solid inhibitor loading exceeds 5%, the precipitation mechanism might start to dominate the release rate of phosphonate inhibitor. Since the released inhibitor might react with ions such as calcium in the aqueous phase to form a precipitation in a complex reaction, not much increased concentration of inhibitor has been observed. A model was developed to predict the lifetime of the solid inhibitor based on the lab and field data as well.

Duenckel et al. [64] reintroduced chemically infused porous ceramic proppant technology with designs that will incorporate the porous proppant without negatively impacting the conductivity of non-porous proppant packs. This was accomplished through the selection of both the magnitude of porosity and the type of ceramic proppant. The porous proppant has been infused with the appropriate production chemicals and was then encapsulated. The encapsulation of the product reduces the amount of chemical lost during placement and improves the chemical elution profile, resulting in a much longer treatment life. The infused ceramic proppants can be introduced during the initial fracturing of the well by adding a designed small weight fraction to the rest of the proppant volume in the fracture treatment. Leasure and Duenckel [65] present a case history on using these infused and encapsulated solid scale inhibitors in five wells at the Uinta Basin. No signs of scale have been observed in any of the trial wells after first 6 month of treatment. This scale inhibitor delivery technology could be extended for other production chemicals such as paraffin inhibitors, halite inhibitors, gel breakers and others.

5.1.3. Slow-released paraffin inhibitor

Paraffin accumulation is another concern during oil production. Paraffins are defined as hydrocarbon molecules with carbon chain lengths above 18. Within a reservoir, paraffin is in equilibrium with other fluids. Upon pressure and temperature drop during production, the lighter hydrocarbons which act as solvents for paraffin under reservoir conditions could be volatilized. As a result, the heavy paraffin is no longer soluble in the remaining fluid and tends to precipitate out. Paraffin inhibitors are molecules designed to kinetically inhibit seed crystallization and mass agglomeration of paraffin wax. The traditional way to prevent paraffin inhibition is to run a continuous application into the fluid stream, batch application downhole and squeeze application at the near wellbore.

Gupta and Walter [66] extended the concept of using water-insoluble substrates as carriers to incorporate well treatment agents. The well treatment chemicals included corrosion inhibitors, paraffin inhibitors, salt inhibitors, gas hydrate inhibitors, asphaltene inhibitors, oxygen scavengers, biocides, foaming agent, emulsion breakers and surfactants. The lifetime of the composite introduced in the single treatment step is at least six months. Gupta et al. [67] presented an application of this method of delivering solid production chemicals added to the fracturing fluid for scale, paraffin and asphaltene inhibition. The solid inhibitors for scale, corrosion or salt deposition or for biocide activity desorb into the produced water, while the solid inhibitors for paraffin or asphaltene inhibition desorb into the hydrocarbon phase.

Since November 2007, this new approach to deliver solid paraffin inhibitors has been applied in over 2000 wells, primarily in the US and Canada [68–70]. The details of some field applications are summarized in Table 5. The solid inhibitor composite is distributed throughout the proppant pack during the hydraulic fracturing treatment. The release rate depends on the temperature of the oil and the rate of production. Higher production rate wells correlate with faster consumption of the solid inhibitor [67].

Since the introduction of this chemical delivery technology in 2005, more than 15,000 wells have been treated to prevent scale, paraffin or asphaltene deposition. Gupta et al. [71] discussed using high-strength bauxite as the substrate for solid inhibitors. When bauxite containing up to 20 wt% production chemicals in its porosity was tested for its closure stress resistance, no conductivity loss was observed up to 16,000 psi closure stress.

5.1.4. *Slow-released breaker*

A concept has been patented by Duenckel [72] for introducing a chemical breaker into the fracturing fluids system. After fracturing and proppant placement, the viscous fluids need to be removed from the proppant matrix. In addition, the filter cake formed on the fracture surface needs to be cleaned as well. Thus, breakers are used as part of the fracturing fluid package to clean up the gels and filter cakes. Breakers used in this application include enzymes, as well as oxidizing agents such as peroxides, persulfates, perborates, organic acids and chelating agents [1]. Typically the breakers designed to break the crosslinked fluid are added directly to the fracturing fluids. The new method utilizes chemical breakers coated onto the surface of a non-porous proppant or placed in the pore space of a porous proppant then coated with an encapsulating outer layer (polyvinylidene chloride) that can be tailored to delay the release of the breaker. The method avoids pre-mature fluid viscosity breakdown resulting in proppant screen out. It also provides better cleanup for the residue gel and gel filter cake since the breakers are located on the proppant surface directly in contact with the gel residues.

5.1.5. *Multiphase flow enhancer*

Traditional proppants have water-wet surfaces, which tend to retain the water blocks within the proppant pack and reduce the relative permeability to hydrocarbons. Palisch et al. [73] developed a new technology to modify the proppant grains with a thin, durable coating which is neutral-wet. The modified surface does not have an affinity to water, oil or gas, therefore it will improve the fluid recovery after stimulation process, and also it will increase the production rate for hydrocarbons. This concept yields significant advantages under multiphase flow conditions. The application temperature for this coating has been tested up to 400 °F.

5.1.6. *Contaminant removal*

It would be desirable to have a type of proppants that would acts as a traditional proppant to keep the fracture open as well as perform filtering, cleaning or removing contaminants. One concept of using proppant grains to remove one or more of the contaminants from a production well have also been developed [74]. Depending on the nature of the contaminants, they can be removed by any chemical, physical or biological ways. This can be achieved by incorporating contaminant removal component either coated onto the proppant grains or filled in the pores of porous proppants.

5.2. *Proppant with different shapes*

Traditionally the ideal proppant shape should be spherical or nearly spherical and non-angular because in this case, a tighter proppant pack and optimized pore throat size will form. The sphericity and roundness standard evaluates the proppant shapes. Fig. 4 [75] shows the standard reference scale used for rating proppant shapes. A lower Krumbein number indicates a more angular proppant. Angular and pointed proppant particles tend to break off points, which lead to lower conductivity at higher closure stress. ISO13503-2:2006/Amd.1:2009(E) [76] specifies the sphericity and roundness requirements for different proppants. Ceramic proppant and resin-coated ceramic proppants require an average sphericity of 0.7 or greater and an average roundness of 0.7 or greater. All other proppants shall have an average sphericity of 0.6 or greater and an average roundness of 0.6 or greater. Perfectly spherical proppants with narrow size distribution provide fractures with the highest conductivity.

In recent years, different shapes of proppants other than conventional spherical shape have been developed. The concept of using elongated, rod-shaped proppants was introduced recently [77–79] since the rod-shaped proppants (Fig. 5, left) theoretically offer a higher conductivity due to a higher porosity in their packing. From theory to practice, McDaniel et al. [77] measured the untapped pack porosity in the lab for spherical proppant and rod-shaped proppant, which came to be 37% vs. 48%. The conductivity results have also demonstrated the benefit of rod-shaped proppant over spherical proppant across the entire closure stress range (Table 6). However, the variation in rod length and diameter can increase the risks of placement, impact conductivity and affect proppant flowback performance. The rod length distribution should be estimated to ensure that the amount of the short rods and long rods is within the specified

Table 5
The effects of applying solid paraffin inhibitor.

Wt% of chemical loading	Surface area of the substrate (m^2/g)	Coating	Size	Formation	Results	Reference
Not reported	Not reported	No	20/40	Permian Basin Wells	Increased and prolonged production has been observed.	Smith et al. [68]
Not reported	Not reported	No	Not reported	Viking Formation in southern Saskatchewan Canada	~40% increase in the oil production in the first 350 days	Wornstaff et al. [69]
0.2	2	No	20/40	Eagle Ford Shale Oil in South Texas	No deposition has been observed in over 10 months (3 months if no treatment)	Szymczak et al. [70]

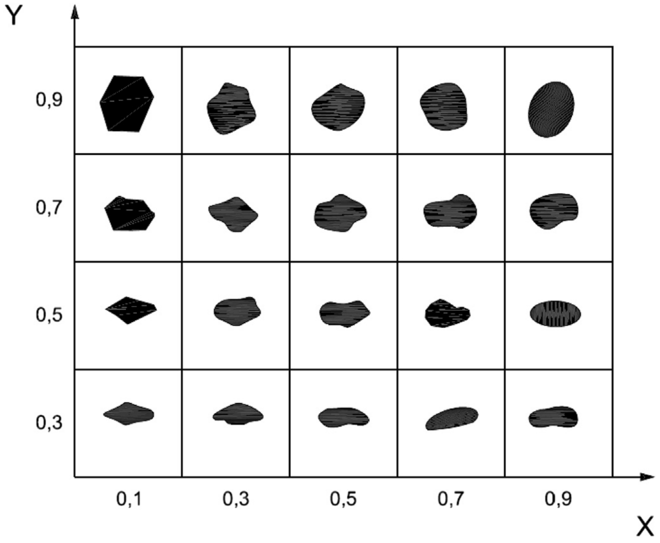

Fig. 4. Chart for visual estimation of sphericity and roundness (X-Roundness; Y-Sphericity) (Source: Krumbein and Schloss [75]).

limits for adequate product performance. It has shown superior proppant flowback control in the Egyptian Eastern Desert [79,80].

Liu et al. [81] investigated a different shaped high drag ceramic proppant. The concept is based on the relationship that increasing the drag force of the proppant particles will reduce the proppant settling velocity. The shaped proppant is designed and optimized in a way that center of gravity and centroid of volume do not align in a stable manner, so the proppant particles tumble and flutter when settling in a fluid. The new designed shaped proppant (Fig. 5, right) has shown slower settling time compared to conventional spherical sand proppant. More testing needs to be conducted in order to prove the concept.

5.3. *Proppant agglomerates*

As described previously, different ways have been investigated to make lightweight proppant. Besides making the proppant itself lighter, Hughes et al. [82] invented a way to deliver the proppants as lighter agglomerates. The proppants which have been treated with hydrophobic coatings were suspended in an aqueous carrier liquid and a gas was used to wet the surface of these particulates to bind them together as agglomerates. The agglomerates formed in this way contain gas, and have a bulk density lower than the density of the particulates.

Table 6
Baseline long-term conductivity testing (Data source: McDaniel et al. [77]).

Closure stress (psi)	Baseline fracture conductivity (mD-ft)			
	20/40 Sand	12/18 ISP (resin coated)	12/18 HSP	Rod-shaped proppant 14 mesh
2000	5000	22,000	36,000	62,000
4000	2000	17,000	30,000	35,000
6000	0	13,000	20,000	26,000
8000	0	8000	11,000	15,000
10,000	0	5000	5000	10,000

5.4. *Self-suspending proppant*

Mahoney et al. [83,84] invented a novel self-suspending proppant (SSP) that can self-suspend in a carrier fluid. The proppant is made by modifying the proppant particulates with a water-swellable coating such as a hydrogel, wherein the hydrogel coating localizes on the surface of the proppant particle. The suspended proppant could be delivered to the downhole, similar to the traditional proppants. Upon hydration and swelling of the hydrogel layer in the fracturing fluid, the hydrogel layer becomes swollen with water, such that the expanded hydrogel layer thickness can be about 10% to about 100% of the average diameter of the proppant substrate. Thus, it significantly lowers the density of the entire proppant particulates and the expanded proppant can self-suspend in the fracturing fluid without significant viscosification of the carrier fluid. The major benefit of the SSP is better placement of proppant in the fracture leading to lower water injection requirements, lower proppant usage, and improved well productivity. However, the hydrogel coating tends to absorb moisture from the environment. As it absorbs moisture, it becomes less free-flowing. So any storage and transportation of SSP would need to be designed to prevent exposure to moisture. More work could to be done to improve the SSP handling issues.

5.5. *In-situ generation of proppant*

Chang et al. [85] investigated a revolutionary way to generate the spherical beads/proppants in the fracture instead of pumping proppants into the well. The new fracturing fluid is solids free and contains chemical precursors that will set into spherical particle beads deep within the reservoir to serve as proppants.

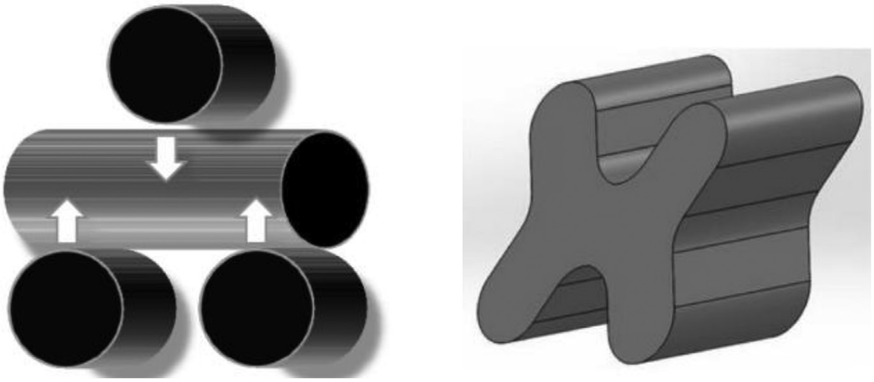

Fig. 5. Other shapes of proppant (Left: source-Edelman et al. [79]; Right: source-Liu et al. [81]).

The generated proppants will keep the flow channels open and allow oil and gas to flow out. The chemistry can be tuned to generate different particle sizes and under different temperature. The stiffness of the in-situ set proppants increases as the closure stress increases. They remain elastic as well to prevent from crushing. This will be a game-changing study if high-strength and chemically inert high quality proppant can be generated in-situ.

5.6. *Open-channel fracturing*

Some other new proppant technologies such as creating discontinuous proppant packs in the hydraulic fractures have been developed. Since the early days of hydraulic fracturing, engineers strove to fulfill the fracture with proppant to create a continuous proppant pack. It is used both as a mechanical support to maintain the fracture open and also as a porous media for hydrocarbons to flow back. The “flow-channel fracturing” technique [86,87] is based on the concept that proppant can be placed discontinuously within the fracture. This technique uses a pumping scheme where proppant is added in short pulses, alternating with pulses without proppant. Specialized fibers render the integrity of the proppant pulses by binding the proppant particles together, thus keeping the proppant in the form of individual clusters in the fracture (Fig. 6: source: d'Huteau at al. [88]). This way, hydrocarbons can flow through the channels separating the proppant clusters rather than flowing through the proppant pack itself as in conventional fractures. From this principle, the conductivity of the channel fracturing technique would well exceed that of a continuous proppant pack, resulting in improved hydrocarbon productions. The advantage of this technique is to create higher fracture conductivity while using less proppant.

Inyang et al. [89] developed another way to generate stable and highly conductive channels within a propped fracture to maximize transport capability of hydrocarbons from formation reservoir to the wellbore. This technique also relies on the delivery of proppant-laden slugs alternated with proppant-free pulses. The difference of this technique from Gillard et al. [86] technique is that proppant-laden slurry was prepared by mixing proppant coated with an agglomerating agent in a gel fluid instead of fibers. With addition of agglomerating agents, the proppant clusters have a tendency to maintain better integrity in the fracture.

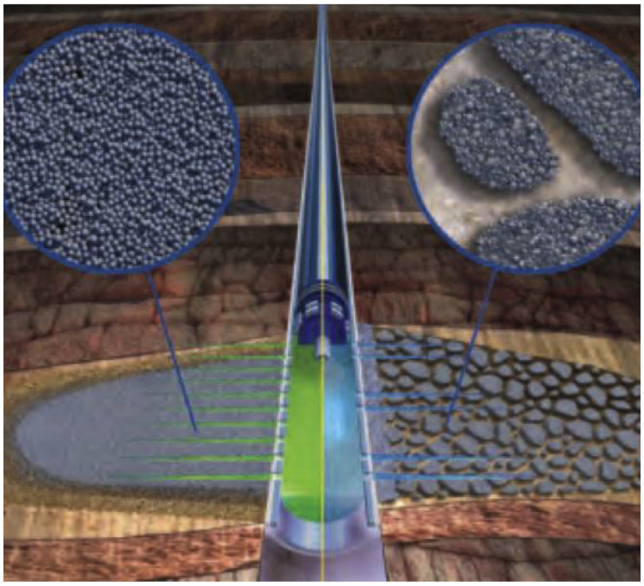

Fig. 6. Left: continuous proppant pack; Right: discontinuous proppant pack (source: d'Huteau at al. [88]).

5.7. *Alternative ways for proppant suspension*

Some opinions emphasize the ideal proppant suspension and transport under downhole conditions as the key for placing proppant throughout the fracture area to achieve optimum fracturing treatment outcomes. Conventional crosslinked fluids or linear fluids may not provide the ideal proppant placement, and could furthermore cause damage to fracture conductivity. A new fracturing fluid system with nearly perfect proppant suspension and transport properties has been introduced recently [90–92] to mitigate the issues. The new system is based on “soft particle” fluids as illustrated in Fig. 7. Due possibly to the steric hindrance of these soft particles, it would be unlikely for the proppant particles to travel downward quickly under the influence of the gravity, which has been shown in the experiments such as the static proppant settling tests and the flow visualization tests in a large-scale slot cell. In addition to the near perfect proppant suspension and transportation, the fluid also shows near 100% regained perm in the proppant pack conductivity tests, likely related to the material compositions of the soft particles. This new fluid system may be used in jobs requiring high propped fracture area and regained permeability.

6. Proppant selection criteria

Since proppant cost constitutes a significant portion of a well treatment cost, the ultimate goal for selecting the right proppant is to maximize the Net Present Value (NPV) for a given well.

Unconventional resources are reservoirs where the permeability is very low (<0.1 mD) [93,94]. Wells drilled in shale and tight reservoirs cannot be economically produced unless they are stimulated by a large hydraulic fracture treatment or produced by use of horizontal or multilateral wellbores [95]. Currently, a combination of horizontal wells and multiple propped fracture treatments is utilized as completion method of choice for unconventional reservoirs.

In low permeability reservoirs, hydraulic fracturing design focuses more on creating fracture networks than conductivity since the hydraulic fracture surface area strongly influences production. A brittle rock/shale can be fractured more easily than a ductile one [94,96]. Slick water and hybrid fracturing treatment fluid systems (alternate slickwater and gelled fluids) are typically used to create complex fracture network in tight formations [93]. For ductile rocks and shale reservoirs, a viscous fracturing fluid is injected to create the conventional bi-wing fracture system. When a low viscosity fluid is used, the proppant suspension and transport is limited only to the fracture tips. When using slickwater, it is difficult to transport conventional ceramic proppants deep into the fracture network. Brannon and Starks [97] and Parker et al. [4] have found that exotic proppant materials such as ultra-lightweight and thermoplastic alloys could be carried deeper into the formation. In many unconventional reservoirs, the equivalent bi-wing fracture length (fracture surface area divided by average fracture height) is extremely large [23]. The complexity of hydraulic fracture networks in shale formations depends on factors such as the orientation and density of natural fractures and horizontal stress anisotropy.

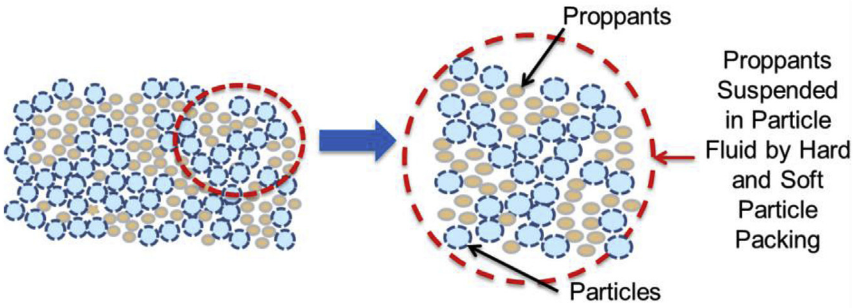

Fig. 7. Soft particles suspend the proppant by forming particle network to entrap proppant in voids (source: Zhou et al. [91]).

One type of proppant can be used for the entire fracturing job. Sometimes, a mix of different types and sizes of proppants, such silica sand, RCP and ceramic proppant, can be used in the fracturing treatment such as in the case of hybrid fracturing designs. Depending on the treatment fluids, viscosity, and expected settling rates, proppant may be segregated by tail-in, evenly blended, or blended with dominant concentrations of one particular size.

Proppant selection in hydraulic fracturing is a critical economic and technical decision that affects stimulation and field development economics. Maximizing well production is the desired outcome in designing the stimulation process. At the same time, minimizing drilling and completion costs also needs to be considered in the completion design. The choice of proppant directly impacts overall job economics, treatment size, and the ultimate productivity of the well. The decision is commonly driven by balancing production of the well through estimates of dimensionless fracture flow capacity (F_{CD}) and stimulation cost.

6.1. *Performance of proppant selection/technical selection*

As mentioned earlier, the performance of proppants needs to be measured before a fracturing job. The standard API/ISO procedures need to be followed since it provides the quality control methodologies for proppant selection.

Several simulators have been developed to assist in the design of an optimum treatment by predicting the production outcome based on the known reservoir conditions and completion methods. These tools can be integrated into simulation workflows starting with a hydraulic fracturing simulator for unconventional reservoirs to predict the fracture network geometry, proppant placement and ultimately production outcome. Weng et al. [98] developed an Unconventional Fracture Model simulator (UFM). Mirzaei and Cipolla [99] developed a simulation workflow linking the UFM with a state-of-the-art reservoir simulator capable of applying unstructured gridding around a complex hydraulic fracture network. Cohen et al. [100] presented the results of a parameter study which included the proppant size, fracturing fluid viscosity, volume of treatment, pumping rate, proppant concentration and injection sequence in the fracturing treatment to predict the production. They found that smaller proppants enable slower decline of the production rate in the long run, while larger proppants maximize the initial production rate and a combination of different proppant sizes optimizes the production.

To effectively evaluate the combined dynamic interactions of reservoir transient flow, gel cleanup, multiphase and non-Darcy flow, Predict-K simulator was developed by Stim-Lab [101]. It combines reservoir transient production forecasting for an arbitrary shape, rectangular, bounded reservoir with a damaged hydraulic fracture. The effects of closure stress embedment, spalling, filter cake deposition and erosion, bulk gel damage, multiphase flow, and non-Darcy flow have also been taken into account to a certain extent. The correlations used to drive the predictions of conductivity are based on more than 26 years of laboratory measurements conducted by the Stim-Lab Proppant Consortium. The simulator is still under improvement and has fairly good agreement between post-frac production rate forecasts and the actual production.

6.2. *Economics of proppant selection*

A longer and more conductive hydraulic fracture will achieve more production than a smaller, less conductive fracture. However, fracture treatment design is a tradeoff between increased cost of adding length and conductivity, and the economic benefits of the resulted increase in production. Most of the approaches used for cost-benefit based optimization of fracture design vary parameters such as fluid and proppant volumes, concentrations, types and flow rates.

Table 7 shows the price range for different types of proppant. Proppant cost is a significant portion of a well treatment cost. For a small sand proppant treatment design, the proppant may account for 10–20% of the total cost of the treatment; whereas, in a large treatment using synthetic manufactured proppant, the proppant cost can be in excess of 50% of the total cost.

Yang at al. [102,103] studied similar reservoirs in Wolfcamp/Clearfork basin and did a statistical study with focus on proppant type selection, proppant amount optimization and proppant mesh size. They found that natural sand proppant wells have the advantage of completion cost saving over ceramic proppant wells, while the production of both cases is comparable. In ceramic proppant case, the cost of proppant dominates the NPV. Increasing ceramic proppant amount will decrease the NPV.

Mack and Coker [23,40] mentioned that the three common economic metrics of NPV, Internal Rate of Return (IRR) and Payout should be considered. In unconventional reservoirs, the three metrics typically suggest similar capital allocation decisions since 30%–40% of the estimated ultimate recovery from unconventional wells is recovered in the first two years of

Table 7
Price of different types of proppants (Source: O'Driscoll [5]).

Proppant	Price, $ per lb
Sand	0.019 to 0.058
RCS	0.195 to 0.245
Ceramics	0.27 to 0.90

operation. The authors developed a basic economic model to calculate the NPV, IRR and payout time of the well. The uniqueness of their model is that their NPV calculation considers the revenue generated from oil and gas production using the assumed declined curve. Assuming that the cost increase in the initial investment for replacing sand with upgraded proppant is C and the production increase is $P\%$, the percentage production increase required to break the cost even is

$$P\% = \frac{C}{NPV + Well\ Cost} \tag{1}$$

Overall, the decision regarding the proppant selection should be based on economic optimization. Ceramic proppant should only be selected over sand if there is a clear economic justification.

7. Discussions and conclusions

Since the first fracturing was done with silica sand in 1947, many types of proppants have been used in fracturing processes. With the development of deeper reservoirs and more complex fracture geometry and formation properties, the performance requirements for proppants have become more and more demanding. For example, proppants need to be stronger yet with lower density. Advancement in synthetic materials helps to achieve such goals as the durability of synthetic material under high temperature and high pressure conditions has been improving. In unconventional jobs, a significant amount of proppant embedment has been observed in shale formation with higher clay content. As the Young's modulus of shale formation decreases, proppant embedment increases. In these situations, questions are raised if it is still valuable to choose high-strength proppant in hydraulic fracturing treatment. Developing unconventional sources is very cost-sensitive, especially when using proppants with advanced characteristics. Proppants no longer serve only for supporting stress; they are also used as a means to prolong hydrocarbon productions. Chemically modified proppant surfaces can function to prevent scaling, condensate trapping, and water blocking, to name a few. Overall, lightweight, high strength, high conductivity, chemically inert, and cost effective proppants are needed to develop unconventional resources. Also, research on improving multifunctional proppant elution profiles and extending the lifetime of the chemically infused proppant is needed as well.

This paper presents a review of the different types of proppants, the standard testing methods for proppant performance, damage factors which cause an overestimation of the conductivity in laboratory test results compared to the observed field conductivity, proppant selection criteria for unconventional reservoirs, and challenges of new proppant development for unconventional reservoirs. The following major conclusions can be drawn.

1. Sand and ceramic proppant are the two basic types of proppants. Modified proppants include resin coated proppant and lightweight proppant.
2. Proppant selection which includes the proppant type, size and shape is a very critical element in stimulation design.
3. Lightweight, high strength, uniform-sized, chemical inert and cost effective proppant are needed for unconventional resources.
4. Research is needed to improve multifunctional proppant elution profiles and extend the lifetime of the chemically infused proppant.
5. New research areas are emerging such as multifunctional proppant, self-suspending proppant and in-situ proppant generation.

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