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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,