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A METHOD OF PROPPANT PACK PERMEABILITY ASSESSMENT

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Abstract: Hydraulic fracturing methods used for low permeability reservoirs such as shale gas or tight gas require the use of proppants. The current standard used for proppant assessment does not take into account its interaction with the rock and the embedment effect. In this paper a new method of proppant pack permeability assessment is proposed where proppant is placed into a rock sample with induced fracture. Three types of proppant were assessed to verify the method i.e. offshore sand, onshore sand and ceramic proppant. The rock sample was a Tumlin sandstone. As the flowing medium supercritical carbon dioxide was used. Tests were performed with 300-500 μm size proppants at flowing pressure of 3 MPa and confining pressure of 5 MPa. Additional test was conducted with 1–2 mm sand proppant at two confining pressure, i.e. 5 MPa and 16 MPa. Proppant were characterized in accordance with the Krumbein/Sloss diagram. Similar values of permeability for the proppant concentration of 0.5 kg/m2 were obtained ranging from 2.3 to 3.3 D although the highest permeability was achieved with Baltic sand proppant and ceramic proppant. For the larger size of proppant (1 – 2 mm) the initial permeability with confining pressure of 5 MPa was initially larger but when the confining pressure was increased it declined by 37%. This proves that in the proposed method we can observe changes in the permeability of the fracture with change in confining pressure apply subjected to the sample.

Keywords: *copper nitrate, electrorefining, high purity copper, hydrometallurgy*

Introduction

Hydraulic fracturing methods are commonly used to enhance production of low permeable reservoirs such as shale gas or tight gas formations. The main goal of hydraulic fracturing treatment is to create a highly conductive system of fractures interconnecting the pores and allow gas flow to the well. There are numerous kinds of hydraulic fluids used for the treatment and these are i.a. gelled fluids, including linear or cross-linked gels, water with friction reducers (slickwater), foamed gels and others. Fracturing fluids are not only used to create/expand fractures but also to transport proppant into fractures. Proppants are sand or other granular substances injected into the formation to hold or “prop” open reservoir formation fractures created by

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hydraulic fracturing. In general we can divide proppants into three types (see Table 1), i.e. natural, ceramic and other.

Table 1. Types of proppant

Natural	Ceramic	Other
Sands	LWC – Lightweight Ceramics	Light weight polymers
Resin-coated sands	IDC – Intermediate Density Ceramics	High density bauxite
	HDC – High Density Ceramics	
	Resin-coated Ceramic Proppants	

A perfect proppant should provide a high conductivity of the fracture within long period of time. As the conductivity it is meant permeability multiplied by the width of the fracture. High conductivity of the fracture is provided when the size of the proppant is maximally uniform i.e. the 90% of the proppant falls between designated particle size range (typically in mesh size). Outlook on the typical proppant sizes is given in Table 2.

Table 2. Typical proppant sizes

Tyler Mesh Size	Particle Size Range (μm)
10/14	1400–2000
12/18	1000–1700
16/20	850–1180
16/30	600–1180
20/40	420–850
30/50	300–600
40/70	212–420
70/140	212–106

The proppant shape has a an impact on the conductivity of the fracture (or permeability of the proppant bed). Therefore, a wide range of particle sizes and shapes results in a tight packing arrangement, reducing permeability/conductivity. A narrow range of sizes and a spherical shape will lead to greater conductivity.

An important feature of the proppant is its strength. The greater the depth the higher the pressure and proppant is more prone to crushing. Crushing the proppant results in shattering and releasing the fines which in turn may decrease the permeability of the proppant bed. There are other properties of the proppant which may affect its performance in the reservoir and these are: acid solubility and turbidity. Proppant testing methods are described in the EN:ISO standard 13503-2:2006 “Petroleum and natural gas industries - Completion fluids and materials – Part: 2

Measurement of properties of proppants used in hydraulic fracturing and gravel-packing operations".

The problem with the abovementioned standard is the fact that it does describe proppant properties as a material but it does not give information on the performance of the proppant in contact with the reservoir rock. The main problem is the so called "embedment" effect which is often observed in some of the formations. Proppant grains are pushed into the rock due to formation pressure and reduce the conductivity of the fracture. In this case the proppant retains its properties (it is not crushed nor dissolved) but its size or shape causes it to embed into the rock, thus reducing the gas flow. In this article a new method of proppant testing is proposed which allows to assess the behavior of proppant in contact with reservoir rock by measuring the changes in permeability of the fracture. As the flow medium carbon dioxide was used due to the fact that a few studies show CO_2 fracturing technology as an alternative to hydraulic fracturing technologies (Almond and Harris, 1984; Rogala et al., 2013; Rogala et al., 2014) .

Materials

For the purpose of the study three proppants were selected. Two natural ones, that is marine sand from Baltic coast (BS), onshore sand from Ostrowiec Swietokrzyski (OS) and one ceramic proppant (CP). The sphericity and roundness of proppants was examined in accordance with the EN:ISO 13503-2:2006 standard (EN:ISO 13503-2:2006). The sphericity and roundness is assessed by selecting under microscope 20 random grains and grade each grain visually on roundness and sphericity by comparing to the Krumbein/Sloss diagram (Fig. 1).

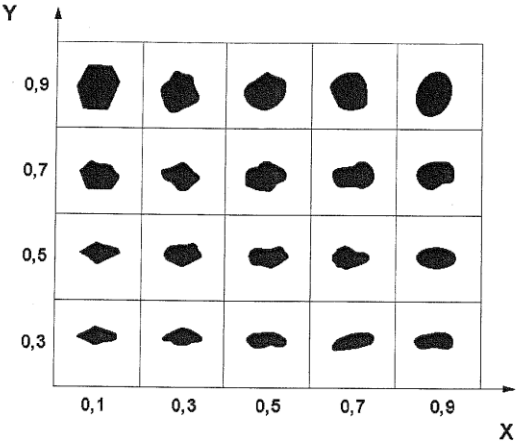


Fig. 1. Krumbein/Sloss diagram for visual assessment of sphericity and roundness (EN:ISO 13503-2:2006)

The arithmetic mean gives the grade of sphericity and roundness of the proppant. In the study the scanning electron microscope (SEM) and stereoscope microscope was used for this purpose (Ardelli, 2014). In general, the proppant for the tests was in one size: 300 – 500 μm which corresponds to commonly used mesh size of 30/50. Additionally, one test was performed for large size proppant with uncommon size of 1000 – 2000 μm (OS 1-2) for the reasons explained in the latter part of the article. Sample photos from SEM and stereoscopic microscope of BS and CP sample are presented in Figures 2 and 3 respectively.

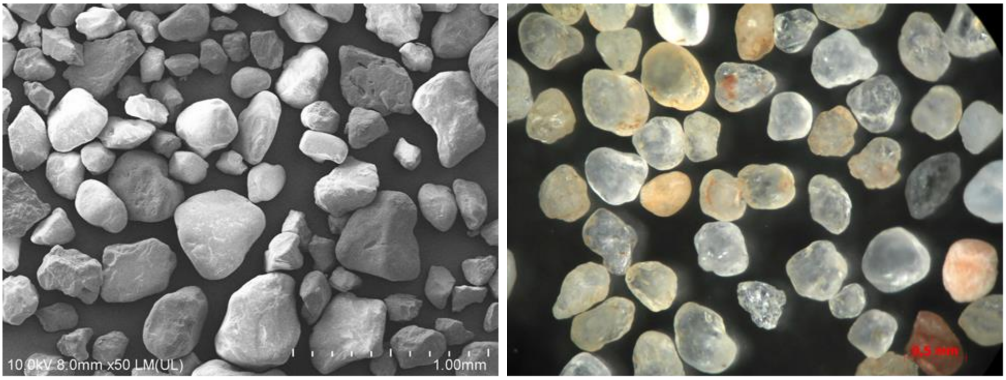


Fig. 2. SEM photo of BS sample (300–500 μm) under 50× magnification and stereoscopic microscope photo at 50x magnification of OS sample (300–500 μm) (b)

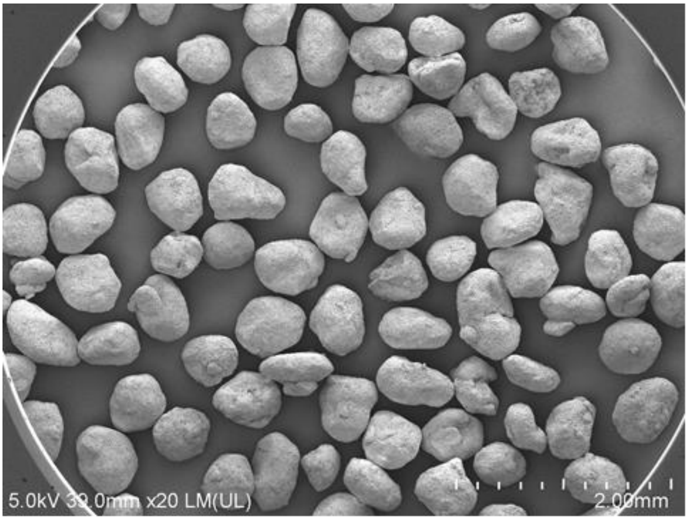


Fig. 3. Photos of CP sample (300–500 μm) under SEM

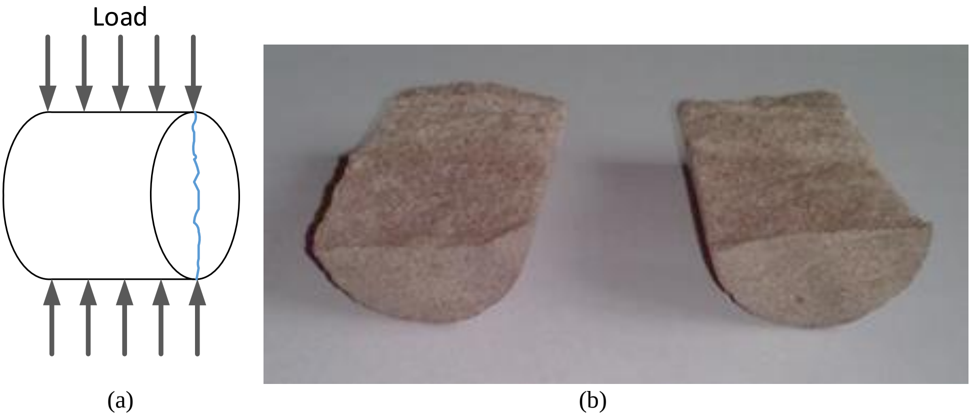
Results of sphericity and roundness examination are presented in Table 3.

Table 3. Sphericity and roundness of proppants used for permeability tests

Proppant	Size, µm	Sphericity, -	Roundness, -
Ostrowiec S. sand (OS 1-2)	1000–2000	0.7	0.4
Baltic marine sand (BS)	300–500	0.4	0.2
Ostrowiec S. sand (OS)	300–500	0.8	0.5
Ceramic proppant (CP)	300–500	0.9	0.7

Surprisingly two natural proppants, BS and OS, significantly differ in shapes and onshore sand (OS) has better sphericity and roundness. As it was expected ceramic proppant was graded as the one with the highest sphericity and roundness.

Rock selected for the permeability tests with proppant was a Tumlin fine-grained sandstone (Holy Cross Mountains in Central Poland). The Tumlin sandstone has a porosity of approximately 10.5%, compressive strength of 80 MPa and permeability of approximately 50 mD. The samples were cored from large blocks to the size of 2.54 cm in diameter and length of 4 cm. In order to simulate reservoir conditions an artificial fracture along the sample had to be induced. For that purpose a load was applied along the external cylinder surface of the core (see Fig. 4) until the moment the sample cracked. This procedure allowed to obtain a split sample with a fracture along the whole length that could be filled with proppant and simulate reservoir conditions.



(a) (b)

Fig. 4. Direction of the load applied to the sandstone core sample (a) and photo of the sample after the split (b)

The reason for choosing the Tumlin sandstone was its isotropy and known properties. These features allowed to obtain similar sample for each permeability test as the test was usually destructive to the sample. Typically, the sample was either cracked after the test due to the relaxation forces when confining pressure was released or due to the oil intrusion if the test failed.

Methods

In order to measure the permeability of the core sample filled with proppant a custom made permeability setup was constructed (Fig. 5). To calculate the permeability of the specimen a steady-state flow method was applied. In this method a constant stream of gas is supplied to the sample from the cylinder of known volume. The sample is subjected to a pressure gradient to facilitate the gas flow through the sample. In order to maintain a constant flow a needle valve was installed behind the core cell and the reducing valve to maintain the constant pressure. Pressure in the gas cylinder is monitored by the pressure transducer therefore the flow rate can be calculated by knowing the drop in pressure within the certain period of time.

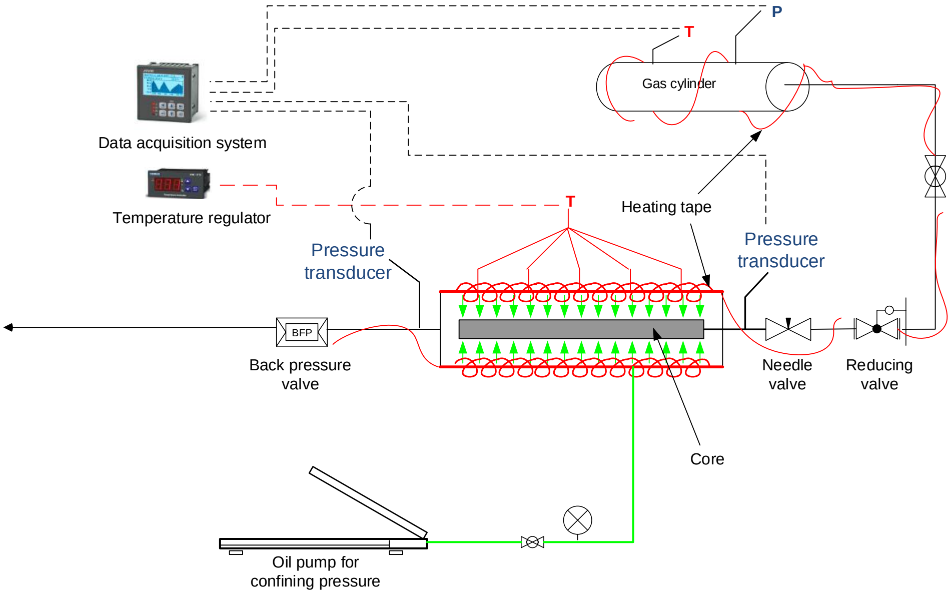


Fig. 5. Scheme of the laboratory setup used for permeability experiments

The core sample filled with proppant was placed in silicone sleeve and inserted into the high pressure cell where it was subjected to confining pressure exerted by hydraulic oil. This step is crucial in order to obtain a proper permeability measurement as the gas can flow on the sides of the sample when the confining pressure is too low. In this study we applied confining pressure which was at least 50% higher than the average gas flowing pressure. The permeability of the sample was calculated with the use of the following formula based on the modified Darcy equation (1):

$$k = \frac{2qP_o L\mu}{A\left(P_i^2 P_o^2\right)}, \tag{1}$$

where k is the permeability, q is the gas flow rate, L and A is the length and cross-sectional area of the sample respectively, μ is the viscosity of gas, P_i and P_o is the inlet and outlet pressure respectively. As it was mentioned, the flow of gas could be calculated by measuring the drop in pressure of the gas in a cylinder of known volume and known temperature of the gas. As the experiments were conducted with supercritical CO_2 to calculate precisely the CO_2 density a highly accurate equation of state by Span and Wagner (1996) was used).

Experiments were conducted with the proppant concentration of 0.5 kg/m^2 and the confining pressure of approximately 5 MPa and 16 MPa. In Fig. 6 sandstone sample filled with proppant before placing in the permeability setup is shown.

Fig. 6. Photo of the sandstone core filled with CP sample before placement in the permeability setup

Results and discussion

Sandstone cores were filled consequently with three types of proppant i.e. Baltic sand (BS), Ostrowiec Swietokrzyski sand (OS) and Ceramic proppant (CP) in size of 300–500 μm. In one of the experiments it was decided to fill the sandstone sample with coarse fraction of proppant (1–2 mm) in order to verify to what extent it may affect the permeability of fracture. Such large size of proppant was selected to “prop” the sandstone which porosity was rather large and in previous experiments proppant embedment was noticed. Moreover, it was decided to increase the confining pressure in the last experiment with OS 1–2 sample to 16 MPa in order to observe the effect of fracture closure. Results of experiments are presented in Fig.7.

Tests conducted with four types of proppant of 300-500 μm in size revealed that the highest permeability of fracture was obtained with the Baltic sand (BS) and ceramic proppant (CP) sample. A slightly lower permeability was obtained for the OS sand sample. Although, the OS sand has a better grade of sphericity and roundness than BS sand - the permeability is somewhat lower. In all cases however the range of permeability in a sand pack with the same proppant concentration and confining pressure is similar. Only in the case of sample OS 1–2 with the grain size of 1000–

2000 μm the permeability was significantly higher. This is due to the fact that larger grains do not embed as much as the fines and have larger pores when compacted. Yet, when the confining pressure was increased the proppant was crushed and fracture closure was observed (see Fig. 8). In this case the permeability declined by 37%.

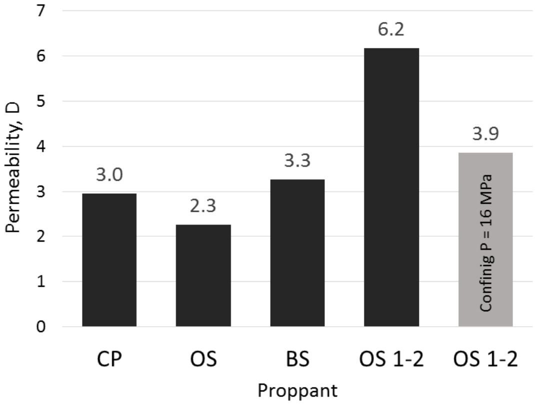


Fig. 7. Results of fracture permeability tests with different proppants at confining pressure of 5 MPa (for the sample OS 1-2 the test was also conducted for the confining pressure of 16 MPa) at the temperature of 45˚C

Fig. 8. Photo of the crushed sample OS 1-2 after the pressure was increased to 16 MPa. The red circle indicates the most destructed zone

Presented results are the initial assessment of the proposed method of proppant pack permeability testing. Due to the fact that the number of publications in this field is scarce the results were compared with data from the publication of (Wen et al., 2007). In their case the FCES-100 test unit based on the API standard was used. The range of obtained permeability for the 30/60 mesh proppant was two to three times higher. It is difficult to compare directly the results as the proppant concentration was larger – 10 kg/m^2 and the confining pressure (referred as closure pressure) was much higher 10-90 MPa. Nevertheless, the proposed method is convenient and relatively easy method of proppant testing in samples where the surface of fracture is naturally rough unlike the other methods where the surface is cut and polished. Another advantage is the fact that in this method we can test small samples that can be cut from well cores.

Conclusions

A new method of proppant pack permeability testing was proposed. In this method the proppant is placed in a rock sample with induced fracture of rough surface. To verify the method tests were conducted with three types of proppants – two natural ones (sands) and one ceramic proppant. In all cases with the same flow pressure and confining pressure similar results were obtained although the highest permeability was achieved with Baltic sand proppant and ceramic proppant. For the larger size of proppant (1 – 2 mm) the initial permeability with confining pressure of 5 MPa was initially larger but when the confining pressure was increased it declined by 37%. This proves that in the proposed method we can observe changes in the permeability of the fracture with change in confining pressure subjected to the sample.

The main advantage of this method is the fact that we deal with rough surface of the rock which is the case in reservoir conditions – taking into account effects such as cracking of the rock on the surface of fracture. Current methods of proppant testing focus mainly on properties of the proppant as the material and as it was observed in the conducted test – the sphericity and roundness does not always reflects the permeability of the proppant pack.

At this stage of development, the method has some disadvantages and the main one is the relatively low flow pressure and confining pressure which can be applied to the sample. The construction of sample cell has to be improved in order to withstand higher pressure without unnecessary oil intrusions that destroy the sample as it often happened during the course of this study. This makes the method more time consuming and somehow complex in terms of sample preparation. Yet, the initial results are encouraging and will be developed in further studies.

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