Fuel 181 (2016) 463–477

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Proppant transport study in fractures with intersections

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HIGHLIGHTS

- Proppant transport is studied in fractures with intersections.
- The equilibrium sand bed height decreases as the shear rate increases.
- Proppant placement in the bypass slot increases as the shear rate increases.

ARTICLE INFO

Article history:
Received 4 February 2016
Received in revised form 26 April 2016
Accepted 28 April 2016
Available online 11 May 2016

Keywords:
Shale
Complex fracture systems
Proppant transport
CFD simulation

ABSTRACT

Slickwater fracturing is a popular stimulation treatment in the unconventional oil and gas industry. It creates thin and long fractures that connect to pre-existing natural fractures and generate complex fracture networks. A large fraction of the fractured area is not usually propped due to the high density of typical proppants (sand) and low viscosity of the fracturing fluid. The goal of this work is to understand and optimize proppant transport in complex fracture networks. In this paper, proppant transport in fracture intersections is studied experimentally (using laboratory size slots) and numerically (using a multiphase dense discrete phase model). The orientation of natural fractures, proppant size and shear rate have been varied and the injected proppant volume is kept constant. Both experiments and simulations show three zones: bottom immobile sand bed zone, middle flowing slurry zone, and top clear fluid zone. The sand injected early forms the bottom of the sand bed; the sand injected later moves downstream and forms the top part of the bed. The entrance eroded region increases as the shear rate (or equivalently the water injection rate) increases. The sand bed length increases as the shear rate increases. The equilibrium sand bed height decreases as the shear rate increases and the sand size decreases. Proppant placement in the bypass slot increases as the shear rate increases and the bypass angle decreases. The numerical model using a dense discrete phase model (DDPM) captures the key features of the sand bed formation and transport.

1. Introduction

As the global demand for energy rises and discovery of new hydrocarbon resource drops, recovery from known unconventional resources such as shale gas and oil becomes increasingly important. Shale reservoirs need to be fractured hydraulically to produce at an economic rate. Long propped fractures that intersect pre-existing natural fractures or microfractures [1] are preferred to maximize productivity for ultra-low permeability shales [2]. Polymeric fracturing fluids can carry the proppants deep into fractures, but create short fractures because of high viscosity [3,4]. Slickwater fracturing is a popular stimulation technique for shale reservoirs because it can create large fractures at a lower cost [5,6]. Large fractures intersect with more existing natural fractures and create a complex fracture network. However, one of the main concerns during the slickwater fracturing process is the proppant transport and placement in such complex fracture networks.

Kern et al. [7] have studied the transport of sand and water in a vertical slot formed by two parallel Plexiglas plates. The sand settles down and accumulates to form a sand bed in the slot. The sand bed reaches an equilibrium state, after which newly injected sand moves deeper into the slot along with some fluidized sand and deposits downstream to elongate the sand bed. This implies that during fracturing, the sand injected earlier settles down near the wellbore, and the sand injected later flows deeper into the fracture. Fig. 1 shows a schematic diagram of sand deposition and transport for a fracture initiated from a vertical well, proposed by Kern et al. [7].

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http://dx.doi.org/10.1016/j.fuel.2016.04.144
0016-2361/

Nomenclature

Regular symbols

$\vec{I}$	unit tensor
Re	Reynolds number
e	restitution coefficient
g_o	radial distribution function
C_D	drag coefficient
t	time (s)
p	pressure (Pa)
$\vec{g}$	gravitational vector (m/s^2)
k_Θ	granular energy diffusion coefficient (kg/(m s))
d	diameter (m)
w	slot width (m)
h	slot height (m)

Greek symbols

α	volume fraction (%)
ρ	density (kg/m^3)
$\vec{v}$	velocity vector (m/s)
$\bar{\bar{\tau}}$	stress strain tensor (kg/(m s^2))
β	interphase momentum exchange coefficient (kg/(m^3 s))
Θ_s	granular temperature (m^2/s^2)
γ	collisional dissipation of energy (W/m^3)
Φ	interphase energy exchange (W/m^3)
μ	viscosity (kg/(m s))
λ_s	bulk viscosity (kg/(m s))
λ_f	fluid gravity Reynolds number (dimensionless)
ϕ	internal friction angle (°)

Wang et al. [8] have proposed a three-zone proppant flow model based on the lab data from STIM-LAB and a power law correlation for the sand bed height in fractures with smooth surfaces. In the correlation, the bed height is a function of proppant settling velocity, fluid, and proppant Reynolds number. Gadde et al. [9] proposed a correlation for two-dimensional (2-D) proppant flow with fracture roughness based on their lab results. The size ratio between proppant diameter and fracture width, proppant loading and fluid rheology were included in the correlation.

Sahai et al. [10] created a primary fracture slot intersecting to a 90° secondary fracture bypass and investigated proppant flow from the primary slot into the bypass. They evaluated and compared parameters like pump rate, proppant loading and proppant size. They observed a threshold pump rate above which proppants flow into the bypass; otherwise proppants only roll into the bypass from the proppant bed due to gravity and erosion. Alotaibi et al. [11] extended this work and highlighted the mechanism of proppant transport during proppant bed development. They further included friction loss and proposed a scalable correlation for 30/70 brown sands to estimate equilibrium sand bed height for different flow rates and sand concentrations. Unlike proppant transport in a single primary fracture, which has been comprehensively studied, the research of proppant transport in 3-D fracture networks is still rare. No data is available to quantitatively describe the amount of proppant flow into bypass fractures at angles other than 90°, and no model is developed to simulate such data. In this paper, lab scale experiments are conducted with slot intersections at several angles.

Computational Fluid Dynamics (CFD) has been used widely to model particle transport in many applications [12,13]. There are two widely used multiphase models in CFD: Eulerian-Granular model which is an Eulerian–Eulerian approach, and Discrete Phase Model (DPM) which is an Eulerian–Lagrangian approach. The Eulerian-Granular model comes from incorporating the kinetic theory of granular flow (KTGF) for particle transport [14]. KTGF is one of the most significant theories for simulating particle flow. Granular temperature, which accounts for the random motion of particles, is the key concept of this theory. Energy dissipates during random collisions between particles. This approach treats all the phases as interpenetrating fluid continuums in an averaging scheme, and therefore it is also known as the two-fluid model (TFM). One advantage of this averaging scheme is the incorporation of a large number of particles because the computation cost does not correspond to the number of particles. Lu and Agrawal [12] adopted this approach to study sand erosion problems in multiphase-flow systems. They stated that the Eulerian-Granular model works from dilute to highly concentrated systems, and gives more accurate erosion prediction than the Eulerian–Lagrangian approach. The disadvantage of this model is three-fold. First, it cannot track individual particle trajectory due to the averaging scheme. Second, the particle–wall interaction is not well captured. Third, a uniform particle size is assumed.

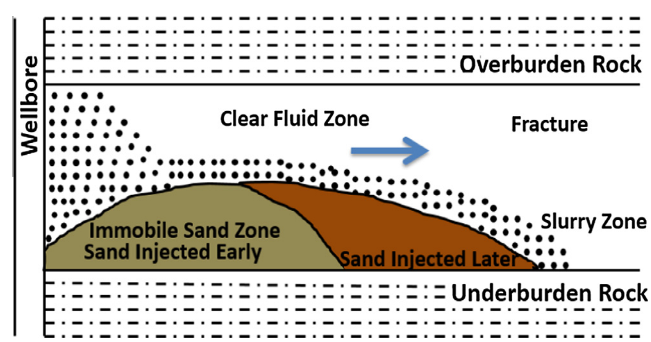

Fig. 1. Schematic figure of sand transport in a vertical planar fracture.

The DPM approach assumes that particles do not interact with each other, and therefore it only can be employed if the volume fraction of the particles is low (less than 10%). It treats the carrier phase as a continuum by solving the Navier Stokes (N–S) equation and tracks the discrete phase as individual particles by coupling them with the flow field. Zhang et al. [15] simulated proppant transport and distribution in a single stage of plug-and-perf completion, and successfully matched the experimental data from Deshpande et al. [16]. The DPM can include proppant size distribution and trajectory, but fails when proppants settle and form a bed.

The DPM (Eulerian–Lagrangian) approach can be extended to a high solid phase loading if coupled with a Discrete Element Method (DEM) [17]. In a DEM–CFD method, the motion of discrete particles is obtained by applying Newton's law of motion to all particles, therefore the inter-particle and particle–wall interactions are well captured. The flow of continuum fluid is described by the local averaged N–S equation in CFD module. Tomac et al. [18] included lubrication forces into the DEM–CFD method, and simulated proppant flow in a thin fracture. They concluded the size ratio between proppant diameter and fracture width affects the flow significantly. Moreover, the lubrication effect plays a big role at larger proppant loadings, larger fluid viscosities and lower pressure gradients. This method treats the particles individually and