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Numerical simulation on solid-liquid two-phase flow in cross fractures

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HIGHLIGHTS

- The dimensionless controlling parameters were derived to describe the particle-laden flow in cross fractures.
- Two-Fluid Model closed by the kinetic theory of granular flow was adopted to describe the solid-liquid flow.
- Larger bypass angle between the main slot and branch slot leads to less particle's flow into the branch slot.
- A new dimensionless number Π can describe the ratio of the liquid's carrying capacity to the particles' sedimentation effect.

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ABSTRACT

This paper presents a series of numerical simulation on solid-liquid two-phase flow in cross fractures based on the Two-Fluid Model and the kinetic theory of granular flow (KTGF). First, the model is validated by previous experimental data. Second, the dimensionless controlling parameters are derived to describe the particle-laden flow in cross fractures, including the angle between the main and branch slots (bypass angle) θ, inlet particle volume fraction α_{s0}, the ratio of particle size to branch slot width d_s/w_b, the Archimedes number Ar and the Reynolds number Re. Third, the effects of the dimensionless parameters are investigated. The results show that particles tend to accumulate at the intersection between the main slot and the branch slot. Larger bypass angle between the main slot and branch slot leads to less particle's flow into the branch slot. The distance of the branch fracture from the inlet of the main fracture induces different particle-flow characteristics into the branch slot. Particle volume fraction at the stable stage increases with the decrease of d_s/w_b. The deposition thickness of particles increases with the increase of the inlet volume fraction and Ar number, while decreases with the increase of Re number.

1. Introduction

Hydraulic fracturing is a common method to form connected fracture networks in the tight oil or gas reservoirs by injecting high speed and high pressure fluid. Accompanied with the hydraulic fracturing process, proppants are carried into the fractures. Well distributed proppants throughout the fracture network are capable of keeping the cross fracture network open and increasing the flow conductivity. The distribution range of the proppant is of great importance to keep the flow conductivity in the complex fractures (Tsai et al., 2012).

Previous researches have been conducted to understand the flow behavior of the proppant-laden fluid in a single vertical fracture. A slot made by two Plexiglas plates was firstly used by Kern et al. (1959) and subsequently improved by Babcock et al. (1967) to simulate sand deposition and transportation in a vertical planar fracture. The sand settles down and forms a stable dune at the bottom of slot due to the density of sand is larger than that of water when the mixture of sand and water is injected into the fracture slot (shown in Fig. 1). The height of the sand dune increases progressively to a steady state. The increase in the height of the sand dune reduces the flow area of fracture's cross section and, accordingly increases the velocity of proppant-laden fluid. When the sand bed and the fluid velocity reaches a dynamic equilibrium, the height of the sand is called "equilibrium height", and the velocity is called "equilibrium velocity" (Babcock et al., 1967). Similar phenomenon and physical processes were observed in experiments by Wang et al. (2003) and Sahai et al. (2014).

Recently, several studies on the proppant transport in the complex fracture networks were conducted. Sahai et al. (2014) fabricated a lab scale experimental apparatus with four different slot configurations to simulate proppant flow from the primary to

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Nomenclature

C_D	drag coefficient
d_s	particle diameter (m)
D_{ij}	strain tensor for solid phase (s^{-1})
D_H	hydraulic diameter (m)
e	coefficient of restitution
Fr	Froude number
g	gravitational acceleration (m s^{-2})
g_0	radial distribution coefficient
G_k	generation of turbulent kinetic energy (kg $m^{-1}s^{-3}$)
H	height (m)
I	turbulence intensity
k	turbulence kinetic energy (m^2 s^{-2})
k_{Θ_s}	diffusion coefficient for granular energy (kg m^{-1} s^{-1})
K	interphase exchange coefficient
l	turbulence scale (m)
L	characteristic size (m)
L_s	length (m)
P	pressure (Pa)
Re	Reynolds number
Re_s	relative Reynolds number
Re_{D_H}	turbulence Reynolds number
S	modulus of the average strain rate tensor
S_{ij}	strain tensor
t	time (s)
$U_{s,\|}$	particle slip velocity parallel to the wall (m s^{-1})
v	velocity (m s^{-1})
v_c	terminal settling velocity of particle swarms (m s^{-1})
w	width (m)

Greek letters

α	volume fraction
γ	collisional dissipation of energy (kg m^{-1} s^{-3})
δ	voidage
ε	dissipation rate of turbulent kinetic energy (m^2 s^{-3})
θ	angle
Θ	granular temperature (m^2 s^{-2})
I	stress tensor
I_{2D}	second invariant of the deviatoric stress tensor
λ	bulk viscosity (Pa s)
μ	shear viscosity (Pa s)
ξ	specularity coefficient
Π	the ratio of the Reynolds number and the Archimedes number
ρ	density (kg m^{-3})
ρ^*	density ratio
τ	stress tensor (Pa)
φ	angle of internal friction
Φ	transferrate of kinetic energy (kg m^{-1} s^{-3})

Subscripts

a	main slot
b	branch slot
col	collision
fr	friction
i, j	component
kin	kinetic
l	liquid phase
m	mixture
max	maximum value
s	solid phase
t	turbulent flow
x, y, z	axis

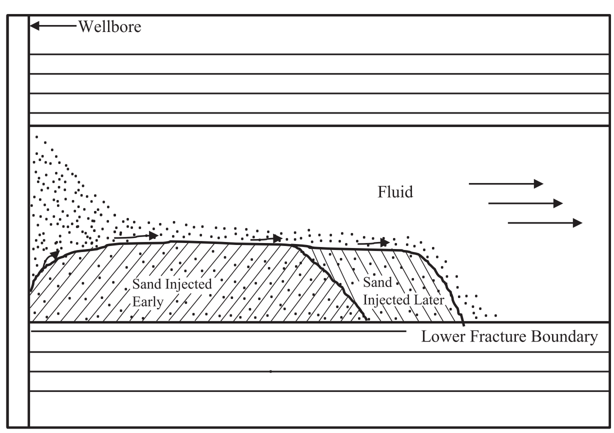

Fig. 1. Sketch of sand transport in planar fracture (Kern et al., 1959).

secondary fractures. For all the configurations, the bypass angle was 90° and, the width of the slots equaled. The particle size, flow rates and particle volume fraction were considered in experiments to understand the controlling factors of the proppant transport. The proppant either enter into the secondary fracture by the drag force of the fluid or roll into by gravity. Tong and Mohanty (2016) studied the proppant transport in fractures with bypass angle 45°, 90° and 135°, respectively, considering the effects of shear rate and proppant size. Proppant in the secondary fracture increases with the increase of the shear rate and the decrease of bypass angle. However, the effects of the width of the secondary slot and the distance of the intersection from the inlet on the proppant transport and deposition in the cross fractures are not well understood.

The proppant transport and the deposition in the fracture network are very complex and related with complex fracture geometries and network structures (e.g., bypass angle, the width of the fractures), proppant properties (e.g., proppant size and density), fluid properties (e.g., fluid viscosity and density), and boundary conditions (e.g., injection rate, proppant volume fraction). Some studies have been conducted to illustrate the effects of single parameter, but the coupling effect of the controlling factors on proppant-laden flow is not well understood. Dimensional analysis