CFD Modeling of Low-Density Particle Transport into Perforations for Multistage Fracturing Applications of Horizontal Wells*

Vijaya Patnana[1] and Travis Larsen[2]

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[1] Halliburton, Pune, India (vijaya.patnana@halliburton.com)
[2] Halliburton, Pune, India

Abstract

Multistage fracturing operations in horizontal wells rely on efficient transport of proppant or diverter particles to achieve adequate fracture conductivity and control fluid distribution along the wellbore. Transport of solid materials involves two steps: conveying material through the wellbore and delivering the material into the desired perforations and fractures. Most of the previous oilfield-related publications focused extensively on transport of various sieve sizes of quartz sand used as proppants [i.e., with values of specific gravity (SG) above 2]. In this work, these will be generally referred to as “high-density particles.” However, little information is currently available that describes transport of low-density particles (such as 1.25 SG) into perforations of different orientations.

Low-density particle movement through the wellbore and into a perforation considering different orientations is modeled using commercial computational fluid dynamics (CFD) software. This paper discusses the numerical methodology and models used for simulations, the importance of accounting for gravitational effects and sufficient entry length for flow establishment before encountering the first perforation, and the effects of modifying flow rate, pressure drop across the perforation, and perforation orientation on the transport efficiency (E) of delivering particles to the perforations. This modeling was based on 1-cP water in a 4-in. inner diameter (ID) horizontal pipe and 0.5-in. perforations at input rates of 10 to 20 bbl/min.

The values of transport efficiency of a specific low-density particle (1.25 SG) predicted in this work, where gravity and long entry lengths are accounted for, are different from values previously reported in simulation works where insufficient entry length was considered. Detailed analysis emphasizes the importance of these considerations and explains how these factors affect the results. Within the limits of a heterogeneous slurry flow regime, the results demonstrate that increasing fluid velocity increases the inertia of the particles, which proportionately reduces percentage of particle mass flow rates into down- or side-oriented perforations; however, no significant modification in particle mass flow rates was observed for the top-oriented perforation in the range of simulated flow conditions as total flow rate increased.

The recommendations can be used to optimize treatment design parameters to help achieve more efficient and uniform delivery of solid particles into perforation clusters during horizontal stimulation operations. The CFD-based methods and procedures developed in this work can be further extended to study a variety of applications where similar transport and delivery concerns are present.

Introduction

The success of multistage fracturing in horizontal wells depends on effective delivery of particles (proppant, diverter) to fracture networks through perforations of clusters to help improve cluster and production efficiencies. This basically involves two steps: transport in wellbore (analogous to flow through a pipe) and delivery to perforations (analogous to flow breakup at a split pipe, replicating T-junction). Early studies on sand particle transport (with SG above 2) through a wellbore and, in turn, into orthogonal perforations were conducted on vertical pipe with flow in the gravity direction (Haynes et al., 1974; Torrest et al., 1975; Gruesbeck et al., 1982).

The correlations of critical deposition velocity (i.e., velocity threshold below which particles settle to the bottom) are developed based on experimental data for slurry flows in horizontal pipeline (Oroskar and Turian, 1980; Turian et al., 1987; Shah et al., 1990). Experimental evidence on entry pipe length (i.e., pipe length needed for stable flow profile of particles) for horizontal pipe flows is on the order of 50 pipe diameters for particle concentration, and velocity profile development across cross-section is published (Colwell and Shook, 1988). The lower density particles, with higher dispersive effects, require entry lengths greater than 50 pipe diameters.

Both experimental measurements and model predictions for horizontal slurry flows have demonstrated that the concentration profile of settling particles is asymmetric with solids concentration high at the bottom of the pipe (in the absence of a positive concentration gradient) and monotonically decreases as one approaches the top of the pipe (Roco and Shook, 1981, 1984; Brown and Shook, 1982; Nasr-El-Din et al., 1987, 1989). This warrants the importance of gravity being included in simulations, and the same is proven by Jain et al. (2013).

Experimental studies on particle transport through the wellbore and, in turn, into orthogonal perforations were conducted on horizontal pipes (Nasr-El-Din et al., 1989). Numerical studies were also conducted (Filippov et al., 2016; Wu et al., 2016, 2017). In simulations, however, gravity is neglected, or sufficient entry length is not provided to maintain stable concentration profile of particles across cross section before delivery to perforation representation. Additionally, most of the oilfield-related literature focused on transport of high-density particles (i.e., sand 2.65 SG).

In this publication, transport efficiencies for low-density particles (1.25 SG, 0.08- or 0.2-in. diameter) are calculated in a 1-cP fluid with consideration of gravity and sufficient entry length. The detailed analysis emphasized the importance of gravity and entry length considerations and the prediction of the transport efficiency for a variety of wellbore rates and perforation orientation.

Entry Length Profile for Slurries

Uniform velocity across inlet boundary cross section is typical during simulations for slurry transport in horizontal pipe. While gravity acts on the particles during flow through the horizontal pipe, the particles continue to form an asymmetric profile across the cross section of pipe. The stable and unchanged profile of particles form after a flow length of 50 to 60 pipe diameters (Colwell and Shook, 1988).

Importance of Gravity for Simulations

Sufficient entry length establishes the particle flow profile across the cross section of pipe when gravity is turned ON. While established profile of particles flow through split pipes, the particle flow profile becomes disturbed. Downstream pipe lengths and gravity reestablishes the slurry flow profile for simulations with multiple clusters; hence, the gravity feature should remain ON for simulations with complex geometries.

Transport Efficiency (*E*)

While established profile of particles flow through split pipes, the particles have two choices to pass into: running down the main pipe or taking a turn into the perforated branch. There are a number of factors (Filippov et al., 2016; Wu et al., 2016, 2017) that influence which flow path the particles take. The success of particles turning into the branch is assessed in terms of the particle transport efficiency (*E*), which is defined as:

$$\boldsymbol{E} = \frac{\dot{\boldsymbol{m}}_{\boldsymbol{perf,s}}}{\dot{\boldsymbol{m}}_{\boldsymbol{inj,s}}} * \frac{\dot{\boldsymbol{m}}_{\boldsymbol{inj,f}}}{\dot{\boldsymbol{m}}_{\boldsymbol{perf,f}}}$$

Where $\dot{\boldsymbol{m}}_{\boldsymbol{perf,s}}$ is particle mass flow rate through the perforated branch; $\dot{\boldsymbol{m}}_{\boldsymbol{inj,s}}$ is the particle mass flow rate at injection or inlet plane; $\dot{\boldsymbol{m}}_{\boldsymbol{perf,f}}$ is the clean fluid mass flow rate through the perforated branch; $\dot{\boldsymbol{m}}_{\boldsymbol{inj,f}}$ is the clean fluid mass flow rate at injection or inlet plane.

Simulation Geometries

Typical plug-and-perf treatments consist of a number of groups of perforations (called clusters) using perforations that are typically oriented down, side, and/or top, most commonly using perforation phasing of 0, 60°, 90°, and 180° within a cluster. During slurry flow through a long horizontal wellbore, the particle settling dynamics at reduced wellbore rates, such as after passing more than one cluster, cause the particles to concentrate toward the bottom half of the cross section. Thus, it is evident that perforation orientation affects transport efficiency, and understanding these effects helps in optimizing the control parameters for achieving the desired delivery of particles into perforations. Therefore, the simulation geometries involve long horizontal sections before arriving at the first cluster. A perforation can be modeled by T-junction representations with upstream pipe flow splitting into one branch (perforation) of either a top-, bottom-, or side-oriented perforation and another branch of downstream pipe section.

The overall application geometry was broken down into two parts for computational simplicity: Geometry 1, long horizontal flow (replicating wellbore section before reaching treatment zone) geometry created to establish particle cross-sectional profile for treatment zone (Figure 1a), and domain mesh is represented in Figure 2; and Geometry 2, T-junction geometry created to understand particle delivery into a perforation in terms of transport efficiency (Figure 1b), and domain mesh is represented in Figure 3.

CFD Model Formulation and Methodology

The methodology and models for particles and fluid motion are discussed in Filippov et al. (2016) and is adapted in the current study. The following computational domain types are generated for current study:

- Geometry 1: Three-dimensional (3D) modeling and simulations of 1.25 SG, 0.08-in. diameter particle redistribution in a long horizontal pipe flow for establishing stable cross-sectional profile of particles.
- Geometry 2: 3D modeling and simulations of 1.25 SG, 0.08- and 0.2-in. diameter particles turning into different oriented perforations, which used the outlet boundary profile of Geometry 1simulations as an inlet profile boundary condition.

The gravitational force is accounted for in all simulations, and simulations were performed with consideration of water or slickwater with viscosity of 1 cP as the carrier fluid.

Results and Discussion

Establishment of Entry Length Profile

Because this modeling was performed only for 1.25-SG density particles, the velocities modeled are lower than for normal oilfield applications during fracture geometry building and transport of higher density proppants. Profiles are simulated for the following physical and boundary conditions: geometries are long horizontal cylinders (Geometry 1) with the diameter of 4 in.; pump rates considered are 10, 15, and 20 bbl/min; particle density is 1.25 SG; particle diameter is 0.08 in.; inlet particle concentration is 1 lbm/gal (0.087476 volume fraction); and uniform flow profile is at the inlet.

Three straight lines were drawn (Figure 4a) from inlet to outlet during post-processing for extracting the data. Line-Below is at a height of 0.25D, Line-Mid is at a height of 0.5D, and Line-Above is at a height of 0.75D (with 0.001 m tolerance from inlet, exit, and symmetry plane). Beyond approximately 60-pipe diameters, concentration profiles were found stabilized (from 60 to 70 pipe diameters in Figure 4b, Figure 4c, and Figure 4d) and flat behavior afterward was observed, which supports flow profile establishment.

Comparison of Gravity for Simulations

Profiles are simulated for the following physical and boundary conditions: geometries are T-junction geometries with down-oriented perforation (Geometry 2) with the diameter of the main pipe at 4-in.; diameter of split pipe (perforation) at 0.5-in.; pump rate considered is 10 bbl/min; particle density is 1.25 SG; particle diameter is 0.08 in.; inlet particle concentration is 1 lbm/gal (0.087476 volume fraction); outlet profile from Geometry 1 is imposed onto the inlet plane of Geometry 2; T-junction is at a distance of 10 pipe diameters from the inlet; and total length of geometry is 15 pipe diameters.

Three straight lines were drawn (Figure 5a) from inlet to outlet during post-processing for extracting the data. Line-Below is at a height of 0.25D, Line-Mid is at a height of 0.5D, and Line-Above is at height of 0.75D (with 0.001 m tolerance from inlet, exit, and symmetry plane). Sufficient entry length established the particle flow profile across the cross section when gravity is turned ON for Geometry 1 simulations.

After superimposing the outlet from Geometry 1 onto the inlet of Geometry 2 and running simulations with gravity turned OFF for Geometry 2, particles were gradually resuspended toward the top portion of the pipe and lost its established profile (as developed from Geometry 1) before reaching the T-junction. This leads to improper prediction of transport efficiency (*E*).

After superimposing the outlet from Geometry 1 onto the inlet of Geometry 2 and running simulations with gravity remaining ON for Geometry 2, it is observed that the particle profile is maintained properly (note the green curves in Figure 5b, Figure 5c, and Figure 5d before 10 pipe diameters) before nearing the T-junction. While the established profile of particles had a choice to flow through either the split pipe or to follow the path of the main pipe, the downstream particle flow profile was disturbed because of loss of fluid velocity and got reestablished gradually over the length of the pipe (from 10 to 15 pipe diameters in Figure 5b, Figure 5c, and Figure 5d). Note that the downstream pipe lengths and gravity reestablishes the slurry flow profile for simulations with multiple branches. Considering this, all the simulations in this publication are run with gravity turned ON.

Perforation Orientation Influence on Transport Efficiency (*E*)

The following physical and boundary conditions are used for simulations. Geometries are T-junction geometries with down-, side-, and top-oriented perforations (Geometry 2) with the diameter of the main pipe at 4 in.; diameter of split pipe at 0.5 in.; pump rates considered are 10, 15, and 20 bbl/min; particle density is 1.25 SG; particle diameter is 0.2 in. (typical of larger low-density particles in present day being used); inlet particle concentration is 1 lbm/gal (0.087476 volume fraction); symmetry (sliced to half) for top- and down-oriented perforations and full geometry for side-oriented perforation; pressure outlet boundaries with a constant 600 psi at the main pipe outlet and 200 psi (high-mass flow to perforations) and 590 psi (low-mass flow to perforations) at the perforation outlet; the outlet profiles from corresponding Geometry 1 is imposed onto the inlet plane of corresponding Geometry 2; T-junction is at a distance of 10 pipe diameters from the inlet; and the total length of geometry is 15 pipe diameters.

Simulations performed for down-, side-, and top-oriented perforations individually for low-mass flow rate into the perforation (up to 4% of inlet mass) and high-mass flow rates into the perforation (up to 30% of inlet mass) were observed. The transport efficiency (*E*) values were compared for varied flow rates of 10, 15, and 20 bbl/min, and the results were plotted in Figure 6a and Figure 6b. With increasing pump rate, a reduced amount of particles mass flow rate into down- or side-oriented perforations (Figure 6a and Figure 6b) and an increased amount of particles mass flow rate into top-oriented perforation were observed; however, no significant increase in particles mass flow rate is observed for the top-oriented perforation from 15 to 20 bbl/min modification in rate.

Conclusions

The following conclusions were reached:

- Sufficient entry length before perforations should be maintained for flow development for slurry simulations in horizontal wells.
- Gravity should be turned ON for slurry simulations, even for particle density as low as 1.25 SG and 0.08-in. outer diameter (OD).
- The proximity of particles to the perforation plays an important role for particles to move into the perforation. At lower inlet velocity, more particles tend to move closer to the bottom of the pipe and, hence, concentration in the bottom perforation might exceed concentration in the main pipe. The top-oriented perforation might take relatively fewer particles.
- The length between multiple T-junctions (perforation cluster locations) should be scaled appropriately to match established profile of particles and, in turn, transport efficiencies based on treatment variables.

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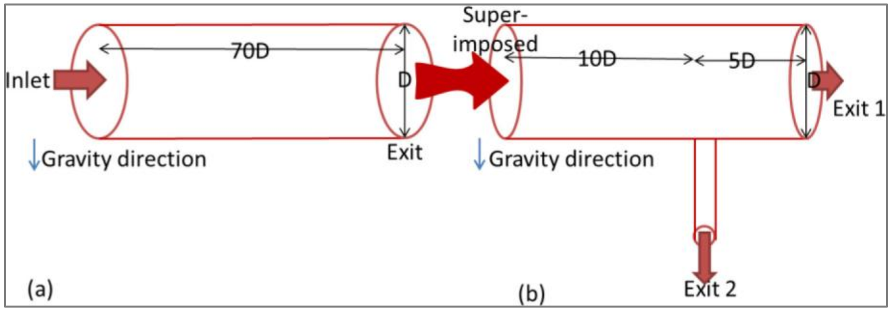

Figure 1. Physical computational domains: (a) flow establishment and (b) particle delivery.

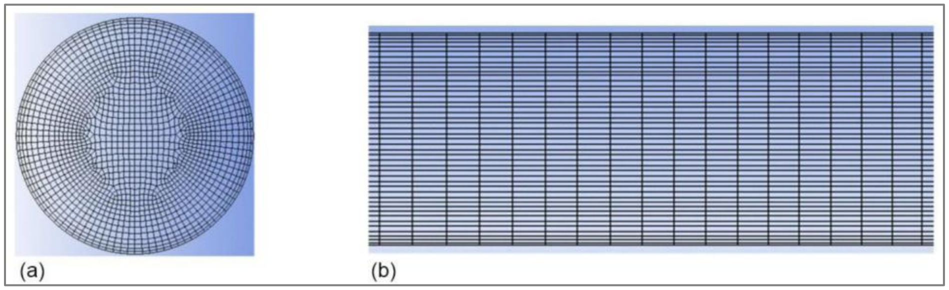

Figure 2. Horizontal flow geometry for establishing cross-sectional slurry distribution profile; mesh for (a) inlet section and (b) part of symmetry section.

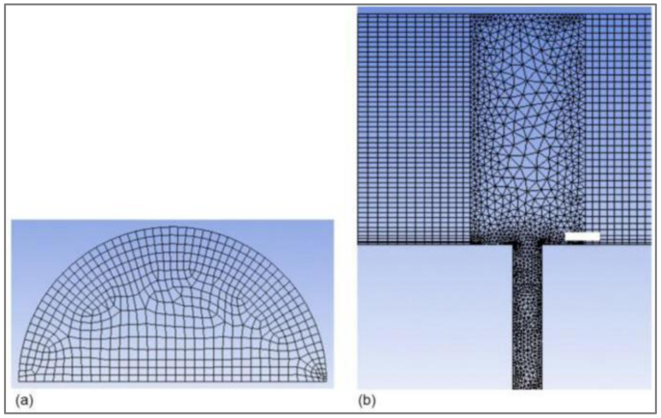

Figure 3. T-junction geometry with down-oriented perforation branch; mesh for (a) inlet section and (b) part of symmetry section.

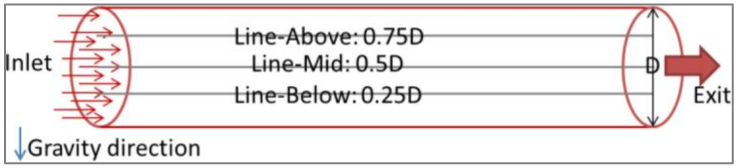

Figure 4a. Nomenclature: Representation of lines in the horizontal flow geometry domain.

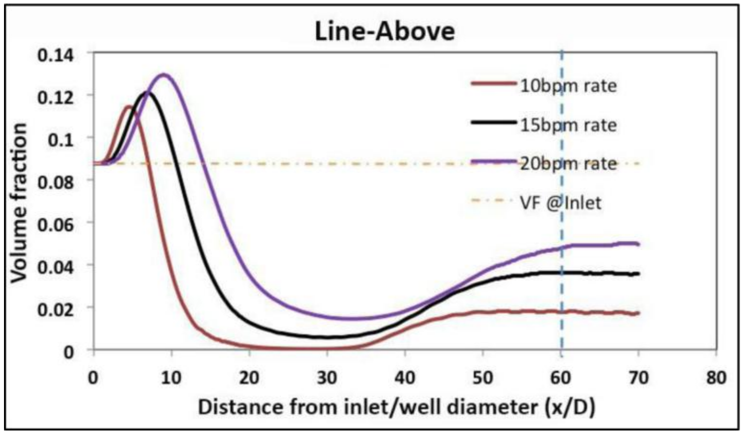

Figure 4b. 1.25 SG, 0.08-in. diameter particle flow establishment profiles in 4-in. pipe for Line-Above.

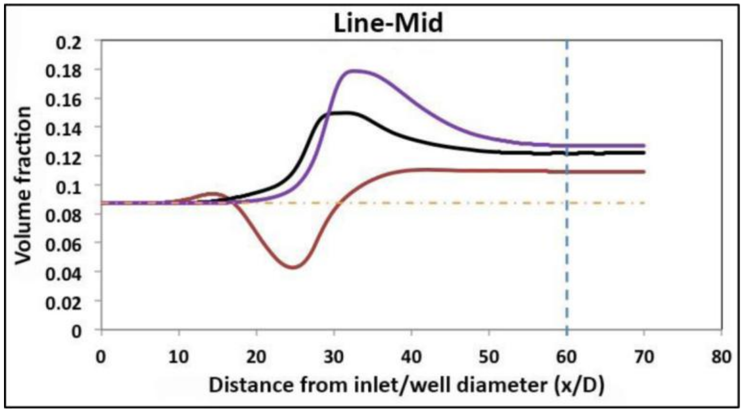

Figure 4c. 1.25 SG, 0.08-in. diameter particle flow establishment profiles in 4-in. pipe for Line-Mid.

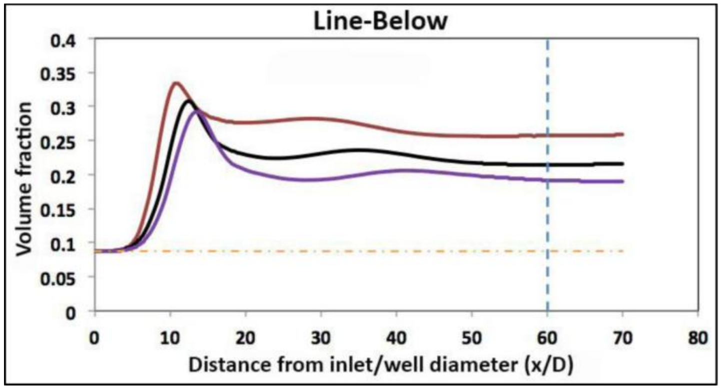

Figure 4d. 1.25 SG, 0.08-in. diameter particle flow establishment profiles in 4-in. pipe for Line-Below.

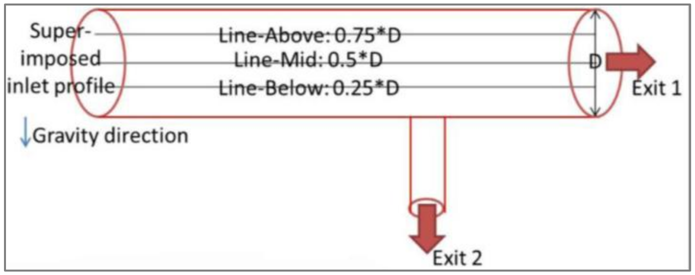

Figure 5a. Nomenclature: Representation of lines in the T-junction geometry domain in 4-in. pipe. 0.5-in. perforation.

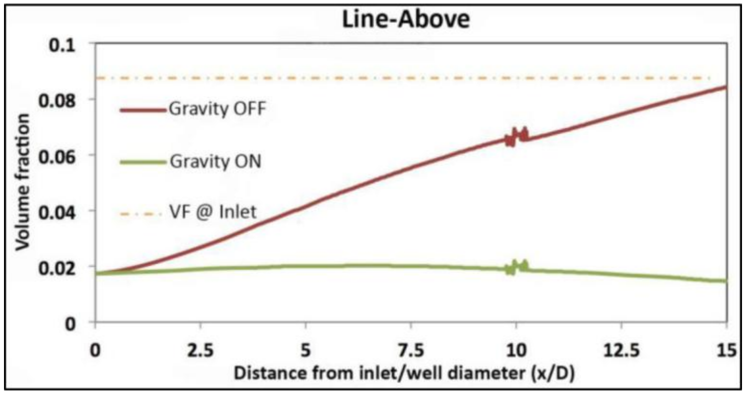

Figure 5b. 1.25 SG, 0.08-in. diameter particle volume fraction profiles along the length of lines for Line-Above.

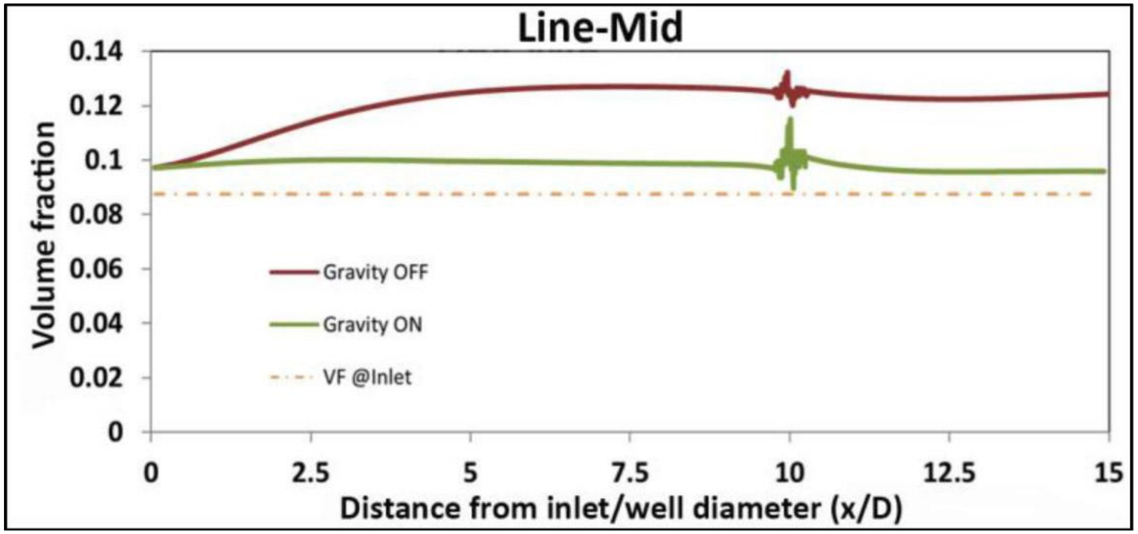

Figure 5c. 1.25 SG, 0.08-in. diameter particle volume fraction profiles along the length of lines for Line-Mid.

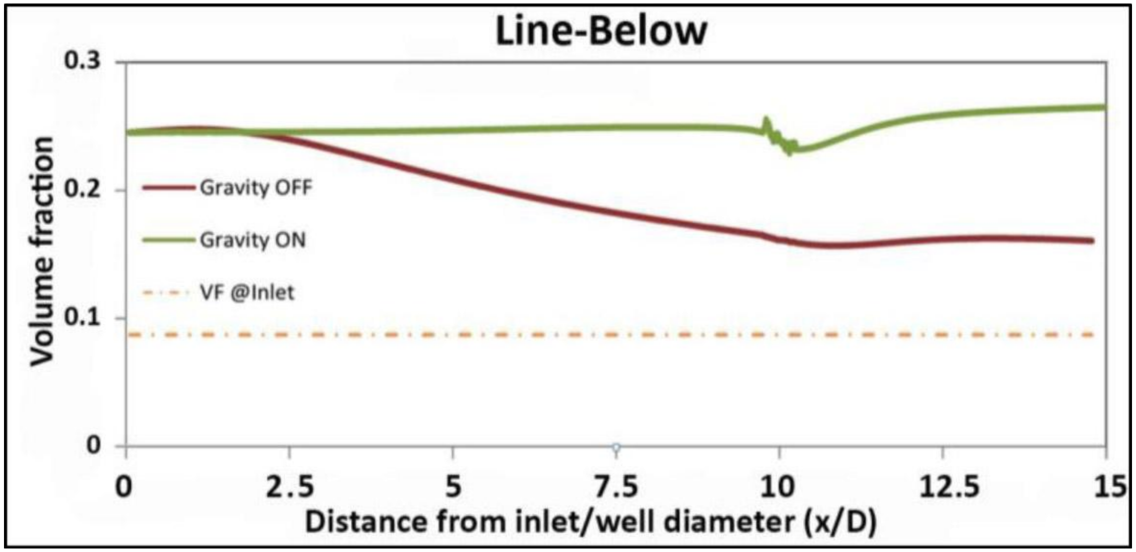

Figure 5d. 1.25 SG, 0.08-in. diameter particle volume fraction profiles along the length of lines for Line-Below.

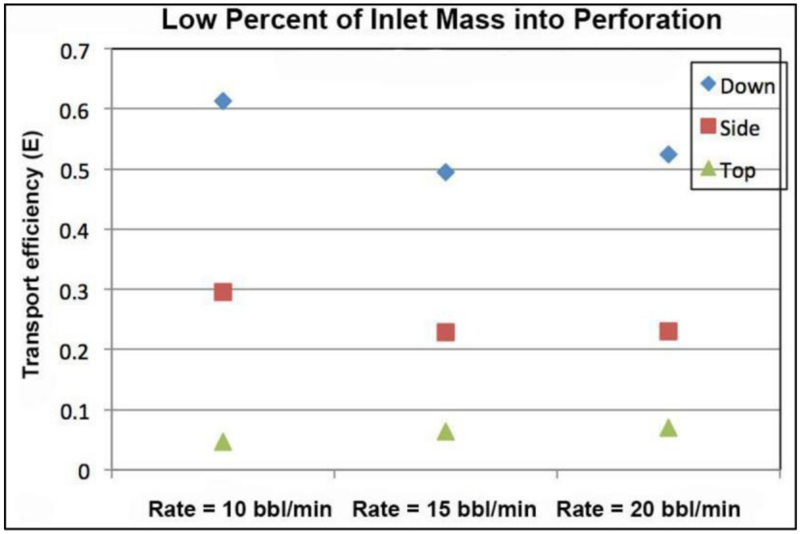

Figure 6a. Transport efficiency of 1.25 SG, 0.2-in. diameter particles for down-, side-, and top-oriented perforations for low (approximately 2 to 4% of inlet mass flow rate into the perforation).

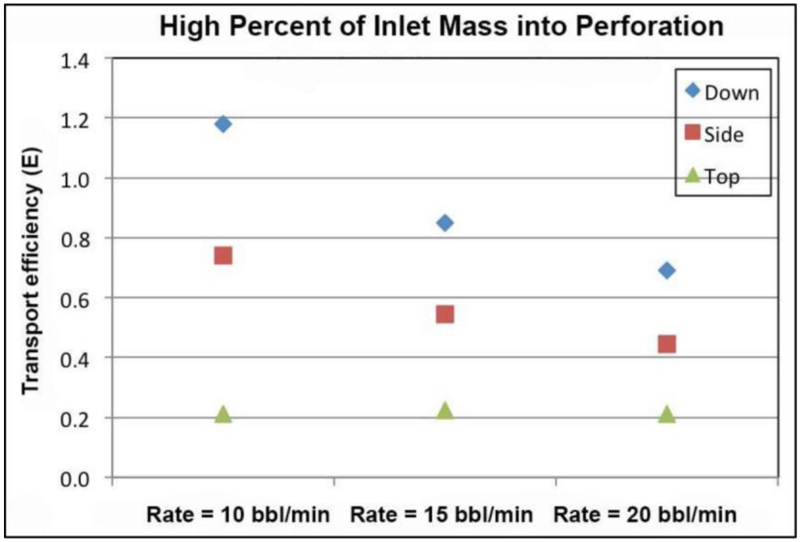

Figure 6b. Transport efficiency of 1.25 SG, 0.2-in. diameter particles for down-, side-, and top-oriented perforations for high (approximately 15 to 30% of inlet mass flow rate into the perforation).