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A CFD simulator for multiphase flow in reservoirs and pipes

Dimitri Gidaspow [a,*], Fang Li [a], Jing Huang [b]

[a] Chemical and Biological Engineering, Illinois Institute of Technology, Chicago, IL, United States
[b] Energy System Division, Argonne National Laboratory, Argonne, IL, United States

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ABSTRACT

A computational fluid dynamics (CFD) code for flow of oil, gas and sand in reservoirs and pipes was developed to help understand the flow in wild wells that are drilled for offshore oil production. In the reservoir, there is a large entrance effect produced by turbulence. In the pipe, the code computed turbulent velocity profiles and Reynolds stresses similar to fully developed single phase turbulent flow. The Fanning friction factor for oil flow at a Reynolds number of about 16,000 is 0.004, compared with the single phase turbulent friction factor of 0.007. The computed low frequency oscillations are consistent with wild well behavior.

1. Introduction

We have developed a computational fluid dynamics (CFD) computer code for flow of oil, gas and sand in reservoirs and pipes that will help to understand flow in wild wells that are drilled for offshore oil production. We have simulated the flow of mud, gas and oil, as described in the Sunday, December 26, 2010 New York Times article, "Deepwater Horizon's Final Hours". With a low level of mud in the pipe and some trapped gas in the well, the mud gets blown out, followed by gas and then oil. The driving force for flow is the buoyancy between the oil, gas and mud in the pipe and an equivalent height of water.

We have used a modification of our CFD code described in the 2009 book [1]. Conventional state of the art multiphase flow simulations in the reservoirs are done using Darcy's law [2]. Our simulations using CFD show that near the well the flow is highly turbulent. Our measure of turbulence is the computed granular temperature of the sand near the well.

In the tall well we are computing a core-annular flow in dilute oil–gas flow, in agreement with literature. We have also computed the friction coefficients of gas and oil flows in the well at the high gas and oil flow rates. In the one dimensional models, such as those used for licensing nuclear reactors, the fully developed friction coefficients are an input into the codes [3].

2. Multiphase CFD model

The basic mass and momentum balances for the sand, oil and methane [1] are as follows (f = methane, s = sand or oil).

Continuity equation for phases $k=(f,1,\ldots,N)$.
f = fluid phase, methane; k = particulate phase, sand or oil droplets

$$\frac{\partial}{\partial t}(\varepsilon_k\rho_k)+\nabla\cdot(\varepsilon_k\rho_k\mathbf{v}_k)=0 \tag{1}$$

Momentum equations

(a) Fluid phase

$$\frac{\partial}{\partial t}\left(\varepsilon_f\rho_f\mathbf{v}_f\right)+\nabla\cdot\left(\varepsilon_f\rho_f\mathbf{v}_f\mathbf{v}_f\right) = -\nabla P_f+\rho_f\mathbf{g}+\sum_{l=1}^{N}\beta_{fl}\left(\mathbf{v}_l-\mathbf{v}_f\right)+\nabla\cdot\left[\tau_f\right] \tag{2}$$

(b) Particulate phase $k=(1,\ldots,N)$

$$\frac{\partial}{\partial t}(\varepsilon_k\rho_k\mathbf{v}_k)+\nabla\cdot(\varepsilon_k\rho_k\mathbf{v}_k\mathbf{v}_k)=-\nabla P_k+\frac{\varepsilon_k}{\varepsilon_l}\left(\rho_k-\sum_{l=f,1}^{N}\varepsilon_l\rho_l\right)\mathbf{g} + \sum_{\substack{l=f,1\\ l\neq k}}^{N}\beta_{kl}\left(\mathbf{v}_l-\mathbf{v}_f\right)+\nabla\cdot[\tau_k]. \tag{3}$$

These 2(N + 1) nonlinear, partial differential equations must be solved for the 2(N + 1) dependent variables: The continuous phase pressure P_f, the particulate phase volume fractions ε_k, (k = 1,..., N), the fluid and particulate velocity component u_k and v_k(k = 1,..., N) in two directions, respectively.

* Corresponding author.
E-mail address: gidaspow@iit.edu (D. Gidaspow).

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Constitutive equations for stress

(a) Fluid phase stress

$$\left[\tau_f\right] = \varepsilon_f \mu_f \left(\left[\nabla \mathbf{v}_f + \left(\nabla \mathbf{v}_f \right)^T \right] - \frac{2}{3} \nabla \cdot \mathbf{v}_f [\mathbf{I}] \right). \tag{4}$$

(b) Solid phase stress $k = (1,\ldots,N)$

$$[\tau_k] = \mu_k \left(\left[\nabla \mathbf{v}_k + (\nabla \mathbf{v}_k)^T \right] - \frac{2}{3} \nabla \cdot \mathbf{v}_k [\mathbf{I}] \right). \tag{5}$$

Gas-particulate drag coefficients $k = (1,\ldots,N)$.
for $\varepsilon_f < 0.8$ (based on Ergun equation)

$$\beta_{fk} = \beta_{kf} = 150 \frac{\left(1-\varepsilon_f\right)\varepsilon_k \mu_f}{\left(\varepsilon_f d_k \psi_k\right)^2} + 1.75 \frac{\rho_f \varepsilon_k \left| \mathbf{v}_f - \mathbf{v}_k \right|}{\varepsilon_f d_k \psi_k}. \tag{6}$$

for $\varepsilon_f \geq 0.8$ (based on empirical correlation)

$$\beta_{fk} = \beta_{kf} = \frac{3}{4} C_D \frac{\varepsilon_k \rho_f \left| \mathbf{v}_f - \mathbf{v}_k \right|}{d_k \psi_k} \varepsilon_f^{-2.65} \tag{7}$$

where

$$C_D = \begin{cases} \frac{24}{\mathrm{Re}} \left[1 + 0.15 \mathrm{Re}_k^{0.687} \right] & \textit{for } \mathrm{Re}_k < 1000 \\ 0.44 & \textit{for } \mathrm{Re}_k \geq 1000 \end{cases}$$

$$\mathrm{Re}_k = \frac{\varepsilon_f \rho_f \left| \mathbf{v}_f - \mathbf{v}_k \right| d_k \psi_k}{\mu_f}.$$

Empirical solids viscosity and stress model

Cases 1 & 2.

$$\nabla P_s = G(\varepsilon_s) \nabla \varepsilon_s \tag{8}$$

$$G(\varepsilon_s) = 10^{8.577\varepsilon_s - 8.686} \tag{9}$$

$$\mu_s = \alpha_s \varepsilon_s \tag{10}$$

where $\alpha_s = 0.01$ for oil and $\alpha_s = 10$ for sand.

$$\xi_s = 0 \tag{11}$$

Case 3.

$$\nabla P_s = G(\varepsilon_s) \nabla \varepsilon_s \tag{12}$$

$$G(\varepsilon_s) = \rho_s \theta_s \tag{13}$$

Table 1
Parameters for simulations.

Parameter	Gas	Oil	Sand
Diameter (μm)	–(Continuous phase)	100	10
Density (g/cm^3)	0.27E-02	0.85	2.94
Cases I & II			
Viscosity coefficient (g/(cm/s))	0.1813E-03	0.01	10.00
Case III			
Viscosity coefficient (g/(cm/s))	0.1813E-03	50.00	10.00
Inflow into reservoir			
Inlet velocity (cm/s)	4.04	3.37	3.37
Temperature (Kelvin)	300		
Initial pressure	1025 atm (10.386804E+07 Pa)		
Pipe break pressure	148 atm (1.503652E+07 Pa)		

Table 2
System geometry and system properties.

Well diameter-semi (m)	0.265
Well height (m)	3962.4
Reservoir diameter (m)	2.495
Reservoir height (m)	1524
Grid number	55×492
Time step	1×10^{-5}

where θ_s is the granular temperature, which is the measure of particulate fluctuation energy. As an approximation, the granular temperature is obtained from the square of the solid velocity, using Eq. (9) of Gidaspow, et al. [4], as follows:

$$\theta_s = \frac{4}{15} V_s^2. \tag{14}$$

Similarly, the viscosity was estimated to be, as follows:

$$\mu_s = 50\varepsilon_s. \tag{15}$$

Non-slip boundary conditions were used in all simulations.

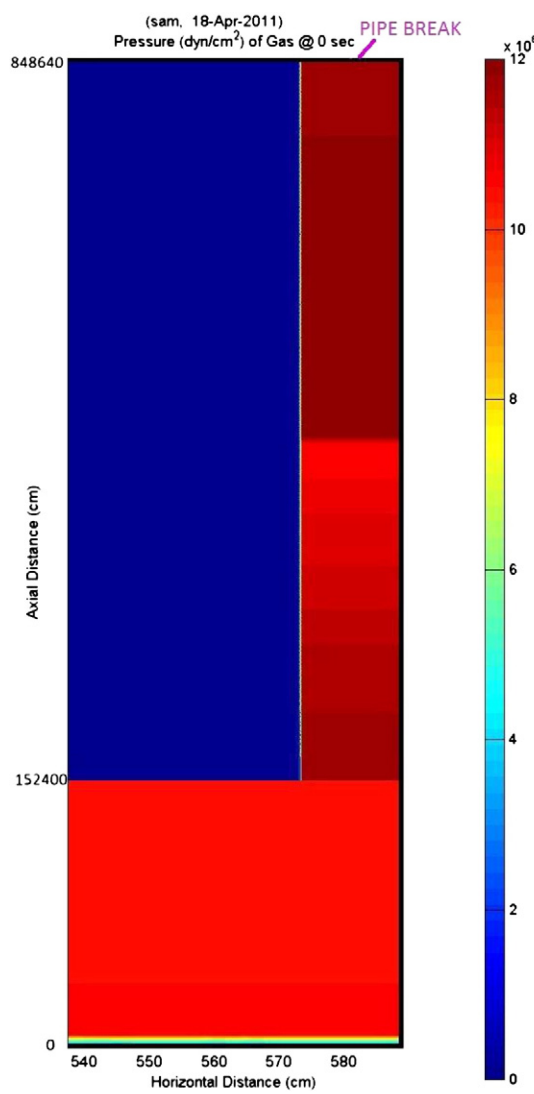

Fig. 1. Initial pressure distribution for the BP oil spill in the reservoir and well. Color scale: 12×10^8 dyn/cm^2 maximum, dark red; 0 minimum, blue.