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Computational Modeling and Experiments on Shale Shaker Performance

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Abstract

The aim of this work is to develop a computer model to predict performance of a shale shaker. The model is developed in two parts – a cake-filtration section describes cake formation on a screen mounted on the shaker and a drainage section models liquid drainage from the cake material. The final equations that describe the whole process were derived from multiphase and fluid flow equations as well as flows through porous media.

The model results are complemented by pilot-scale experiments that mimic screen performance on a vibrating packed-bed assembly. Full-scale experiments on the actual shaker machine were also performed to validate the model results.

Introduction

Shale shakers are the most commonly used solid-liquid separation devices used in petroleum drilling operations. Vibratory screens are placed in the shakers that perform the filtration separation operation. The screens may be placed either in series or parallel configuration depending on shaker design and multiple screens are usually used during a single operation. Several mathematical models of screen operation and performance are reported in the literature, but a fully working model is not currently available.

Our numerical model applies to the operating conditions prevailing during screen operation including accelerations acting on the machine, rheological behavior of the drilling fluid (in the form of a Bingham plastic model), and particle sizes. The pilot-scale experiments mimic several screen operating parameters except the tilt of the screen (deck angle). The pilot-scale experiment is limited in flow rates to less than 0.0637 gal/min per square inch of screen area (0.006225 (m^3/m^2)/s). A sketch of the model geometry is shown in Fig.1.

Computer Model

The computer model only considers the liquid drainage from the sand cake where the drilling mud depth is greater than the cake depth. The sand cake that forms on the screen moves in the x-direction due to the vibrations of the screen. The model assumes the surface of the mud is horizontal, the cake of sand that forms on the screen is continuous and uniform over the screen width, and the screen is tilted at a positive, non-zero, angle rising out of the mud along position x. The model ignores liquid drainage from the cake after the cake moves out of the mud up the inclined screen.

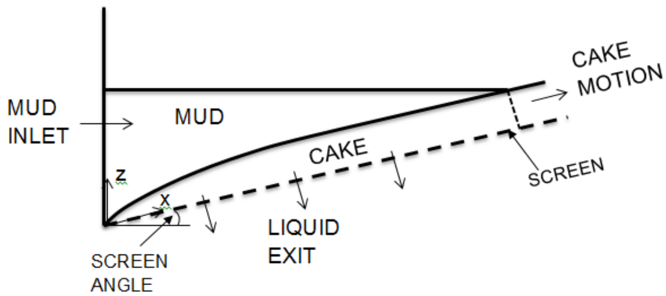

Fig. 1. Sketch of vibrating screen and sand cake model geometry.

Cake Filtration Model

The equations for the cake filtration model were derived from basic fluid flow, multiphase equations, and mass and momentum balances. A detailed description of this model was presented during the 2010 AADE conference.[1] In the current work the previous model has been further refined by applying the correlation for friction factor for a yield stress fluid flowing through a porous medium[2,3] to the cake formed on the screen from the drilling mud. The correlation for the friction factor of a yield stress fluid flowing through the cake is given by (Eq. 1):

$$f_{CAKE} = \frac{60}{Re_p}\left[1 - \frac{4}{3}\left(\frac{3.5\,He_p}{fRe_p^{\,2}}\right) + \frac{1}{3}\left(\frac{3.5\,He_p}{fRe_p^{\,2}}\right)^4\right]^{-1} + 0.6 \qquad \text{(Eq. 1)}$$

Kao[4] derived the friction factor for a yield stress fluid flowing through a cylindrical tube from the definition of friction factor and the velocity profile[5] for laminar flow. By assuming the laminar flow and turbulent flow friction factors are linearly additive, the friction factor for flow through a pore in the screen is approximated by the expression in (Eq. 2).

$$f_{SCREEN} = \frac{16}{Re}\left[1 - \frac{4}{3}\left(\frac{2\,He}{fRe^2}\right) + \frac{1}{3}\left(\frac{2\,He}{fRe^2}\right)^4\right]^{-1} + 0.001 \qquad \text{(Eq. 2)}$$

These equations have multiple roots which make them difficult to apply in computer models. They were further approximated by fitting the equations to polynomial forms shown in (Eq. 3) and (Eq. 4) to make the calculation of the friction factors explicit.

$$f_{CAKE,apr} = 5.741 * Re_p^{-1.969} * He_p^{0.958} + \frac{60}{Re_p} + 0.6 \quad \text{(Eq. 3)}$$

$$f_{SCREEN,apr} = 5.724 * He^{0.905} * Re^{-1.96} + \frac{16}{Re} + 0.001 \quad \text{(Eq. 4)}$$

The friction factors are used to determine the velocity of the liquid, v_z, through the cake and the screen at each position x and ultimately to determine the capacity (total flow rate) of the screen.

Fig. 2 shows a plot of variation of velocity through the screen along the whole length of the screen for different values of step size in x (position along screen). The calculations were stopped as soon as the height of the cake reached the height of the incoming mud. In this plot the deck angle was maintained at 1° and the shear stress value was 15 $N/_{m^2}$. The results show the calculations converge to a consistent solution for values of DX = 0.001 and smaller. The velocity calculations are combined with the mass balance (Eq.5) to determine the cake height over position x. A trapezoidal method was used to integrate (Eq. 5) over position x and a one-step predictor/corrector was used to correct the cake height at the position x when calculating velocity used in the trapezoid equation. The velocity, v_x, is the velocity of the cake as it moves along the screen in the x direction. In the current model this value must be determined from experiments. The average value reported in Table 1 is used in the calculations.

$$\frac{\partial h_c}{\partial x} = \frac{1}{v_x}\left(\frac{1-\varepsilon^m}{\varepsilon^m-\varepsilon^c}\right) v_z \quad \text{(Eq. 5)}$$

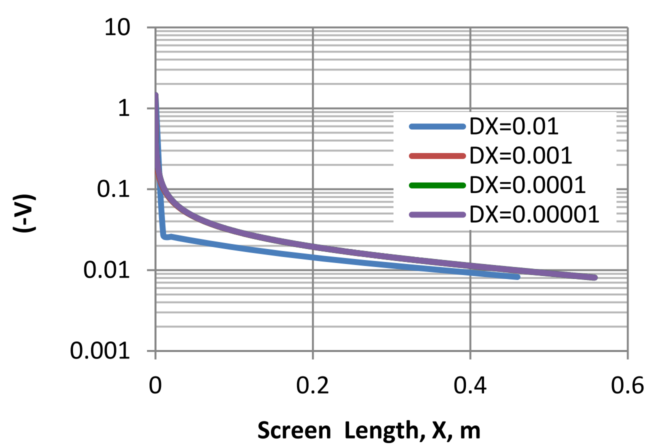

Fig. 2. Variation of Velocity along Length of Screen. The Sensitivity Analysis shows the Appropriate Step Size is DX = 0.0001.

Fig. 3 shows the cake heights calculated for different step sizes DX. Parametric analyses were done on several operating variables to determine which of them would affect shaker performance significantly. A linear curve was fitted to each of the plots and the magnitude of the slope gave an estimate of the sensitivity of performance to that parameter. Figs. 4, 5 and 6 show the effects of incoming mud height $\boldsymbol{h_o}$, screen acceleration, and mud density ρ to have the greatest effect on shaker performance. In all cases the base values used for comparison are shown in Table 1.

Table 1: Base Values of Parameters used in Parametric Studies

Parameter	Value
Shear Stress, $\boldsymbol{\tau_0}$	15 N/m^2
Cake Volume Fraction, $\boldsymbol{\varepsilon^c}$	0.45
g-factor (Acceleration)	4.0
Incoming Mud Height, $\boldsymbol{h_o}$	2 inches
Mud Viscosity, μ	24 cP
Mud Density, $\boldsymbol{\rho^L}$	9.2 lb/gal
Screen Angle, ω	1°
Cake Velocity, $\boldsymbol{v_x}$	0.10668 m/s (10g), 0.0725 m/s (6g), 0.0384 m/s (3g)

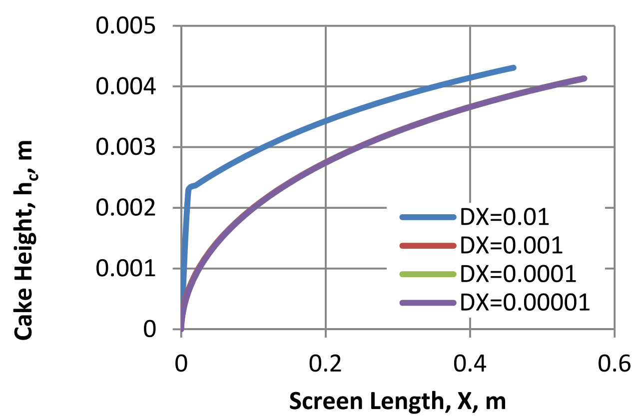

Fig. 3. Convergence of Model Results for Cake Height.

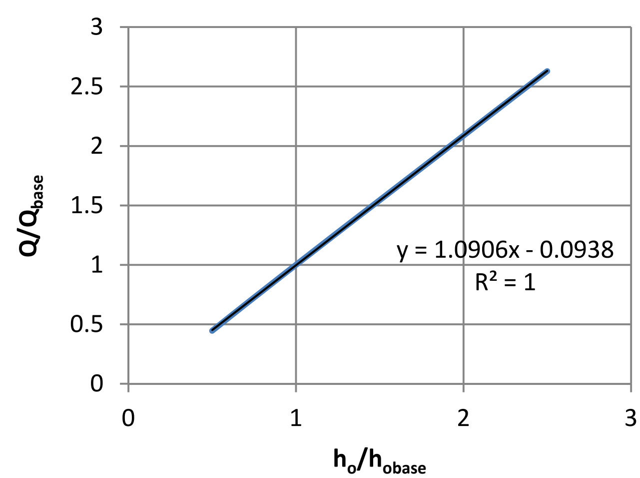

Fig. 4. Effect of Incoming Mud Height on Screen Capacity (Performance).

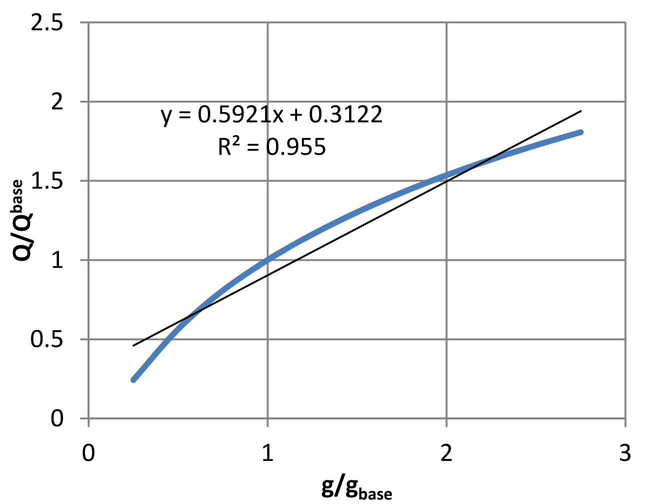

Fig. 5. Effect of Screen Acceleration on Screen Capacity (Performance).

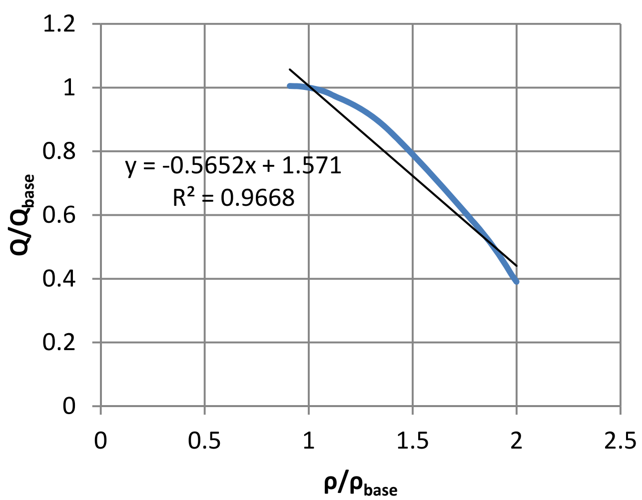

Fig. 6. Dependence of Screen Capacity (Performance) on Mud Density.

Experimental Work

The experimental work was divided into two categories – pilot-scale experiments conducted in the laboratory and full-scale experiments performed on the actual shaker machine at SWECO's facility in Florence, Kentucky. The pilot scale experiments allow us to observe the motions of particles on the screen that are not possible to observe on the full scale equipment.

Pilot-Scale Experiments

A vibrating packed-bed experiment was set up in the laboratory using a Plexiglas tube fitted with an API 140 screen. The tube was filled with sand at varying heights and water circulated through the tube at controlled flow rates. A motor was connected to the assembly which provided the vibratory motion. The amplitude of vibration was varied by attaching flanges to the motor with different offset distances to the center of rotation. Video recordings of the moving sand particles were made using a high speed Mikrotron CCD camera from which the velocities of the particles and rise of the sand bed were observed. An example of the velocity distribution of the sand particles in the packed bed is shown in Fig. 7 and 4. Fig. 8 was drawn for the case of 1.0 cm sand height at a bed acceleration of 9.06g. The steady state pool heights above the sand layer were measured during each experiment. The porosity of the sand bed at each height was determined using the gravimetric method. Table 2 shows the acceleration acting on the packed bed at different amplitudes and Table 3 shows the porosities at various sand heights.

The experimental results show trends similar to those observed on the actual machine. Pool height increases with flow rate as shown in Figure 9.

Table 2: Accelerations Acting on Packed-Bed

Amplitude, r (mm)	G
0.5	1.811
1.25	4.53
2.5	9.06

Table 3: Porosity of Sand-Bed

Sand Height, h (cm)	Porosity
0.5	0.5761
1.0	0.294
1.5	0.3119
2.0	0.34
2.5	0.287

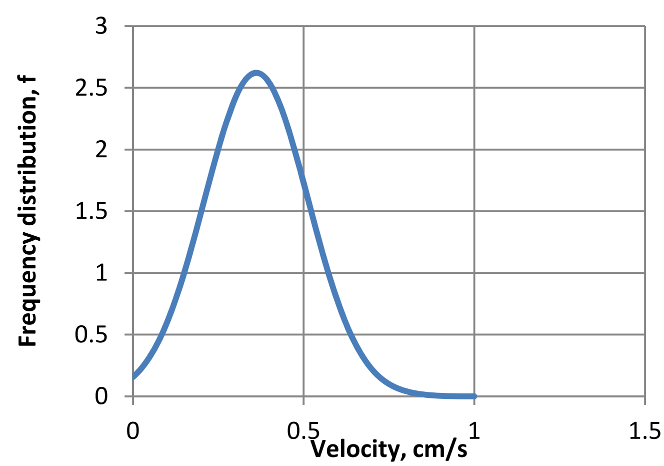

Fig. 7. Velocity Distribution of Particles in the Sand Bed. Experimental Conditions were 0.5 cm sand, 2.5 GPM inlet water flow rate, 9.06g Acceleration.

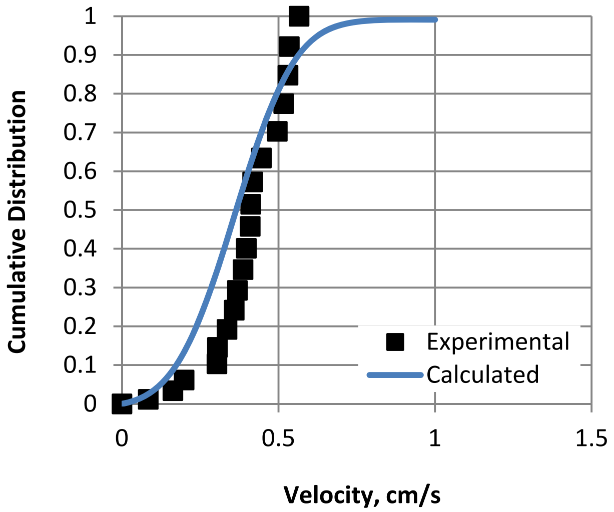

Fig. 8. Cumulative and Experimental Velocity Distributions for 5.0 mm Motor Amplitude, 2.5 GPM Flow Rate, 0.5 cm Sand Height.

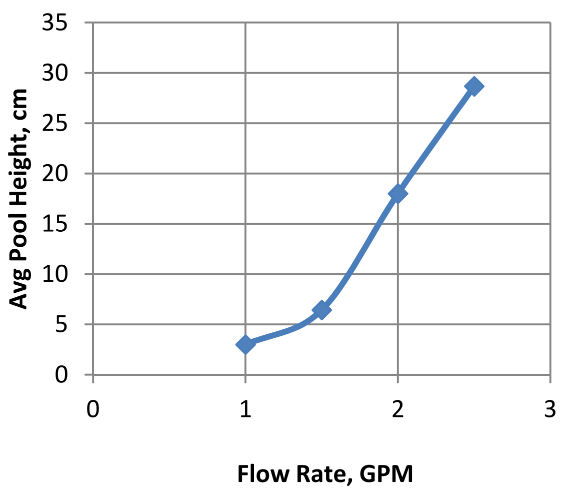

Fig. 9. Variation of Pool Height with Inlet Flow Rate (Pilot-Scale Experiment). Sand Height was 1.0 cm.

Full-Scale Experiments

Full-scale experiments were conducted on an M-I SWACO Mongoose PT shale shaker. Three types of high capacity (HC) screens were tested using various flow rates, accelerations, and physical properties of the mud such as density, plastic viscosity and solids loading. Fig. 10 shows a plot of the variation of capacity on a screen with deck angle at various accelerations acting on the shaker. As expected, capacity increases with deck angle at all accelerations. Also, for a given value of deck angle, greater capacity is obtained at a higher acceleration.

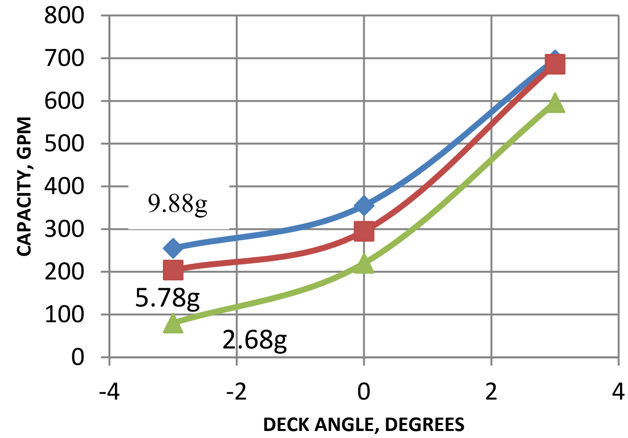

Fig. 10. Variation of Capacity with Deck Angle and Acceleration at a Mud Weight of 9.3 lb/gal.

The effect of plastic viscosity was studied by varying the amount of solid particles and liquid in the feed stream. Here also the same trend of higher capacity with higher deck angle was observed. However, as shown in Fig. 11, at higher mud viscosities, the flow capacity decreases because the higher thickness of the mud slows down conveyance.

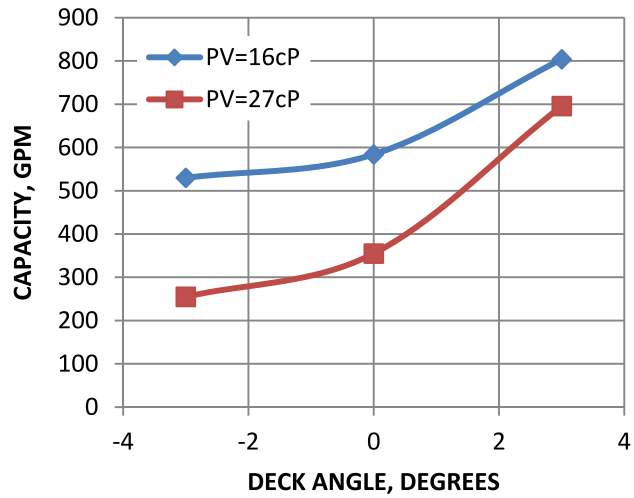

Fig. 11. Effect of Mud Plastic Viscosity on Screen Capacity at Acceleration~10 g.

Fig. 12 is a plot of the effect of solids concentration (or solids loading) on screen performance (capacity). As expected, a higher capacity was obtained at lower solids concentration in the feed at all deck angles, but at concentrations above 15% the capacity appears to become insensitive to concentration. The acceleration was maintained constant at the maximum value (i.e. ~10 g).

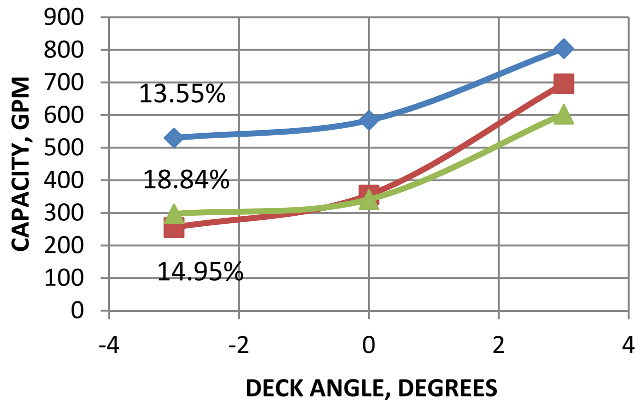

Fig. 12. Effect of Solids Loading of Mud on Screen Capacity at Acceleration ~10 g.

Comparison of the model predictions with the full scale experiments shows similar trends. Fig. 13 shows an example of the comparison of the model and full scale experimental results. The plots show a similar trend (higher capcity at higher accelerations). The predicted capacity is the right order of magnitude but further improvement is needed. The deviation between the two plots may be due to certain parameters that we do not have a good estimate of at present (cake volume fraction, shear stress, and mud plastic viscosity). Improved estimates of these parameters may give a better match of model prediction and experimental performance. Further refinement of the model is needed to relate the cake velocity in the x direction to the operating conditions. Better measurements or estimates are needed for parameters such as cake porosity and yield stress.

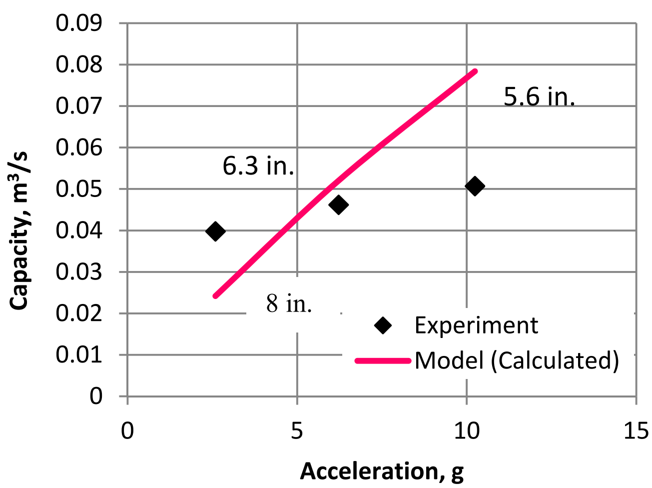

Fig. 13. Comparison of Yield Stress Model and Full Scale Experimental Results.

Conclusions

The following conclusions can be drawn from this work.

- A numerical model has been developed to describe flow of a yield stress fluid through a vibrating screen.
- Parametric studies show the effects of various operating variables on screen performance.
- Model shows good convergence of the numerical method for values of DX equal to 0.001 m or smaller.
- Model results are the same order of magnitude and show similar trends to full scale experimental results.
- A sensitivity analysis of the model parameters show the model is sensitive to inlet mud height, mud density, and screen acceleration.

Future Work

- Particle behavior during screen vibration should be modeled to relate cake velocity in the x direction to the screen motion and to predict cake porosity. This model should be verified with experimental data from full or small scale experiments.
- The model sensitivity analysis should be extended to all model parameters to determine which parameters are most significant for guiding experimental analysis.
- Empirical Relations should be developed between mud concentration, particle size distribution, plastic viscosity, and yield stress. These relations will allow a better comparison between model and full scale experiment results.
- The model and experiments should be extended to include zero and negative screen angles.
- The model should be modified to more closely match the overlapping saw-tooth geometry of the screen sections on the full scale equipment instead of assuming the screen is one continuous long screen.

Acknowledgments

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Nomenclature

Re_p = *Reynolds Number of the particle*
He_p = *Hedstrom Number of the particle*
Re = *Reynolds Number*
He = *Hedstrom Number*
f_{CAKE} = *Friction Factor for cake*
f_{SCREEN} = *Friction Factor for screen*
$f_{CAKE,appr}$ = *Approximate value for cake friction factor*
$f_{SCREEN,appr}$ = *Approximate value for screen friction factor*
GPM = *gal/min*
h_c = *Cake height*
ε^m = *Volume Fraction of mud*
ε^c = *Volume Fraction of cake*
v_z = *Velocity of mud in Z direction*

References

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