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Predicting Mud Removal during Cementing – A New and Simple Approach

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Abstract

Perhaps the most important factor engineers and operators should consider for successful oilwell cementing is adequate drilling-fluid removal, or "mud displacement." To optimize mud displacement, the primary technique used today is to pump a spacer fluid with modified rheology that creates a beneficial fluid-fluid interface. However, the extent to which this "material property hierarchy" affects one fluid displacing another fluid is often unknown, especially in wells where the casing is offset from center. Therefore, this paper addresses the question: "To what extent will changing density, modifying viscosity, or doing both have on mud displacement efficiency in both concentric and eccentric annuli?"

To better describe this influence of rheological hierarchy, volume-fraction vs. time curves derived from computational fluid dynamic (CFD) simulations are used to accurately describe the mud removal process. A test matrix covering typical ranges of densities and viscosities was established and several geometric models, each with different casing standoff percentages, were created in a finite element grid generation program. Initial conditions were set to simulate mud with pre-determined rheological properties sitting static in the annulus. A spacer fluid, also with programmable rheological properties, was then automated to begin displacing the mud at the inlet. The simulations were allowed to run until 99% of the mud was removed from the model. The displacement efficiencies in both the wide side of the annulus and narrow side of the annulus were used as a basis for contour plots. These contour plots, which can span casing standoffs from 0% to 100%, allow the user to quickly assess the *relative* influence density changes and viscosity changes have on displacement efficiency. Upon review, this novel method of data presentation gives a cementer a powerful and simple tool to efficiently design a spacer fluid for optimal mud removal.

Introduction

The present study describes a method of using empirical parameters to accurately describe the mud removal process. This method encompasses two main concepts. The first concept relates to using volume-fraction vs. time curves to estimate the rate of mud displacement in a wellbore annulus. These curves may be derived from CFD simulations, experimental tests, real-world cement jobs, or combinations thereof. For this study the curves were derived using CFD simulations, but an experimental model using sensors could be used to measure the amount of fluid being displaced as a function of time. A commercial CFD package was used for this proof-of-concept study, but any computer programming code capable of modeling fluid flow in a geometric domain may be considered. Previously, a validation study of the commercial CFD code was performed employing a full scheme of physical tests.[1]

The second concept relates to plotting the rate of mud displacement as a function of any two or any three "cementing" parameters. A "cementing" parameter is one that is critical for optimally designing a successful mud removal process. These parameters include, but are not limited to, casing standoff, pump rate, mud properties, displacing fluid properties, and casing movement.

Combining these two concepts creates a unique tool that can help design fluid systems to optimize mud displacement.

Methodology

First, a partitioned, geometric model (**Fig. 1**) of a 5-ft concentric setup was created in a mesh generation program. The dimensions were OD = 6.5 in., ID = 5 in., and annular gap = 0.75 in. Next, initial conditions were set to simulate mud with predetermined rheological properties (modeled Bingham Plastic) sitting static in the annulus. A displacing fluid, also modeled Bingham Plastic, was then programmed to begin flowing 4-bbl/min at the inlet in an attempt to displace the mud. It is important to mention that, for the concentric case, the displacing fluid's velocity profile was described by a true Bingham Plastic velocity profile as prescribed by a user-defined function.[1,2] Finally, the simulation was allowed to run until more than 99% of the mud was removed from the model. Displacement efficiency curves were plotted showing the percent displacing fluid by volume at any time in the model. Also recorded was the time required to completely displace the 5 feet of mud.

Concentric Case

Fig. 2 shows the volumetric displacement efficiency in the 5-ft concentric model as a function of flow time and rheological properties including density, yield point (YP), and plastic viscosity (PV). As expected, there are differing degrees of displacement rates (the slope of these curves) between the nine different rheological hierarchies. For instance, the best case scenario when the mud is displaced most rapidly (i.e. the steepest slope and fastest time to 100%) occurs when a dense

displacing fluid with high rheology displaces a less dense mud with low rheology. The worst case scenario, where the displacing fluid is less dense and less viscous than the mud, shows a longer time to 100% and a flatter slope. Both of these observations are intuitive and reinforce current industry best practices.

Fig. 3 takes the final times of plots like Fig. 2 and more easily describes the rheological hierarchy influence. It shows the different time requirements to arrive at 99% displacement efficiency. For this case, 25 simulations in a concentric annulus were run to cover a wide range of possible densities and apparent viscosities. To arrive at the apparent viscosity, the volume average shear rate (VASR) first needed to be estimated using Eq. 1:

$$VASR = \frac{6Q}{h^2 w} \quad \text{.....1}$$

where Q is the volumetric flow rate, h is the annular gap, and w is the average circumference between the 6.5-in. OD and the 5-in ID. The apparent viscosity, η, can then be found from Eq. 2:

$$\eta = \frac{YP}{VASR} + PV \quad \text{.....2}$$

It was observed that each simulation required a different time to arrive at complete displacement efficiency. Notice the general trend toward the upper right of longer times to 99% mud displacement, which makes intuitive sense. A thin, light fluid would take longer to displace a thick, heavy fluid. Upon review, this data can give the job designer a powerful tool to efficiently select the displacing fluid. Using the 25 data points in Fig. 3, a contour plot (**Fig. 4**) can be created to describe displacement phenomena and to access the *relative* influence of both density changes and apparent viscosity changes. Two new terms are introduced Eqs. 3 and 4:

$$\text{Density Ratio} = \frac{\text{Density of Displacing Fluid}}{\text{Density of Mud}} = \frac{\rho_d}{\rho_m} \quad \text{.....3}$$

and

$$\text{Apparent Visc. Ratio} = \frac{\text{Apparent Visc. of Mud}}{\text{Apparent Visc. of Displacing Fluid}} = \frac{\eta_m}{\eta_d} \quad \text{...4}$$

Using these two terms, a contour plot like Fig. 4 can help answer the question: "To what extent will changing density, modifying viscosity, or doing both have on displacement efficiency?" To properly answer this question, it is necessary to first set the two axes on a 1:1 scale. The legend shows the time required for 99% mud displacement, but this could conceivably show any percentage desired by the user. The y-axis shows the *degree* of density difference between the displacing fluid and mud. The x-axis shows the *degree* of apparent viscosity difference between the displacing fluid and mud. A value of 1.0 on either axis means the two fluids are equal in that variable. The value at plot location [1,1] describes a mud with density of 12.5 lb/gal and apparent viscosity of 108.5 cP being displaced by a fluid with the exact same properties. This is indicated by the black star on Fig. 4, which geometry confirms should fall on the 45° line. In this case, a time of 4 to 5 seconds to fully displace 5 feet of mud at 4 bbl/min is expected if the material properties of both fluids were equal.

Geometric Proof

The y-axis of Fig. 4 shows the dimensionless variable ρ_d/ρ_m and the x-axis shows the dimensionless variable η_m/η_d. It should be noted that *only* the numerators change in these relationships, as the denominators remain constant at ρ_m = 12.5 lb/gal and η_d = 108.5 cP, respectively. Assume a similar plot with three lines drawn from the origin. This gives the simplified plot of **Fig. 5**. Line CL_1, which has an angle greater than 45°, can be analyzed using Eq. 5:

$$\frac{\Delta\left(\rho_d / \rho_m\right)_1}{\Delta\left(\mu_m / \mu_d\right)_1} = \frac{\sin(60)}{\cos(60)} = \underline{\underline{1.73}} \quad \text{.....5}$$

Thus for every 1.73% change in the density ratio, the same impact can be achieved by changing the apparent viscosity ratio 1%. In other words, when the slope of the contour line is >45°, the apparent viscosity ratio dominates. The best practice would be to adjust the apparent viscosity ratio first (i.e. make the displacing fluid more viscous or the mud less viscous). This, of course, should be done only if cost-practical. The analysis of CL_2, which has an angle less than 45°, yields:

$$\frac{\Delta\left(\rho_d / \rho_m\right)_2}{\Delta\left(\mu_m / \mu_d\right)_2} = \frac{\sin(30)}{\cos(30)} = \underline{\underline{0.58}} \quad \text{.....6}$$

Thus for every 1% change in the apparent viscosity ratio, the same impact can be achieved by changing the density ratio 0.58%. In other words, when the angle of the contour line is <45°, the density ratio dominates. The best practice would be to adjust the density ratio first (i.e. make the displacing fluid more dense or the mud less dense).

Eccentric Case

The procedure described above may also be used to investigate eccentric conditions when the wide-side flow tends to travel faster vs. the narrow-side flow. A difference, however, is the use of a constant inlet velocity profile in the CFD code as opposed to a Bingham Plastic velocity profile. The reason: Bingham Plastic profiles are ill-defined in

eccentric cases. Instead, a constant velocity inlet boundary condition was used at a flow rate of 4 bbl/min.

Because the geometry was no longer symmetric, a volumetric approach (as done in the concentric case) by itself would be inefficient to thoroughly define displacement efficiency. To solve this problem, two 2-D grid faces, one for the wide side and one for the narrow side, were incorporated into the model to capture the entire displacement phenomena (**Fig. 6**). As each simulation progressed, the displacement time to 99% was calculated across the entire volume and along these 2-D grid faces. Thus, a new term is introduced for eccentric cases:

$$\text{Displacement Time Ratio} = \frac{\text{Time Required to Displace a Point on the NARROW side}}{\text{Time Required to Displace a Point on the WIDE side}} \quad \ldots\ldots 7$$

This is not a velocity ratio; rather it is a unique displacement ratio for any given location in the well. It is the key parameter of **Fig. 7**, a hierarchy contour plot specific to a 70% standoff situation in a 6.5-in. hole with 5-in. casing. Trends for this eccentric case follow the same general trends observed in the concentric case, but the uniqueness of this contour plot is that it shows a *relative* comparison between what is happening on the narrow side vs. the wide side.

Application

Say a preliminary design suggests using a displacing fluid with the same properties as the mud. This situation refers to point [1,1] on Fig. 7. The plot indicates that a narrow-side interval would take approximately 12x as long to reach 99% displacement as compared to the adjacent wide-side interval. So what can be done to lower this ratio? Fig. 7 indicates that changing the apparent viscosity ratio will have a greater impact than changing the density ratio because the nearest contour line is >45°. Moving to an apparent viscosity ratio to 0.2, for instance, would cut the displacement ratio in half to approximately 6x, a better proposition than adjusting the density ratio. Another practical way to lower the displacement time ratio would be to use centralizers. **Fig. 8** shows a similar situation with a standoff of 85%. Applying an apparent viscosity ratio of 0.2 as before would cut the ratio down to approximately 2x!

A job designer choosing a spacer or flush would want to move toward the upper left red region of these types of contour plots. The trend generally favors displacement. Alternatively, moving toward the bottom right blue/black region would make displacement progressively less efficient. In simplistic terms, a thin spacer is trying to displace a thick mud, which intuitively is destined to fail. To overcome this problem, the designer must place his current selection on the contour plot and look at the angle of the contour lines surrounding this location. If the absolute angle of the nearest contour line is >45°, changing the apparent viscosity would have a greater impact on displacement efficiency. If the absolute angle of the nearest contour line is <45°, changing the density would have a greater impact on displacement efficiency. Finally, if the absolute angle is 45°, he should be indifferent as to which ratio to change first; logically it should be the most cost-effective change or, perhaps, both simultaneously.

Conclusions

Theoretically, this method can be applied to any fluid property, any well geometry, any standoff value, or any designated displacement percentage (e.g. 95%, 90%, or the percent at which cement integrity will remain immune to mud contamination). Also, the 2-D contour plot method may also be extended to a 3-D contour plot including a third dimensionless variable. Variables may include standoff percent, pump rate, RPM of casing rotation, casing reciprocation parameters such as cycles per minute and stroke, and wettability numbers. Even the top-of-cement (TOC) locations in wells with offset casing may be predicted using this method. In fact, numerous possibilities of 2-D or 3-D contour plots could be created. For example, if an engineer wanted to determine how casing rotation would affect displacement efficiency, he could use input RPM, density, and apparent viscosity to build the 3-D contour plot. A generalized version of this idea incorporates dimensionless terms Π_1, $\Pi_{2...}\Pi_N$ plotted with respect to each other with a toggle feature. Using dimensionless terms would enable the user to easily analyze any pertinent relationship(s) between variables. Thus, this method gives flexibility to the cement job designer to plot, at a given point in the well, the critical variables they need to make the best decision.

Acknowledgments

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Nomenclature

2-D = Two dimensional
3-D = Three dimensional
ID = Inner diameter
OD = Outer diameter
PV = Plastic viscosity
RPM = Rotations per minute
VASR = Volume average shear rate
YP = Yield point
Π = Dimensionless term
Q = Volumetric flow rate
h = Annular gap
w = Average circumference
η = Apparent viscosity
ρ = Density

References

1. Savery, M. and Darbe, R.: "Capability of CFD to Simulate Non-Newtonian Fluid Displacement in Annular Gaps," International Oil & Gas CFD Conference, London, Nov 31 - Dec 1, 2006.
2. Fredrickson, A.G. and Bird, R.B.: "Non-Newtonian Flow in Annuli," *Ind. Eng. Chem.*, 50, 347-52 (1958).

Figures

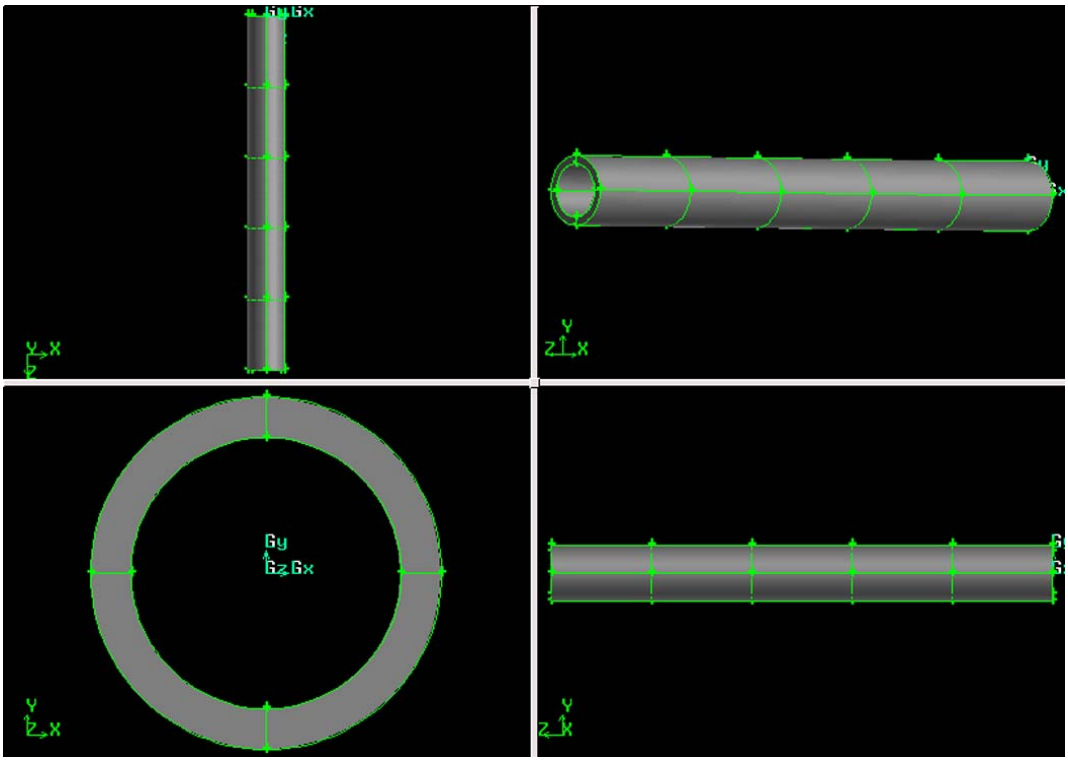


Fig. 1—Five-foot *concentric* model.

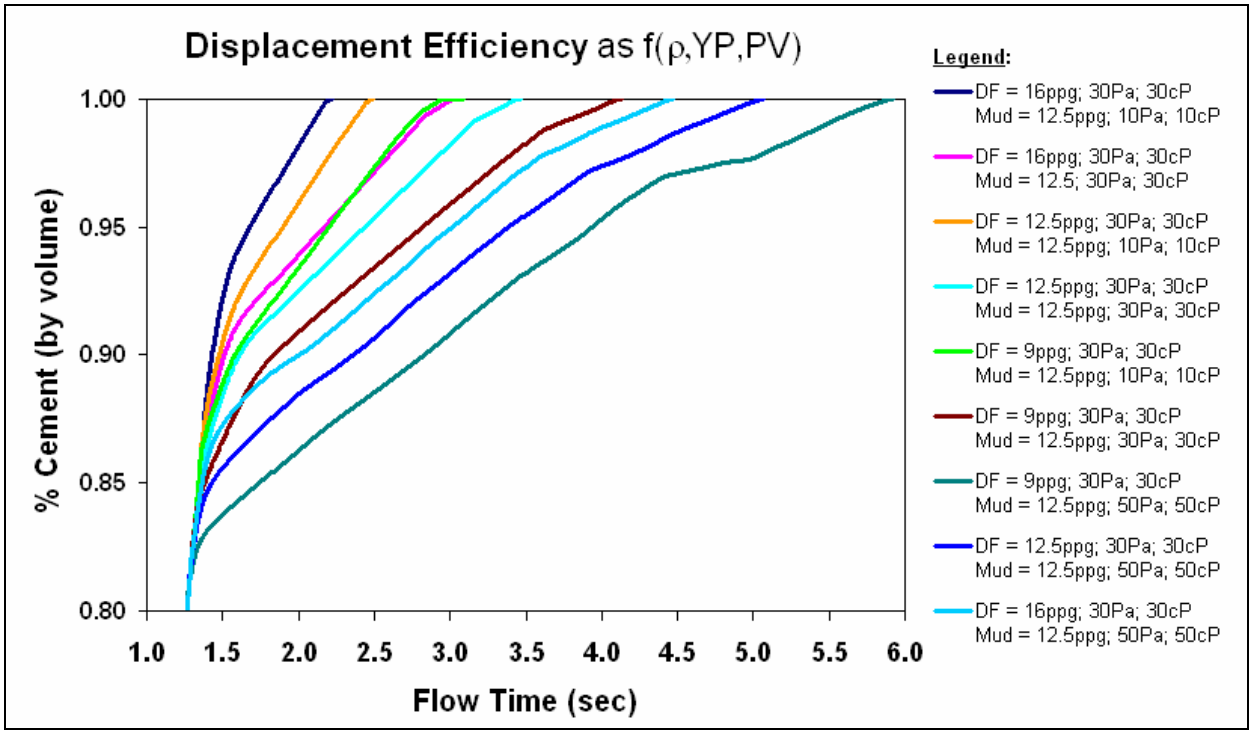


Fig. 2—Variances in displacement efficiency for the *concentric* model as a f(ρ, YP, PV).

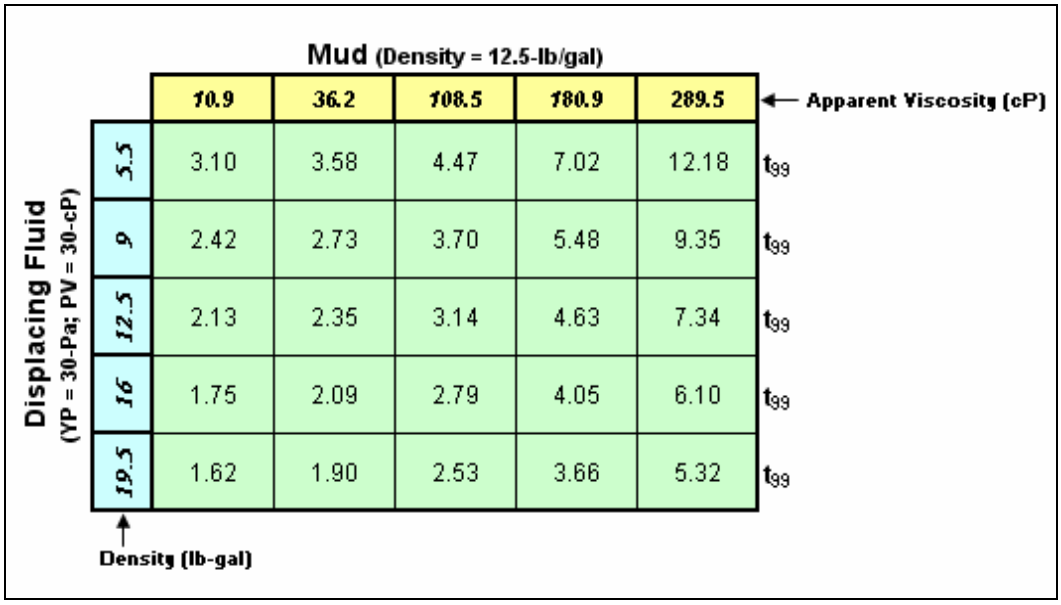


Fig. 3—Times to 99% displacement efficiency for the *concentric* model.

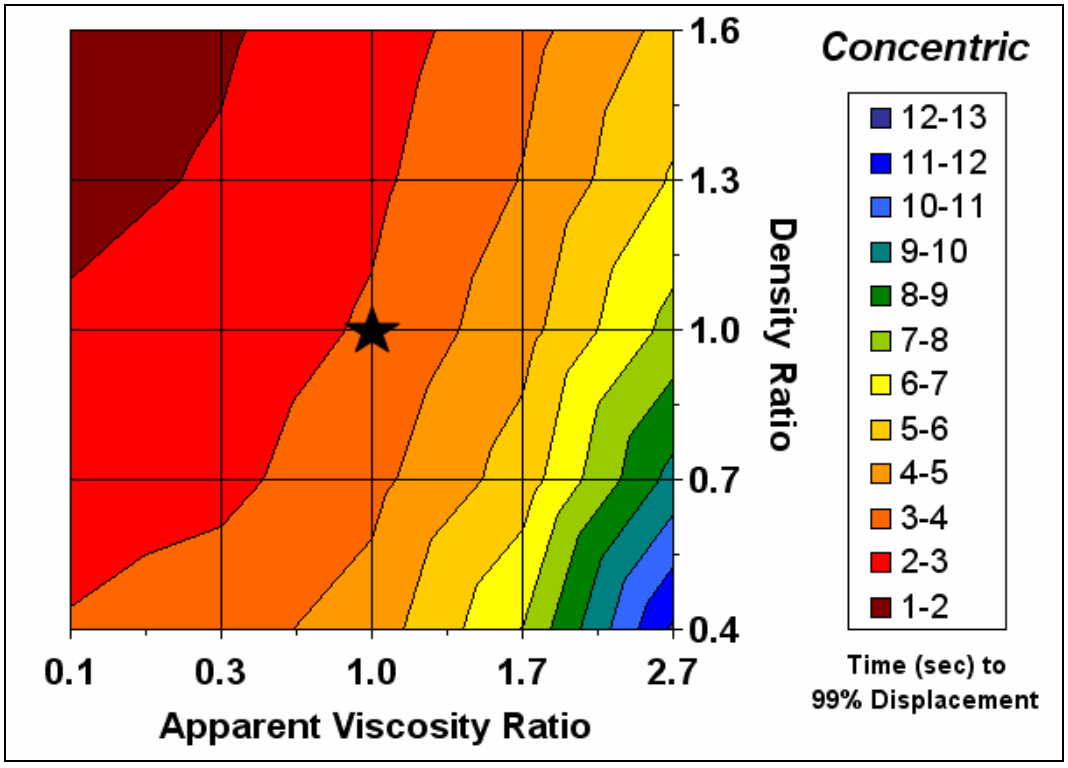


Fig. 4—Hierarchy contour plot for the *concentric* model showing time (sec) to 99% displacement.

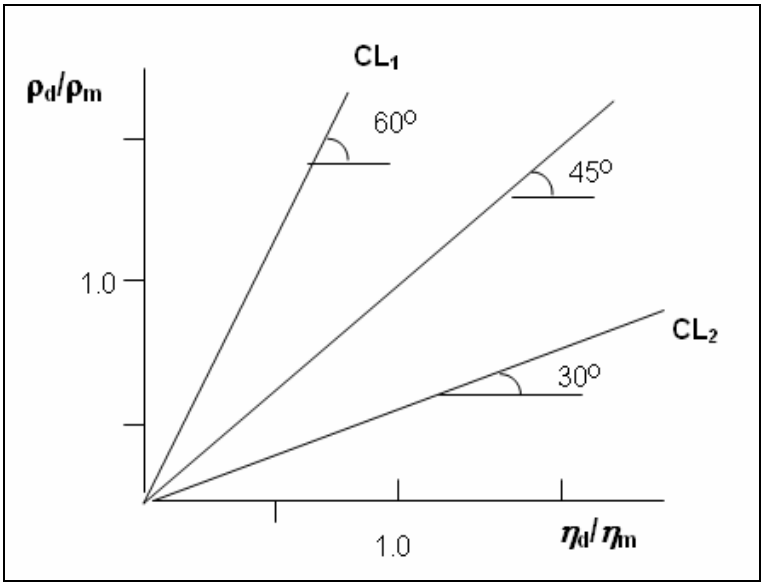


Fig. 5—Supporting chart for geometric proof.

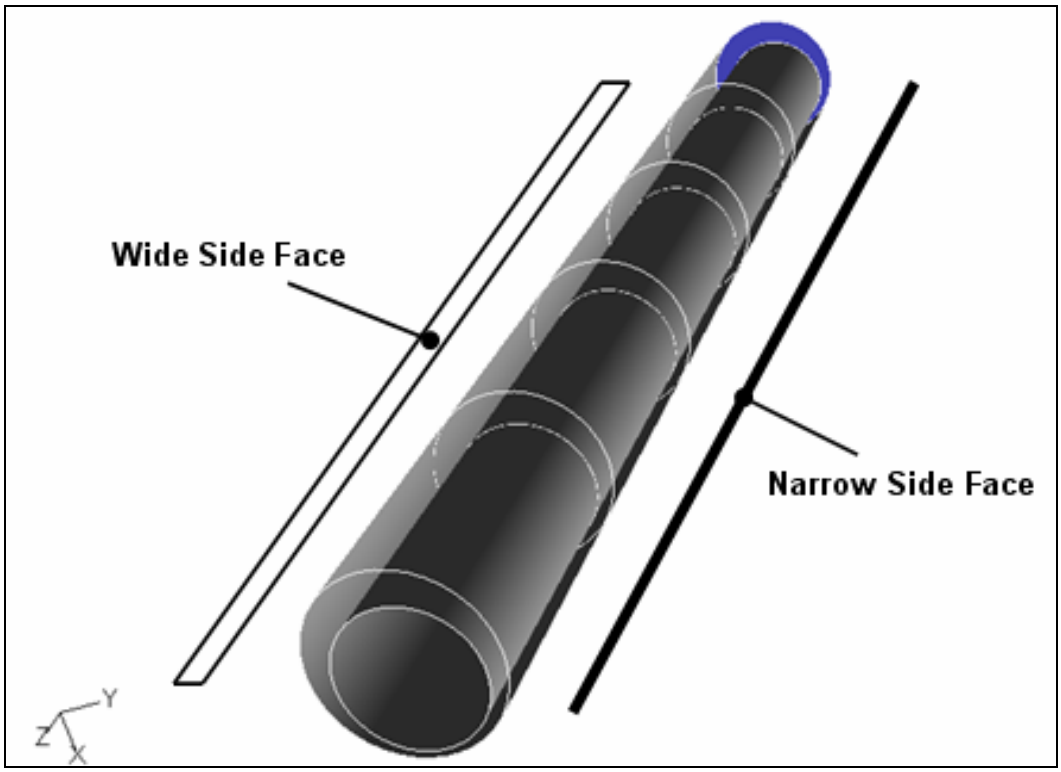


Fig. 6—Five-foot *eccentric* model.

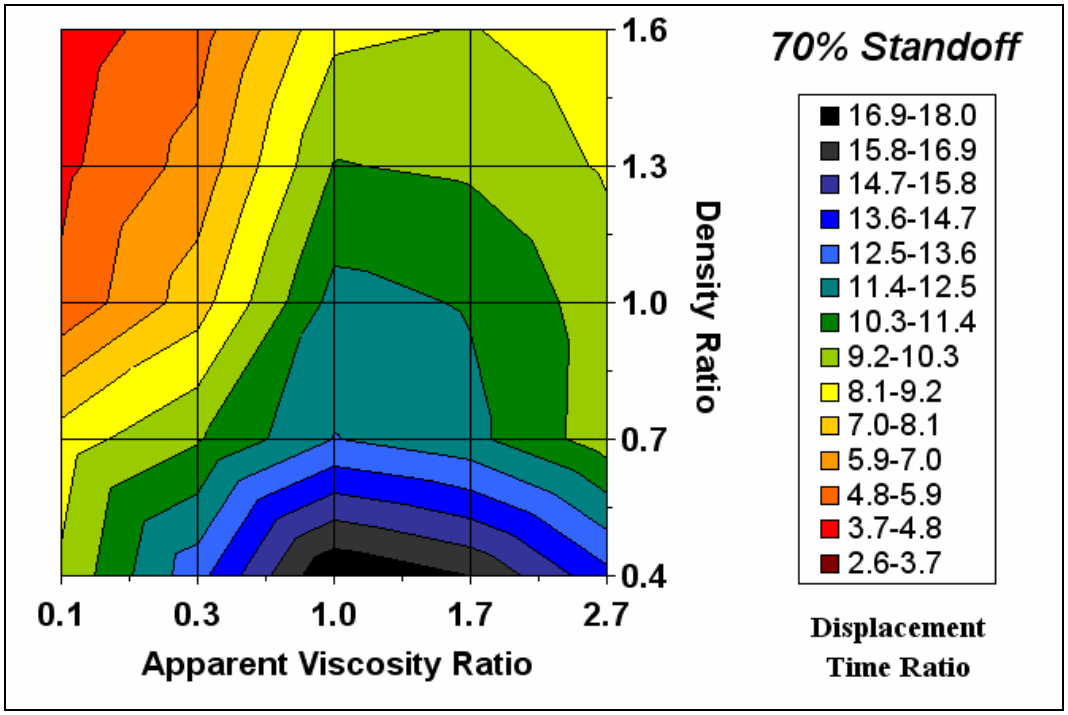


Fig. 7—Hierarchy contour plot for a *70% standoff* model showing the displacement time ratio.

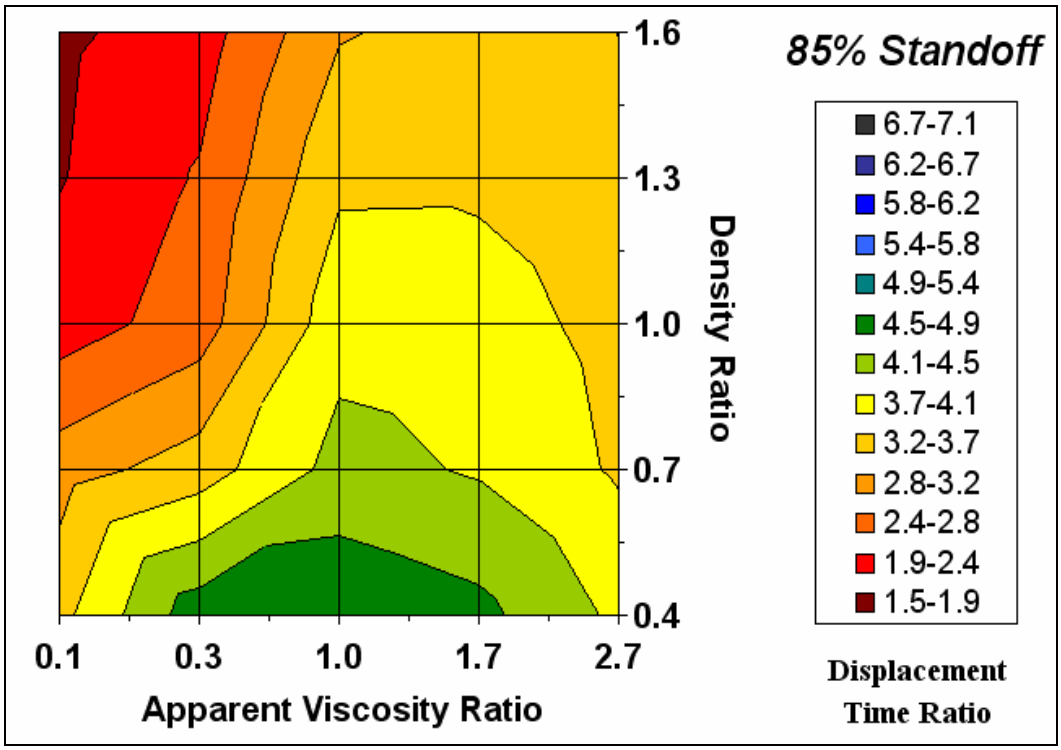


Fig. 8—Hierarchy contour plot for an *85% standoff* model showing the displacement time ratio.