DESIGN RULES AND ASSOCIATED SPACER PROPERTIES FOR OPTIMUM MUD REMOVAL IN ECCENTRIC ANNULI

M. Couturier, D. Guillot, H. Hendriks and F. Callet
Dowell Schlumberger

ABSTRACT

Effective mud removal of drilling fluids from the wellbore is still a major problem in cementing. Although good pipe centralization has been known for years to be one of the keys to the success of the operation, most current design procedures do not allow pipe standoff to be taken into account.

When attempting to displace a mud in an eccentric annulus with a fluid thought to be in turbulent flow, it is shown that the displacing fluid can channel through the mud. An explanation for this phenomenon is given and a solution is proposed. When turbulent flow displacement cannot be achieved, displacement at lower rates has then to be considered and associated criteria leading then to improved mud removal efficiency are also discussed.

These displacement guidelines, as well as other more general considerations, show the need for spacers having well controlled engineering properties: compatibility, rheology, ability to suspend weighting agent, fluid loss. Examples of such spacers are presented and the properties of laboratory and field prepared samples are compared.

INTRODUCTION

The most important and difficult objective to achieve during a primary cement job is to provide downhole zonal isolation, that is to ensure that no fluid movement is possible through the annular cement sheath between the different permeable zones located behind the casing. This requires that the drilling mud originally present in the annulus be completely removed and replaced by the cement slurry, and that the cement, once set, reaches and retains over extended periods of time certain mechanical properties such as bonding, compressive strength and permeability.

Research work on cement placement started in the 1930's and as early as 1940 Jones and Berdine[1] identified some of the most important parameters affecting the success of a primary cementing job. They showed that casing eccentricity is one of the primary causes for channeling of the cement slurry through the mud. Since then, numerous papers describing laboratory experimental results, theoretical modeling or field application work have been published on the subject. It is now generally accepted that the mud and the cement slurry must be kept separated during the displacement process.[2,3] This is accomplished by the use of preflushes such as chemical washes or spacers. However, no final agreement has been reached today on the criteria to select in order to optimize mud removal efficiency. In particular, the influence of the casing eccentricity is still rarely taken into account, even in a qualitative or semi-qualitative way, in the design of a primary cementing operation.

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This paper deals essentially with the influence of casing eccentricity on cement placement and mud removal. Its effect during the mud circulation phase is briefly described and engineering criteria aimed at minimizing channeling of the displacing fluids [preflush(es), and cement slurry] through the mud are presented. Emphasis is put on the features that spacers must exhibit to play their role that is, fluids with controlled properties, placed under specific flow regimes and acting as buffers between the mud and the cement slurry. Then, properties of new spacers designed accordingly are described for applications both above and below critical rate for turbulence.

Effect of Casing Eccentricity on Mud Circulation

The flow of non-Newtonian fluids in eccentric annuli has been the subject of many theoretical studies.[4,5] Since there is no simple analytical solution to such a complicated problem, several simplified models have been developed for practical applications. The model selected by the authors to illustrate the effect of eccentricity on the flow pattern is referred as the basic slot model and is briefly described in Appendix.

When the inner pipe of an annulus is off-centered, the main consequence is that the velocity distribution is distorted, the flow favoring the path of least resistance, i.e., the wide side of the annulus. Figure 1 shows, as a function of pipe standoff, the ratio of the average velocity on the wide side of an annulus to the average velocity on its narrow side for different power law fluids flowing in fully laminar flow. As can be seen the effect is noticeable even for standoff close to 100%, and the more shear-thinning the fluid is (the lower the power law index), the more uneven the velocity distribution.

At low volumetric flow rates, fluids exhibiting a yield stress can even be stationary on the narrow side of eccentric annuli because of the uneven shear stress distribution. This situation is highly undesirable during mud circulation. The stationary mud could gel or be dehydrated through static filtration in front of permeable zones, making the fluid even more difficult to mobilize at a later time. Therefore condition(s) should be defined in order to prevent the occurrence of this phenomenon. Such condition(s) ought to be derived from the shear stress distribution. According to the basic slot approximation, the expression for the shear stress at the wall τ_w for a local annular gap e is given by:

$$\tau_w(e) = \frac{dp}{dl} \cdot \frac{e}{2} \tag{1}$$

where dp/dl is the frictional pressure gradient. So this parameter varies azimuthally around the annulus from a maximum value at the largest annular clearance $e_{max} = (2 - STO) \times (R_o - R_i)$ to a minimum value at the smallest annular clearance $e_{min} = STO \times (R_o - R_i)$, R_o and R_i being the outer and inner radii of the annulus, STO the pipe standoff as per API definition. Therefore, the fluid is stationary on the narrow side if its yield stress τ_y falls in between the maximum and the minimum value of the shear stress at the wall. For this condition not to occur the frictional pressure gradient must be such that:

$$\frac{dp}{dl} > \frac{2 \times \tau_y}{STO \times (R_o - R_i)} \qquad (2)$$

Another consequence of this uneven velocity distribution is the possible coexistence of different flow regimes as noticed by McLean, et al.[6] Following the basic slot approximation, one can define, for power law fluids for example, a local Reynolds number $Re(e)$ at a local annular gap e such that:

$$Re(e) = \frac{\rho \times v(e)^{2-n} \times [2 \times e]^n}{12^{n-1}[(2n + 1)/3n]^n k} \qquad (3)$$

where: n and k are the power law parameters of the fluid, ρ its density, and $v(e)$ the average velocity along the local annular gap e. Since both the local annular gap e and the local average velocity $v(e)$ are larger on the wide side of an eccentric annulus than on the narrow side, the local Reynolds number will follow the same trend. Therefore in eccentric annuli the flow regime can either be fully laminar, fully turbulent or can consist of a mixed flow regime, i.e., laminar on the narrow side and turbulent on the wide one. In particular, a mixed flow regime will occur if the critical flow rate for turbulence is calculated assuming concentric annuli as this is commonly done.

The condition for the fluid to be in turbulent flow all around the annulus can be defined using the basic slot approximation. From the equations developed in Appendix, this condition can be expressed as the critical value of an "average Reynolds number" which definition is the same as for a concentric annulus. This critical value, which is of course standoff dependent, is represented in Figure 2 as normalized by the corresponding value for a concentric annulus. As can be seen, the critical value of the average Reynolds number increases extremely quick as standoff decreases and the results are almost insensitive to the degree of non-Newtonian behavior of the fluid.

An interesting feature of the fully turbulent flow regime, when compared to the fully laminar flow regime, is that the velocity differential between the two opposite sides of eccentric annuli is less important (Figure 3), as observed experimentally by Lockyear, et al.,[7] and almost insensitive to the degree of non-Newtonian behavior of the fluid as for the normalized critical value of the average Reynolds number.

Effect of Casing Eccentricity on the Displacement Process

The phenomena just described during mud circulation can also be encountered during the displacement process. In eccentric annuli, the displacing fluids have a tendency, like the drilling mud, to flow more rapidly on the wide side than on the narrow side of the geometry. The consequence is that displacing fluids may bypass the stationary or slowly moving drilling mud on the narrow side. Then at the end of the displacement, one may be left with a long strip of mud in a given interval depending on the local geometry characteristics. Conditions should again be defined to prevent the occurrence of such a phenomenon.

We will first consider displacements for which the fluids involved are in laminar flow, and then those for which at least the first displacing fluid is in turbulent flow. For displacements occurring in laminar flow, we will suppose that the density of the displacing fluid is greater than that of the displaced one, which is effectively true in most cases. This density hierarchy is known to stabilize the interface between the fluids, and also, to a certain extent to flatten the profile of the interface. On the other hand, for displacements occurring in turbulent flow, the density hierarchy is not necessary as evidenced by water or diesel efficiently displacing fluids several pounds per gallon heavier.[8]

Laminar Flow Displacements

As during mud circulation, the minimum requirement to prevent channeling of the displacing fluids through the mud is to mobilize the mud on the narrow side of an eccentric annulus. But during displacement, buoyancy forces due to differences between the fluid densities should be taken into account and Equation 2 now becomes:[7]

$$\frac{dp}{dl} > \frac{2 \times \tau_y}{STO \times (R_o - R_i)} + (\rho_1 - \rho_2) g \cos\theta \tag{4}$$

where τ_y is the yield stress of the mud, ρ_1 its density, ρ_2 the density of the displacing fluid, g the gravitational acceleration and θ the inclination of the well. Since we consider a situation where the displacing fluid is bypassing the drilling mud, the frictional pressure drop is essential due to the flow of the displacing fluid and therefore can be calculated as if it was the only fluid present in the annulus. Notice that this condition leads to a minimum flow rate for the displacement, rate which is increasing when the standoff decreases. The validity of Equation 4 has been verified experimentally using a laboratory annular flow loop ($R_o = 5$ cm; $R_1 = 4$ cm; $L = 300$ cm). Typical results are shown on Figure 4.

This condition is the weakest that needs to be satisfied. Even when it is satisfied, the velocity of the interface between the drilling mud and the displacing fluid on the wide side of the annulus may differ substantially from its value on the narrow side. This is of course far from being desirable. However, the prediction of the profile of the interface between the fluids during the displacement of a non-Newtonian fluid by another is a very complex problem and is still the subject of theoretical investigations. For day-to-day applications one has to rely on a simplified approach to minimize its distortion.

To define such a criterion, we will suppose that the displacing fluid is flowing on the wide side of the annulus in an angular sector $[0, \alpha]$, the drilling mud occupying the other part of the annulus $[\alpha, \pi]$. V_1 and V_2 will represent the average annular velocity of the drilling mud and of the displacing fluid, (dp/dl), the total pressure gradient. Since it is desirable that $V_2 < V_1$, we will try to define under which condition(s) these velocities are equal to the average displacement velocity V. If it is the case, a lower (resp. an upper) limit for the total pressure gradient on the wide side (resp. on the narrow side) of the annulus can be determined assuming that the displacing fluid (resp. the drilling mud) is flowing in a rectangular channel the width of which is the largest annular gap e_{max} (resp. the smallest annular gap e_{min}) and the area of which is the same as the area it actually occupies. Therefore if:

$$\left[\frac{dp}{dl}\right]_1 + \rho_1\, g \cos\theta < \left[\frac{dp}{dl}\right]_2 + \rho_2\, g \cos\theta \qquad (5)$$

then:

$$V_2 < V < V_1 \qquad (6)$$

Since the frictional pressure gradient of the mud in the narrow channel increases more quickly than that of the displacing fluid in the wide channel, Equation 5 defines an upper limit for the displacement flow rate which is an increasing function of standoff.

Unless the displacement process is entirely governed by buoyancy forces, the consequences of these developments are several. Given, the densities and rheologies of the displaced and displacing fluid, and given the annular geometry, the displacement rate must be performed in a well defined flow rate range. The conditions for this range not to be too narrow are the following:

- The standoff should be as high as possible.
- The yield stress of the displaced fluid should be as small as possible.
- The displacing fluid should have a minimum apparent viscosity when compared to that of the displaced fluid, and the lower the standoff the higher the apparent viscosity ratio must be.

Turbulent Flow Displacement

Following the early work of Howard and Clark[9] and the paper published by Brice and Holmes in 1963[10] presenting the results of a survey of 46 cement jobs performed in Southwest Louisiana, it is generally accepted that turbulent flow for the displacing fluid is an effective way to remove the mud from the annulus.[2,3] Until now, the industry has performed its calculations of critical flow rate for turbulence assuming a concentric casing in the annulus. However, as stated earlier, since standoffs in the field only rarely exceed 85%, at such flow rates displacing fluids are only in partial turbulent flow.

This may have some drastic consequences on the displacement process. Experiments performed in the laboratory annular flow loop mentioned above have shown that under such circumstances, a continuous strip of mud may be left on the narrow side of eccentric annuli. Conversely, when the displacing fluid was flowing at such a rate that it would be in turbulent flow all around the annulus, the mud was totally removed as shown in Figure 5. Since the critical flow rate for turbulence is strongly affected by the casing standoff, taking eccentricity into account for turbulent flow placement leads to the promotion of high pump rates.

Engineering Properties of New Spacers

Turbulent Flow Spacers

The main limitation of the turbulent flow displacement technique is that flow rates must be maintained within acceptable limits in the field. This condition implies the use of fluids with low apparent viscosity. However, in fluids laden with solids such as spacers, low apparent viscosity may lead to particle migration under gravity forces. Problems such as particle sedimentation, density change, free water development, line plugging or deviation from expected rheological properties can develop under surface conditions, but even more severely under downhole conditions where increase in temperature reduces the apparent viscosity. On the other hand, stability of fluids under downhole conditions becomes more and more critical with the development of deep, hot, deviated and horizontal wells.

A new generation of turbulent flow spacers was developed to overcome the settling problem that is often experienced with some existing products.[11] The solution consists in properly designing the rheological properties of the base fluid. As can be seen in Table 1, the new turbulent flow spacer exhibits almost no free water and no settling tendency in a wide density range: nevertheless turbulent flow can be reached at reasonable pump rates in various concentric annuli (Table 2). For eccentric annuli, these figures must be multiplied by the correction factor given in Figure 2.

Fluid loss control is also a parameter to be taken into account when designing spacers. If any water is lost during the placement, the solid-to-water ratio and hence, the density and, to a greater extent, the apparent viscosity increase with the possibility of the spacer coming out of turbulence to give a laminar flow placement at the design rate. This will, under most circumstances, lead to channeling of the spacer through the mud. Table 3 gives values of fluid loss measured using the procedure for cement slurries as set by the API Spec 10 at different temperatures and densities. As can be seen, fluid loss values are less than 100 mL/30 min.

Viscous Spacers

Quite often, turbulent flow placement cannot be achieved in the field, even with specific spacers, due to factors such as large casing size, hole enlargement, casing not properly centralized, low fracture gradient, high pore pressure and equipment limitations. One has then to consider displacement below the critical rate for turbulence: that is, laminar flow placement. Spacers for laminar flow applications must also process certain properties to meet the three design criteria.

First, the spacer must have a rheology that can be easily and accurately controlled as explained earlier. A new spacer was developed for this to be possible for any density from 10 to 20 lb/gal and whatever the weighting agent used. This is accomplished by varying the concentration of the product. The sensitivity of this new spacer rheology to blend concentration is shown in Figure 6 for various densities. This graph helps the user to design the spacer for a given density and rheology. This new spacer also exhibits very good carrying capacity for the weighting agent, i.e., no free water and no settling tendency, as expected with a viscous spacer. Its fluid loss control is almost as good as that of the turbulent flow spacers, as shown in Table 4.

Compatibility of New Spacers

The rheological compatibility of these new spacers with mud and cement slurries was thoroughly tested. Typical results are shown in Tables 5 and 6 as the 100 rpm and 10 min gel (peak readings + readings after 1 min of rotation at 3 rpm) on different spacer/mud and spacer/cement mixtures. Few problems were encountered. Some cement slurry/spacer mixtures develop a weak gel when left static at low temperature, but these gels can easily be destroyed either by shear or by a small increase of temperature.

Field Application of New Spacers

As pointed out by Benge,[12] there may exist wide discrepancies between properties of a spacer under laboratory and field conditions. A spacer must be able to handle a wide range of conditions such as low quality barites, brackish or high salinity waters, or low shear mixing without important changes of properties. More precisely, spacers must be capable of yielding adequate viscosity development and fluid loss control under all field conditions. These new spacers have been used successfully in the field. During these operations, their rheological properties were measured and Table 7 shows that they were close to those measured in the laboratory prior to the cementing job.

CONCLUSION

Laboratory experiments supported by some theoretical studies have allowed the authors to define guidelines for optimum mud removal. These guidelines which take casing eccentricity into account, are specific to a given displacement technique. Turbulent flow displacement is recognized as the most effective flow regime for mud removal provided that the flow regime of the displacing fluid is turbulent all around the annulus. A method to calculate the corresponding critical rate is proposed. For displacements in laminar flow, a criterion is proposed to minimize the distortion of the interface profile between two fluids. A better definition of the rheological properties needed by the spacers for turbulent and laminar flow displacement is derived from this methodology.

In the first case the rheology should be such that the spacer does not show any free water or settling tendency of the weighting agent either on surface or downhole. In the second case, the rheological properties of the spacer must be adjustable. New spacers whose rheological properties satisfy these conditions have recently been developed; other properties, like fluid loss control and compatibility with muds and cement slurries, have also been carefully optimized.

APPENDIX

The basic slot model consists in assuming that the eccentric annular geometry is equivalent to a series of independent rectangular slots of varying height e which expression is given by:

$$e(\alpha) = d \cdot \cos\alpha - R_1 + \left[R_o^2 - (d \cdot \sin\alpha)^2\right]^{0.5} \qquad (1)$$

with: $d = (R_o - R_1) \times (1 - STO)$ (see Figure 7 for the frame of reference. For a fixed pressure drop, the contribution to the flow rate of each slot is determined using well know equations for the flow of non-Newtonian fluids in rectangular slots. We will consider the flow of power law fluids but similar equations can be developed for other model fluids. Provided there is only one flow regime present in the annulus, the expression for the volumetric flow rate is given by:

$$Q = 2 \times \int_0^{\pi} v(e) \times e \times (R_1 + e/2)\, d\alpha \qquad (2)$$

For a given slot, a power law approximation for the friction factor/Reynolds number relationship can be used whatever the flow regime:

$$fr = A \times Re^{B} \qquad (3)$$

So the expression for the local average velocity $v(e)$ is given by:

$$v(e)^{2+B(2-n)} = \frac{6^{B(n-1)} \times k_s^B}{\rho^{1-B}} \times \frac{dp/dl}{A} \times e^{1-nB} \qquad (4)$$

with: $k_s = \left[(2n + 1)/3n\right]^n \times k$. And the value of the local Reynolds number can then be derived.

NOMENCLATURE

dp/dl	Frictional pressure gradient
e	Local annular gal
e_{max}, e_{min}	Maximum and minimum value for e
k	Consistency index
n	Power law index
R_o, R_1	Outer and inner radii of annulus
$Re(e)$	Local Reynolds number
STO	Pipe standoff
V	Total average velocity
$v(e)$	Local average velocity
θ	Well inclination
ρ	Fluid density
$\tau_w(e)$	Local shear stress at the wall
τ_y	Fluid yield stress

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Table 1
Static Free Water and Sedimentation of Turbulent Flow Spacer

Spacer Density (lb/gal)	Static Free Water After 30 min (%)			Static Sedimentation Bottom Density (lb/gal)		
	20°C	50°C	85°C	20°C	50°C	85°C
11.5	0	0	0	12.1	12.2	12.5
13.0	0	0	0	13.7	13.1	13.1
16.0	0	0	0	16.0	16.0	16.1

Table 2
Critical Flow Rate for Turbulent Flow in Different Concentric Annuli

Temperature (°C)	Density (lb/gal)	Qc (bbl/min) 6.5 in - 5.0 in	Qc (bbl/min) 8.5 in - 7.0 in	Qc (bbl/min) 12.25 in - 9.652 in
25	11.5	5.5	7.4	15.0
	13.0	5.9	8.0	15.5
	16.0	8.3	11.3	21.6
50	11.5	3.9	5.2	10.4
	13.0	4.3	5.8	11.5
	16.0	5.9	7.9	15.5
85	11.5	3.4	4.6	9.3
	13.0	4.0	5.4	10.9
	16.0	5.2	7.0	14.0

Table 3
Fluid Loss of Turbulent Flow Spacer

Density (lb/gal)	Fluid Loss at 120°F (50°C)	Fluid Loss at 185°F (85°C)	Fluid Loss at 250°F (120°C)
11.5	54 ml	78 ml	-
13.0	64 ml	78 ml	66 ml
16.0	64 ml	94 ml	-

Table 4
Fluid Loss of Viscous Spacer

Spacer Concentration (lb/gal)	Spacer Density (lb/gal)	Weighting Agent	Fluid Loss at 250°F (ml/30 min)
0.1	10	$CaCO_3$	52
0.1	13	Barite	108
0.1	15	Barite	118
0.1	17	Barite	120
0.1	20	Barite	68
0.2	10	$CaCO_3$	36
0.2	13	Barite	62
0.2	15	Barite	66
0.2	17	Hematite	100
0.2	20	Hematite	108

Table 5
Compatibility of Spacers with Drilling Muds

Test	Mud/Spacer Ratio %	100 rpm	10 min/gal Peak (3 rpm)/+1 min
1	100	14	2/1
	95	13	3/1
	75	11	2/1
	50	9	2/1
	25	8	2/1
	5	7	3/1
	0	5	-
2	100	23	23/7
	95	20	16/6
	75	26	15/7
	50	35	27/15
	25	36	25/17
	5	29	16/12
	0	30	-

Test 1: Mud 10.5 lb/gal - turbulent flow spacer 11.5 lb/gal

Test 2: Mud 12.6 lb/gal - viscous spacer 13.6 lb/gal

Table 6
Compatibility of Spacers with Cement

Test	Cement/Spacer Ratio %	100 rpm	10 min/gal Peak (3 rpm)/+1 min
1	100	29	27/25
	95	18	16/15
	75	22	22/6
	50	10	3/1
	0	11	4/3
2	100	27	23/10
	95	30	27/15
	75	26	44/18
	50	29	36/30
	0	20	11/8

Test 1: Dispersed formulation with latex - turbulent flow spacer

Test 2: Dispersed formulation with fluid loss agent - viscous spacer

Table 7
Comparison of Rheology of Spacers as Mixed in the Laboratory and in the Field

rpm	Viscometer Readings							
	Turbulent Flow Spacer Density = 10.8 lb/gal				Viscous Spacer Density = 12.1 lb/gal			
	Base Fluid		Weighted Fluid		Base Fluid		Weighted Fluid	
	Lab	Field	Lab	Field	Lab	Field	Lab	Field
300	12.5	14	19	22	26	24	39	34
200	10	11	14.5	17	23	23	35	31
100	7	7	9.5	11	18.5	19	25.5	23
6	3	2.5	3	4	9.5	11	13	9.5
3	2.5	2	2.5	3	8.5	9	11.5	8

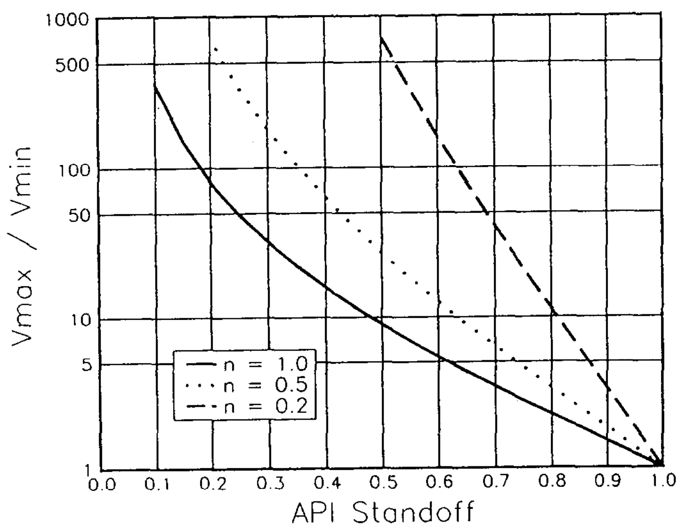

Figure 1 - Comparison of average velocities on the wide and narrow sides of an annulus (Ri/Ro = 0.8) for fully laminar flow

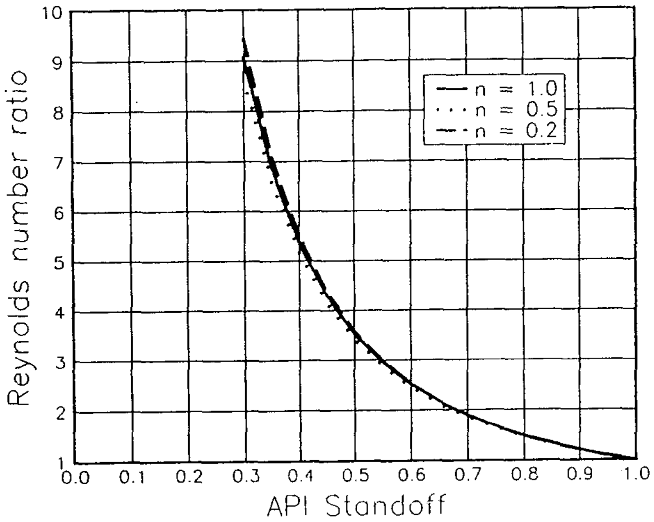

Figure 2 - Critical Reynolds number ratio for a power law fluid to be in turbulent flow all around an eccentric annulus (Ri/Ro = 0.8)

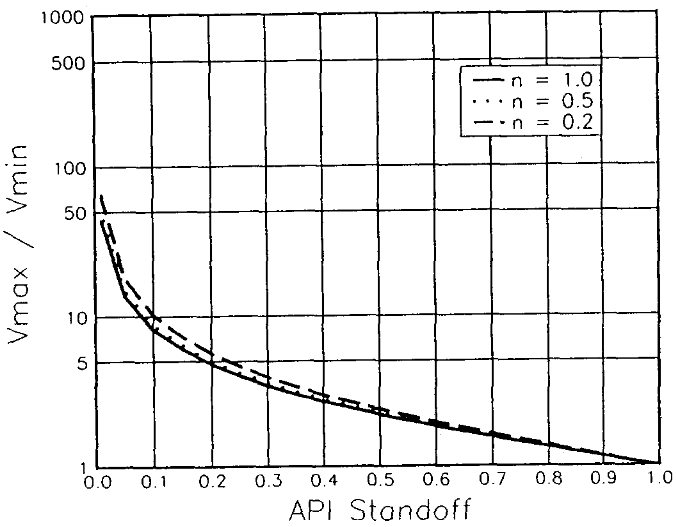

Figure 3 - Comparison of average velocities on the wide and narrow sides of an annulus (Ri/Ro = 0.8) for fully turbulent flow

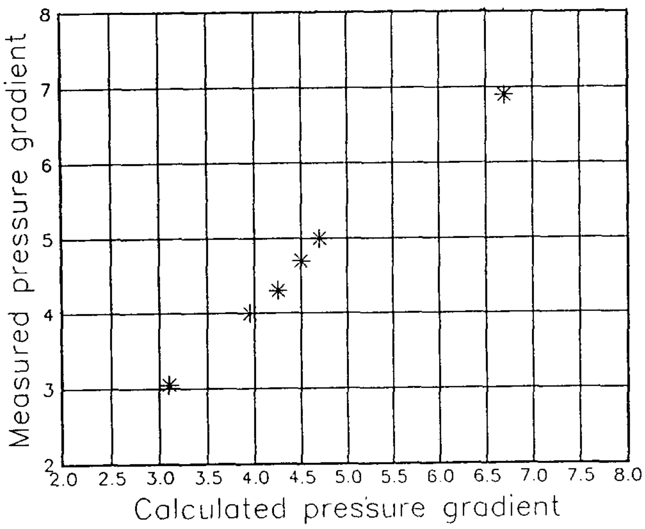

Figure 4 - Measured versus calculated [equation (4)] pressure gradient for full displacement for a standoff range of [25, 100] percent

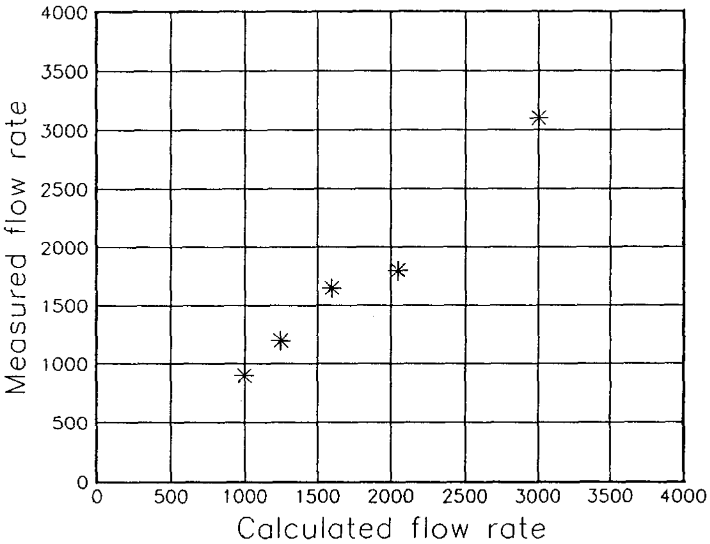

Figure 5 - Comparison of measured and calculated flow rate for full displacement in turbulent flow

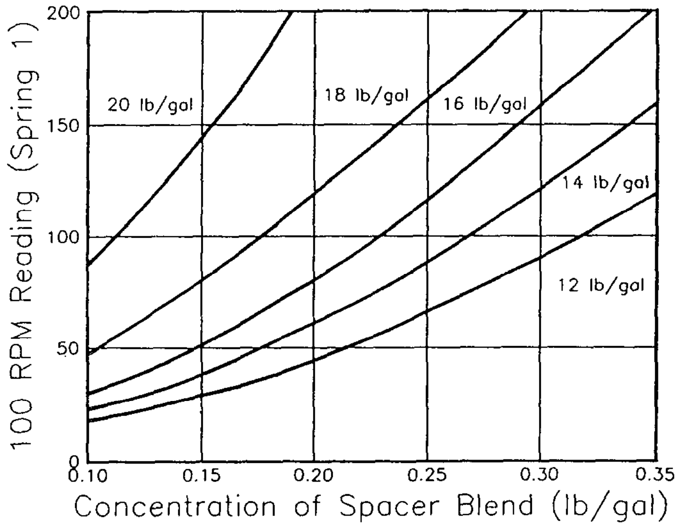

Figure 6 - Rheology of viscous spacer at different spacer densities as a function of product concentration. (Weighing agent: barite)

The Basic Slot Model

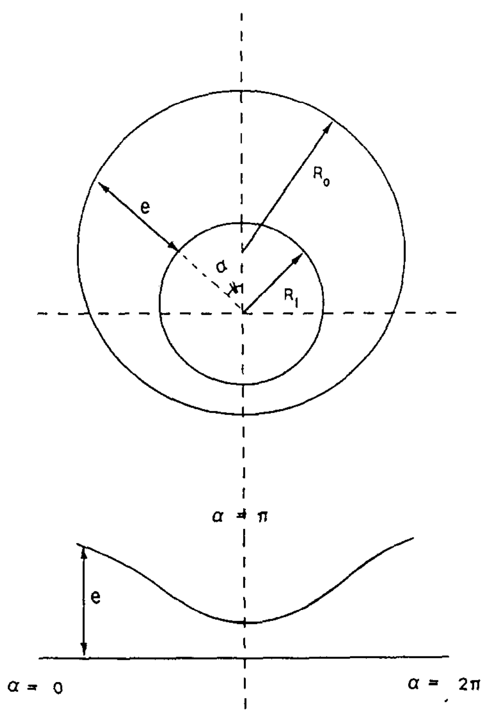

Figure 7 - Frame of reference for basic slot model