

Modeling Gel Breakdown for Improved Pressure Control

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Abstract

Formation of a gel structure is essential for good drilling fluid performance. It is necessary for proper hole cleaning and for suspension of weight materials and cuttings. However, the formation of a microstructure also results in pressure spikes when the gel structure is broken down, such as during pump initiation and tripping pipe, which can be severe and limiting in operations like managed pressure drilling (MPD). There is a general understanding as how to the breakdown and resulting over-pressure are influenced by mechanical (annular size, pump speeds) and chemical (hydrophilic and organophilic clay interactions, emulsion droplets interaction, colloidal/fines loading) controls. The future success of critical operations such as MPD depends on a better understanding of how the gel structure breakdown occurs and modeling which allows incorporation into existing well design programs.

This paper presents a new model for evaluation of gel breakdown in a variety of drilling fluids. This model allows for the recognition of mechanical effects observed in the breakdown and for potential modeling of multiple modes of microstructural bond breakage. By comparison of the decay constants included in this model, differences between mud types can be illuminated. The effects on equivalent circulating density (ECD) predicted with the inclusion of this model are also presented.

Introduction

During the drilling process there are many points during which downhole fluids are quiescent and build a gel microstructure. This gel structure will eventually be broken down – through pump startup, tripping pipe, pipe rotation, etc. – and the resulting energetic destruction of the microstructure will produce a transient increase in pressure downhole. The degree of this transient pressure spike, as well as the length of time over which a pressure in excess of the flow-induced pressure drop is experienced, have long been monitored in order to prevent fracturing of the formation while drilling. More recently, the challenges of depleted/unconsolidated formations, with narrow drilling windows between the pore and fracture pressures, and the demands of managed pressure drilling (MPD) have made understanding and control of the transient breakdown of gel structure even more important.

Traditionally a single rheological characteristic, the API gel strength, has been employed to make a prediction of the static peak overpressure which will occur when quiescent gel

structure is broken down. This method does not allow for simulation of the transient pressure spike, nor does it allow for accurate simulation of breakdown of microstructure if the fluid was not initially quiescent – e.g., if pump rates are actively monitored and adjusted (as in MPD operations) the downhole fluids will actively build structure under dynamic flow conditions, the strength of which will vary from that measured under quiescent conditions. Several authors have worked to produce models for thixotropic yield stress fluids which include time-dependant growth and breakdown parameters in competition which, depending on knowledge of the initial state of the microstructure, allows prediction of the transient state of gel strength.^{1,2} For application in a field environment, where detailed rheological analysis is not possible, these models can prove to be cumbersome to apply. This paper presents a different approach, where transient gel decay breakdown is modeled based on measurements which could be made in the field on a standard Model 35 or Brookfield viscometer. Several possible approaches are presented, with a common reliance on integration of shear history into the model.

Experimental Flow Loop

Testing had been previously performed on a flow loop which is part of the Dynamic Testing Facility³ at the University of Tulsa in which several muds were flowed through a vertical annular section of pipe and the pressure drop was monitored. The experimental flow loop provided temperature control, an annular test section, and a recirculation loop. Mud samples were prepared and mixed in a recirculation tank and then circulated throughout the system. In these tests a vertical annular test section of approximately 9 feet with a 2" ID pipe with 0.5" OD stainless steel pipe inside was used. Two pressure transducers, 19 inches apart, were used to obtain pressure differential readings during the test.

The flow loop experiment was set up such that the test fluid in the annular section was isolated from the loop by two ball valves. After the isolated fluid had remained quiescent for a prescribed period of time, allowing the growth of gel microstructure in the fluid, the valves were manually opened. On opening the flowing loop fluid would be diverted from the recirculating loop to the static annular column and the pressure drop measured over the test section as the gel structure ruptured.

An example of the pressure differential response between

the two transducers is presented in Figure 1.

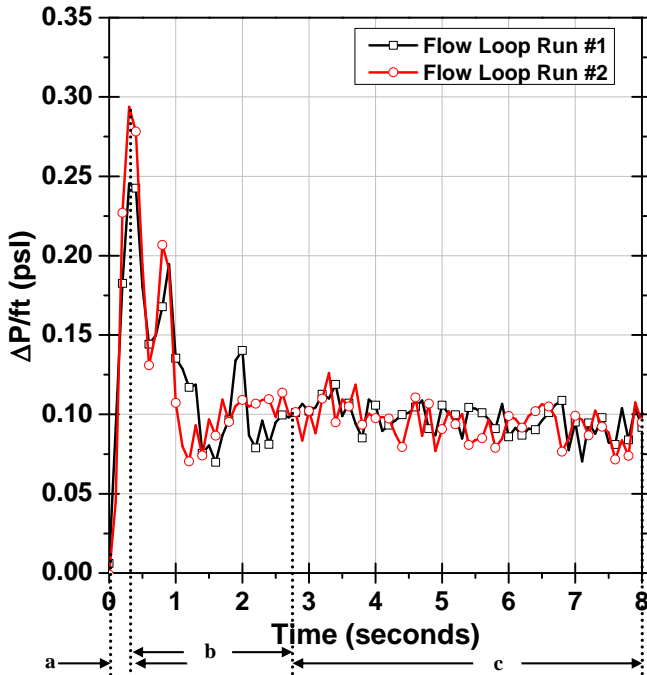


Figure 1 Pressure drop upon flow initiation in a vertical annular section containing an invert-emulsion drilling mud allowed to build gel microstructure for 30 minutes at 45°F.

In this example, a 13.5-lb/gal synthetic invert emulsion fluid was employed and the data from two separate tests of the same fluid at 45°F after 30 minutes quiescent are presented. When flow was reinitiated in the annular section, a steady state flow rate of 15 gpm was applied.

The measured pressure spiked when the ball valves were opened. The initial pressure spike observed is resultant from combined effects of the inertial, frictional, and gel components (see section “a” in Figure 1). After this initial pressure spike the dominant influences on pressure drop arise from vibrations, gel, and viscous effects (section “b” in Figure 1). Once steady state is achieved (section “c” in Figure 1) the pressure drop is predominantly a viscous effect. The vibrations in the pressure drop measurements were found to be due to the elasticity of the acrylic tubing of the vertical test section and from other components in the flow loop system.

From gross observation of this data it is readily apparent that a period of decay occurs, during which the microstructure arising from gel growth is dissociated and the pressure drop in the pipe decreases from a maximum to steady state. This decay, if modeled and related to invariant parameters, would be most useful in the prediction of transient downhole pressures arising from flow of gelled fluids.

In order to isolate the gel effects on the transient pressures, a first-principals approach to evaluation of the raw data was taken, beginning with Navier-Stokes equations for fluid motion. Simply stated the Navier-Stokes equation says the pressure is the sum of a number of contributing parameters.

$$\frac{\partial P}{\partial x} = -\rho \frac{\partial v}{\partial t} + \mu \frac{\partial^2 v}{\partial r^2} + \rho g + f_i \quad (1)$$

The term on the left hand side of the equation is the transient change in pressure drop along the flow path. The first term on the right of the equation gives changes in pressure drop due to changes in momentum of the fluid. The second term describes the frictional losses in the pipe due to viscous flow. The third term accounts for pressure changes due to hydrostatic effects. The final term, f_i , is a general term used to describe other contributors to transient pressure changes; this would include phenomenon such as the pressure required to break gel microstructure.

From this basis, a numerical model was derived incorporating the following components contributing to pressure changes:

1. Momentum effects
2. Frictional pressure drop
3. Hydrostatic pressure
4. f_1 = Gel structure breakdown
5. f_2 = Oscillatory pressure fluctuations due to system elasticity

A numerical approximation was developed and used to model the test results. It has the following form:

$$P_i(t) = \rho L \frac{(Q_i - Q_{i-1})}{(t_i - t_{i-1})} + \frac{\Delta P}{\Delta x} \frac{Q_i}{Q_{max}} L + \rho g L + f_1 + f_2 \quad (2)$$

In this numerical approximation, two extra pressure terms were included, f_1 and f_2 . The second of these is a transient correction to account for the vibrations observed in the data (see section “b” in Figure 1). The first extra term gives the transient pressure resultant from gel destruction. The specific form of the gel destruction model can follow any one of numerous types (as further detailed in the follow section), but should be a function dependant on time, maximum measured gel strength (also time dependant), one or multiple *invariant* decay constants, and the shear history of the fluid.

The results of the above numerical model applied to the data of Figure 1 are presented in Figure 2. Here, the transient pressure response for same fluid from Figure 1, after 10-minute and 30-minute cessation periods for gel growth, are presented along with the model fit. In both cases, a good approximation of the transient pressure was obtained, demonstrating the efficacy of this approach.

Gel Breakdown Model

Selection of the form of the gel breakdown function for inclusion in a transient pressure loss calculation (as performed above) can follow one of many forms. Several are detailed below. While there are many forms available for use, indeed making this approach simple, the remaining problem is selecting a form which produces a set of gel breakdown parameters which are independent and invariant. By invariant parameters, we mean parameters which are independent of the instrument or test method and are material properties. By use of invariant parameters, a simple test may be performed (e.g., the standard API gel strength measurement) and results

compared to those from tests with a differing shear history. Invariant parameters must be those which are determined based on the shear history of the fluid; e.g., the specific shear

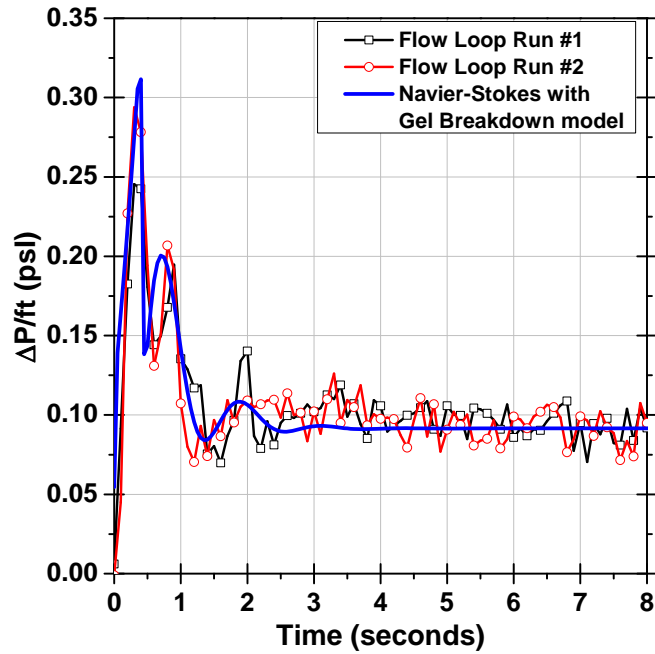


Figure 2 Correlation between the theoretical model and raw data for transient pressures in startup of flow after a 30-minute gel period.

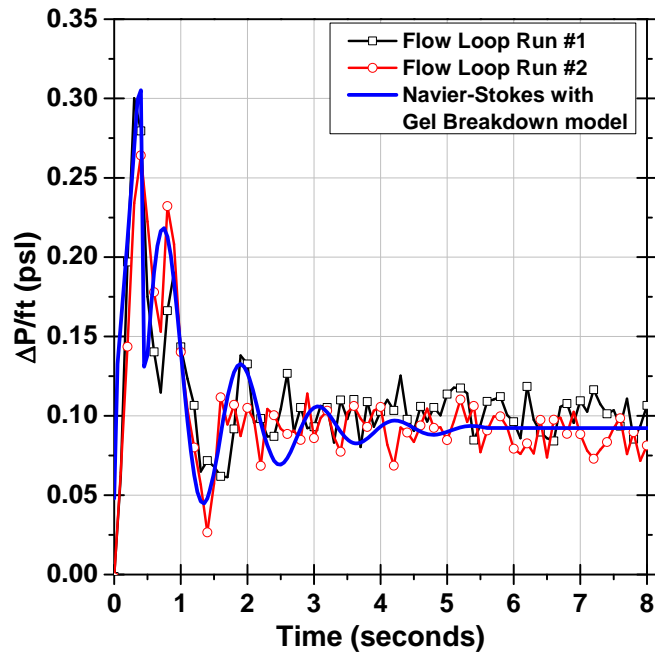


Figure 3 Correlation between the theoretical model and raw data for transient pressures in startup of flow after a 10-minute gel period.

rate or shear rates of tests used to determine the parameters do not change the breakdown parameters and, conversely, these parameters may be applied regardless of the specific shear rate

or shear rates of a fluid in downhole conditions.

In order to bring an estimation of the shear history applied to a fluid, a common *work integral* function is introduced to all potential forms of a gel breakdown model. The work integral is an integral of the transient shear rate experienced by the fluid as flow is initiated and gel structure is broken down, thus describing a cumulative amount of work which has been performed on the fluid in order to break the gel structure and return to steady state flow conditions. Inclusion of the work integral into a gel breakdown model has the following advantages:

- Parameters for gel breakdown are found to be invariant
- The same parameters and gel breakdown model can be used in conditions when shear is variable (e.g. when the flow rate changes when gel structure is incompletely broken).
- The effects of shear induced by pipe rotation can be included in the work integral.

One potential model for gel breakdown including the work integral is that of a simple exponential decay, such as in Equation 3 where the transient stress decay is modeled.

$$\tau(t) = \tau_{SS} + \Delta e^{-\left(\frac{t}{k}\right) \int_0^t \dot{\gamma}(t) dt} \quad (3)$$

In this form, the equation is best suited for working with data obtained from a shear inception test (similar to that called for in standard API gel strength measurements) which can be conducted on a variety of instruments in any number of configurations. Here, Δ is the difference between the steady-state flow stress (τ_{SS}), and the API gel strength as measured after either 10-minutes or 30-minutes (τ_{peak}), k is the gel decay constant, and $\int_0^t \dot{\gamma}(t) dt$ is the work integral.

The value of Δ does not need to be based on the API gel strength, but can more generally refer to the difference between the steady-state flow stress and the stress at the time of initiation in a change in flow, thus allowing for the modeling of an interrupted shear process where the initial state of the gel is quiescent or partially broken. This model was used in Equation 2 in determining the numerical fits to the raw data in Figure 2 and Figure 3. It has the advantage of simplicity, in selecting only a single breakdown parameter to model, and using a τ_{peak} which is readily available in field applications. For improved modeling, rather than selecting a single number for τ_{peak} , it could be taken as a function of time with API gel strengths taken over a range of times in order to determine this function. An example of this method as a fit for an invert emulsion fluid after 10-minute and 30-minute gel periods is presented in Figure 4. This test was conducted at 120°F using a vane stirrer on an Anton Paar MCR 501 rheometer, with a shear rate of 0.1 s⁻¹ applied after the gel period, and the model of Equation 3 was applied over the time period beginning with the peak in stress. The parameters for the fit are presented in the graph, with the decay constant common between the two runs. This method presents a generally acceptable fit, with some significant error in the curvature. While it is relatively simple, it does not well

capture the changes in Δ with gel time or the exact curvature of the decay.

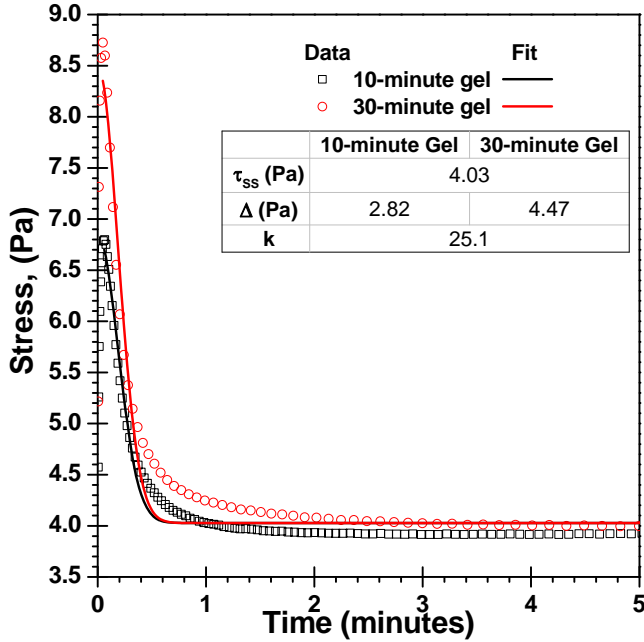


Figure 4 Gel decay curves and exponential decay fits for an invert emulsion fluid when tested at 120°F and 0.1-s⁻¹ after allowing gel structure to build for 10-minutes and 30-minutes.

Another potential model which could be used to obtain invariant parameters and include in a Navier-Stokes equation for pressure drop is the binding isotherm. An example of this form with the inclusion of a Hill slope is given in Equation 4,

$$\tau(t) = \tau_{peak} + \Delta \left(1 - \frac{(k_2 t)^n}{(k_1 \int \dot{\gamma}(t) dt)^n + t^n} \right) \quad (4)$$

where, again, $\Delta = \tau_{peak} - \tau_{ss}$. This has the advantage of using multiple parameters, which interact competitively, allowing for a better description of the transient decay of the gel structure. The competitive nature of this form of equation has the advantage of mimicking the dynamic formation and destruction of microstructure under shear.

A third option, similar to the first potential model presented, would be the use of a multiple exponential decay model. This method has been utilized in the past for describing the stress relaxation of polymers when multiple modes of relaxation are present.^{4,5} For the case of polymers which are stress relaxing, a generalized Maxwell model is employed which employs a series of relaxation times coupled with a multiplier which weights it as a part of the bulk relaxation modulus. Applying this approach, where multiple exponential gel decays modes are weighted by their contribution to the stress exceeding steady-state flow stresses, it is possible to set multiple invariant gel decay constants. An example of the form of this model is given in Equation 5.

$$\tau(t) = \tau_{ss} + \Delta \sum_i A_i e^{-\left(\frac{t}{k_i}\right) \int \dot{\gamma}(t) dt} \quad (5)$$

Here, A_i is the spectrum of weighting factors for gel strength

contribution and $\sum_i A_i = 1$.

An example of this model applied to the data from Figure 4 is presented in Figure 5, where a double exponential decay was used. As in the application of the single exponential model, all parameters in the model were held common when fitting the data from 10-minute and 30-minute gel tests, with the exception of Δ which was allowed to vary. The reasoning behind this is to demonstrate the invariance of the breakdown parameters; the mechanism for breakdown in both the 10-minute and 30-minute gel tests is identical, as both tests were performed on the same fluid under identical conditions. By this argument, the only differentiation should be in the maximal gel strength, tracked by Δ in this model. As observed in Figure 5, a good agreement in the fit of the model to the raw data is obtained. The fit is better in the case of the 10-minute gel, with some variation from raw data observed in the region of curvature for the 30-minute gel data. The overall correlation is much improved over that of the single exponential case.

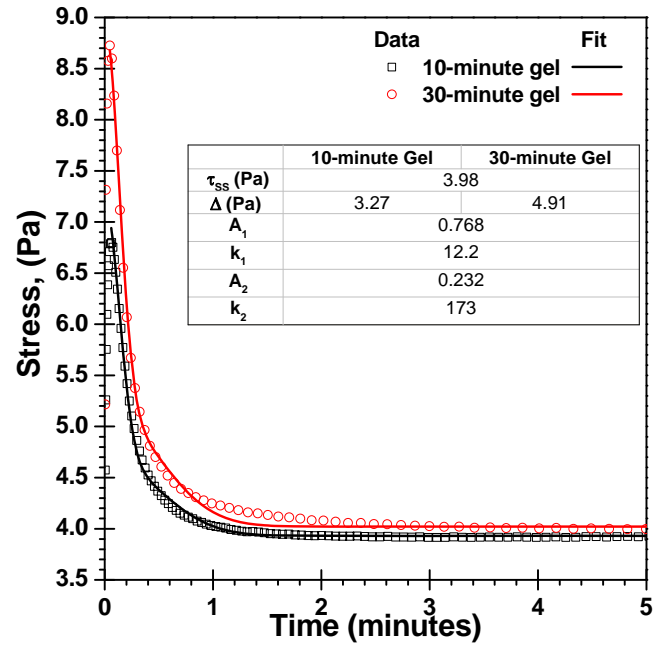


Figure 5 Gel decay curves and multiple-exponential model fits for an invert emulsion fluid when tested at 120°F and 0.1-s⁻¹ after allowing gel structure to build for 10-minutes and 30-minutes.

One express utility of this form of model would be identification of each exponential decay component to a physical motivation for that mode. Each individual decay constant would ultimately describe the rate of decay and strength of influence of different microstructural mechanisms for gel formation and breakdown.^{6,7} By this argument, the fit of data in Figure 5 for the 30-minute gel would benefit from addition of a third decay component with the reasoning that this mode of gel growth is considerably slower than the modes captured by k_1 and k_2 , thus only producing non-negligible effects at long times.

Demonstration of this separability of gel mechanisms is presented in Figure 6 for the case of the multiple exponential model fit to the 30-minute gel data from Figure 5. Here the components of a double-exponential decay fit to the raw data are presented independently, giving a graphical view of the contribution of the k_1 and k_2 components in comparison to each other. From this the differences between k_1 , the fast-decay component, and k_2 , the slower-decay component, can be observed and through minor variations in the fluid a structure-related mechanism assigned to each. For example, it has been previously demonstrated that a microstructure which is based prominently on emulsion dissociates more rapidly and with less energetic requirement for gel destruction; this correlates well to the breakdown observed in the k_1 component. A gel microstructure built with organophilic clays, however, decays over a longer period of time and requires more energy to break, correlating well to the k_2 component. In the case presented in Figure 6, the design of the mud could be altered based on this analysis to favor a more brittle gel structure by increasing the dominance of the k_1 component. Conversely, by altering the dominance in favor of k_2 , a mud with more ductile gels can be produced, with an extreme example being a mud-to-cement formulation.

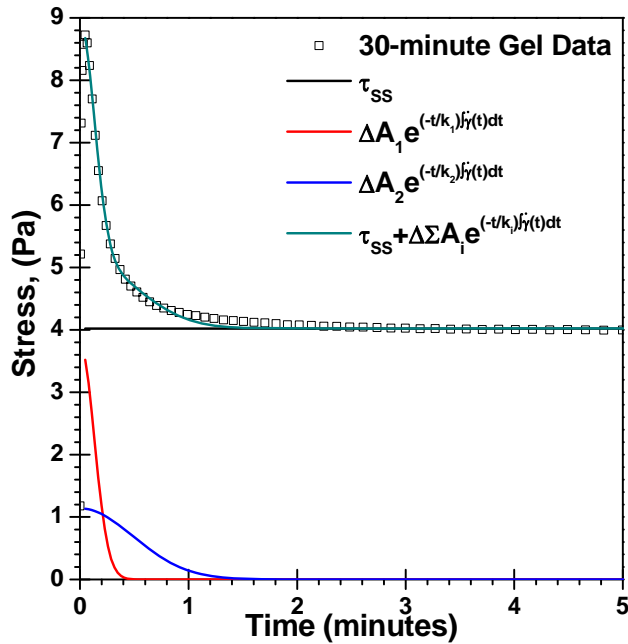


Figure 6 Gel decay after 30-minute gel growth with the multiple exponential model fits broken into individual component contributions.

Coupled Growth and Decay Model

The previous examples of potential models for use in a transient pressure model all follow the decay of the gel structure from its peak to steady-state. When working from a laboratory test, such as the standard API gel strength test or the shear inception test employed in this work, the magnitude of the peak is highly dependent upon the physical conditions of the test. For example, differences is the acceleration rate

from quiescence to the set shear rate is variable from one instrument to another; a lower acceleration rate will result in a peak stress which is lower and occurs at a longer time than for an instrument with a higher acceleration rate. In order to develop gel decay parameters which are both invariant and independent of test, a model which couples decay and growth must be used. One such potential model is presented in Equation 6. The inclusion of the multiple exponential decay is obvious, along with a slight modification to the steady-state stress term accounting for motor acceleration rate and a growth term, $P_1 t^{P_2}$, which models how the stress grows to a peak during flow inception. The form of the growth term can alternatively be selected based on the observed form of growth in the API gel strength over time.

$$\tau(t) = P_1 t^{P_2} \left(\sum_i A_i e^{-(t/k_i)} \int \dot{\gamma}(t) dt \right) + \tau_{ss} (1 - e^{-k_{ss} t}) \quad (6)$$

Application of this model to the data presented in Figure 4 resulted in a very good fit to both start-up and gel decay, as observed in Figure 7. Again, as in the previous model fits, all decay parameters in the model were held common when fitting the data from 10-minute and 30-minute gel tests; gel growth parameters were allowed to vary. The insert graph presents the transient start-up data for the test, along with the fit of the coupled growth and decay model. From the inset in Figure 7 we can see how well this model form captures the transient behavior of the test, which affects how the gel peak is observed.

As in the multiple exponential decay model, only two gel decay parameters were employed in the model fit of data in Figure 7. However, while a the gel decay data with a standard

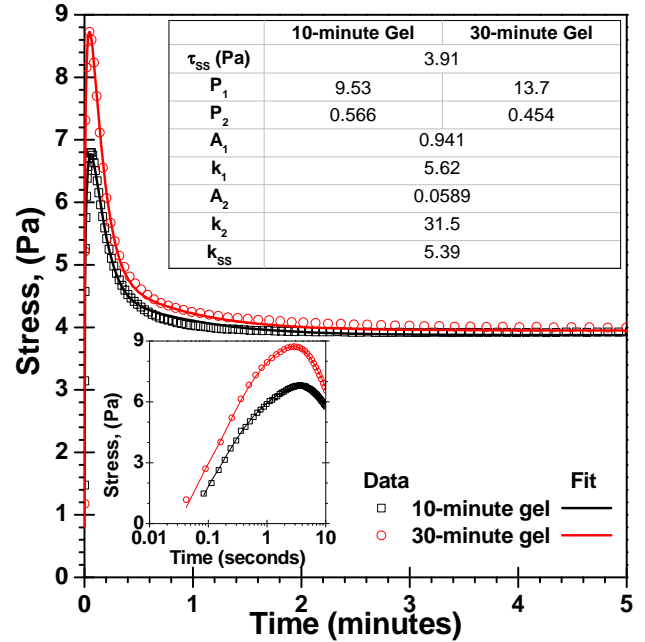


Figure 7 Gel decay curves and coupled growth/decay model fits for an invert emulsion fluid when tested at 120°F and 0.1-s⁻¹ after allowing gel

structure to build for 10-minutes and 30-minutes.

multiple exponential fit would have benefitted from employing a third decay term to reduce the deviation from raw data, a two-term decay in a coupled growth and decay model captures the curvature of the gel decay much more accurately. By capturing the shear history of the test before microstructure decay is predominant, a better model of the data can be obtained with less decay parameters required.

Effect on ECD

Application of a gel decay model to transient downhole pressure changes is presented in Figure 8. In this, a simulation of the increase in ECD of a 13-lb/gal mud is followed during a period of ramping up pump rates from no flow to 600 gpm. For this the simple single exponential decay model of Equation 3 was employed in Equation 2. The transient ECD was followed at a TVD of 5000 ft as the pump rate was increased to 600 gpm over 3 seconds for an mud with an API gel strength of 30 lb/100 ft². In Figure 8, a comparison of two cases is presented, one in which the exponential decay model used a fast decay constant (lower k), and one in which a slow decay constant (higher k) was used. The utility of inclusion of a transient gel breakdown model is readily observed in comparison of the fast and slow decay cases. For all other conditions held the same, a gelled fluid with a fast decay parameter produces a significantly lower rise in ECD than does the same fluid with a slower decay parameter. From this model guidance could be given either for either a modification of the fluid formulation to result in a faster decay or for instruction as to how quickly pump rates can be ramped (or staged) to desired flow rates.

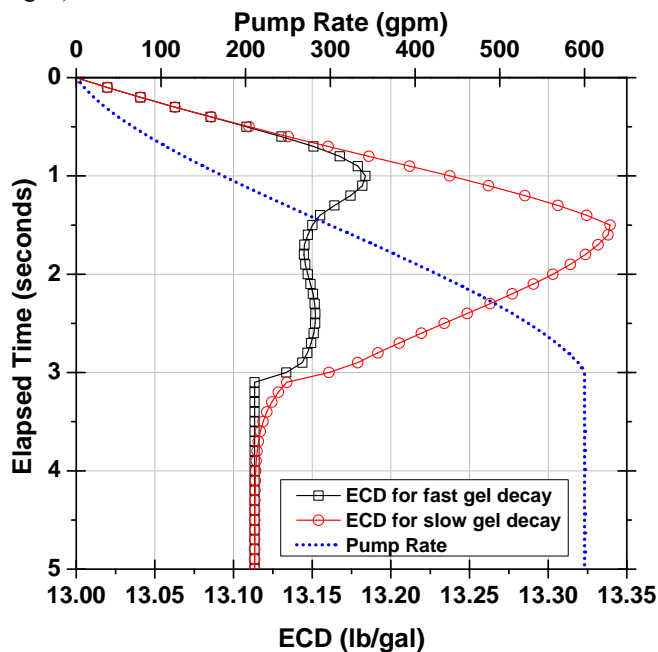


Figure 8 Transient ECD simulation for a 13-lb/gal mud upon pump startup for a single exponential gel breakdown model with either a fast or slower gel

decay constant.

Conclusions

- Gel structure plays a significant role in system pressure drops. The prediction of transient downhole pressures related to microstructure breakdown is important for better fluids control during critical operations.
- Inclusion of a transient gel breakdown model into current pressure drop calculations allows for improved prediction of transient pressure and ECD spikes. The specific model used can take one of several forms. Application of this model enables construction of algorithms to determine optimal startup and operational procedures for various classes of fluids. Transient models could then be utilized to determine an optimum pumps on/off flow rate schedule and to minimize/manage pressure spikes.
- Use of the work integral in the gel breakdown models allows for the inclusion of the shear history affects on decay, resulting in decay constants which are invariant.
- Multiple tests can be designed, as either laboratory or field testing, to determine gel breakdown parameters, with the use of a coupled growth and decay model allowing independence of test conditions.

Acknowledgments

The authors would like to thank Halliburton for the support to perform and present this work. We would also like to thank Evren Ozbayoglu and Gokdemir Gorkem of the University of Tulsa for performing flow loop testing presented here.

Nomenclature

P	= pressure
ρ	= fluid density
μ	= fluid apparent viscosity
g	= gravitational acceleration
V	= fluid velocity
Q	= flow rate
L	= length of test section
$\frac{\Delta P}{\Delta x}$	= pressure drop per unit length at Q_{max}
k	= gel decay parameter
$\dot{\gamma}$	= shear rate
τ	= shear stress
τ_{SS}	= shear stress at steady state flow
τ_{peak}	= API gel strength
Δ	= difference between gelled and steady state stresses
A_i	= gel strength weighting factor, $\sum_i A_i = 1$
P_i	= asd
k_{SS}	= motor inertia parameter

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