OPTIMAL MIXING OF MULTI-COMPONENT LOST CIRCULATION CHEMICAL TREATMENTS

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ABSTRACT

Multi-component, deformable plugging agents used to combat lost circulation are well known in the drilling industry. The role of these materials is to provide wellbore pressure containment and to allow for drilling ahead by sealing thief zones and stopping drilling fluid losses. One class of these materials is formed in situ below the drill bit by bringing together two chemicals delivered separately downhole. When given adequate downhole mixing, these two streams can quickly develop into Bingham-Plastic type materials, generally with high yield points. These types of two-component systems should be subjected to sufficient downhole mixing energy to undergo rapid viscosification in order to plug the local formation fractures. The reacted product must also be able to withstand increased drilling fluid pressures. The amount of mixing energy can be controlled by adjusting the fluid flow rates, modifying the jet orifice dimensions, or doing both. This energy, which is transformed into the viscosification reaction, is expected to play a major role in product rheology and material properties. These properties govern the success or failure in sealing the lost circulation zone and in allowing further drilling. Presented in this work is a unique method to model and quantify the optimal downhole mixing energy for multi-component, squeezable plugging agents.

INTRODUCTION

While drilling oil and gas wells, drilling fluid losses are frequently encountered where natural fractures or crevices occur or when the mud weight required for well control exceeds the fracture gradient of the formation. The loss of drilling fluid into the formation is undesirable because of the expense associated with extended rig time, loss of well control, and drilling fluid waste. It is not only desirable to seal these thief zones, but also to enhance the strength of the formation around the wellbore so drilling can continue deeper without having to set casing. Often treatments in the form of single-stream lost circulation material (LCM) pills or dual-stream chemical systems are employed to seal these thief zones and provide additional wellbore stability. Usually, in the dual-stream case, one stream is pumped down the drillpipe and the other down the annulus until the two mix in situ at the thief zone. Typically these can be pumped with the drill bit attached to avoid tripping out.

Understanding and controlling the mixing energy involved in placing dual-stream treatments is vital for their success. In theory, the two streams can consist of any fluid; but in this study, the first stream is treatment slurry loaded with organophilic clay and reactable polymer. The second stream is oil-based fluid. The application of engineering similitude, in conjunction with a proprietary laboratory method, is used to create a model that transforms bench-top mechanical mixing into forecasted downhole mixing beneath the drill bit. A custom-built apparatus that simulates specific downhole mixing and placement is used to confirm the optimal operating conditions projected from the similitude model and bench-top tests. Results using this methodology are validated in this work.

Previous studies have provided insight into the understanding the placement of treatments such as these can add value when combating wellbore stability problems. The recent 2005 paper by Wang et al. describes approaches to successfully enhance wellbore strengthening and mentions the option of using deformable, viscous, and cohesive (DVC) materials to do so. Kulakofsky et al. describes a real-time operation tool that allows experts to collaborate field operations in an effort to solve wellbore stability problems and then drill ahead to the planned casing depth. Kelley et al. mentions a drill-ahead process and its related chemical system that, when placed downhole and mixed with the drilling fluid, undergoes a chemical reaction that converts the fluids into a squeezable sealant treatment. Finally, Sweatman et al. mentions the development of several novel lost circulation material squeeze systems capable of successfully sealing thief zones and increasing the integrity of weak zones.

THEORETICAL APPROACH

To accurately predict what happens downhole when two streams meet during placement of a lost circulation chemical treatment, the approach taken was to correlate bench-top mechanical mixing to actual downhole non-mechanical (i.e. drill bit jet hydraulics) fluid mixing. To do so, three objectives were set:

1. To design and implement a test procedure using mechanical agitation that will predict, over a range of conditions, the flow rate required through a drill bit jet nozzle to achieve adequate in-situ mixing of two-stream chemical lost circulation treatments.

2. To design a scaled physical model of a drilling operation using engineering similitude that simulates downhole mixing phenomena using different flow rates of the two-stream system.

3. To develop a correlation between the predicted flow rates from the mechanical agitation experiments and the flow rates from the scaled physical model experiments in an effort to predict optimal flow rates (i.e. to create a "mapping function" to design and control job executions in realtime field service operations).

To link mixing energy to product quality of the reacted plugging agent, the term "product quality" first needs to be defined. Some types of chemical lost circulation treatments often have extremely high viscosities—so high in fact, that their viscosities cannot be measured using conventional laboratory equipment. However, the yield point (YP) of the treatments can be found directly. The definition of YP is the amount of stress required to permanently change the shape of a solid or semi-solid material, or, more simply, the force required to get something moving. In this study, the YP of the reacted chemical treatment was deemed the indicator of "product quality." Thus, it is expected that as YP increases for a placed chemical lost circulation treatment, the effectiveness of the treatment to seal the loss zone and to enhance wellbore strength also increases because the treatment can accept a greater load before it dislodges.

An important discovery in this study was that accumulated shear history, or integral shear history (ISH), is key to achieving a high YP. The study showed that ISH is a function of the material's sensitivity to shear, the time the material is exposed to the shear, and the shear rate ($\dot{\gamma}$) the two-stream system encounters when mixed. In a mechanical agitator, the shear rate can be determined as a function of rotations per minute (*RPM*) and a constant K_1:

$$\dot{\gamma} = K_1 \left(RPM \right) \tag{1}$$

From a previous study, K_1 was found to depend on the type of mechanical agitator. In the present study, a multi-blade blender and its known corresponding K_1 value were used. To relate ISH and YP, the classical first order reaction model was used as the base equation:

$$Y(X) = Y_0 + \left(Y_{\max} - Y_0 \right)\left(1 - e^{-kX} \right) \tag{2}$$

where Y_0 is an initial value and $Y_{\max}$ is a final value of some measurable parameter of the material. Furthermore, k is referred to as the reaction constant specific to certain chemical reactions that can be expressed in a wide range of values. This classical model can be modified to fit the parameters in the present study to derive a generalized rheological equation that relates ISH to YP:

$$YP(ISH) = YP_0 + \left(YP_\infty - YP_0 \right)\left(1 - e^{-\alpha(ISH)} \right)^{\beta} \tag{3}$$

where YP_0 is the initial yield point of the reacted product, YP_∞ is the final yield point, α is the pseudo rate constant, and β is a material reaction parameter. By modifying the classical first order model, more flexibility in representing complex reactions is achieved. Therefore, material properties that do not necessarily respond as a first order reaction can be better characterized.

BENCH-TOP MECHANICAL AGITATION TESTING

As stated previously, both the mixing time and mixing shear rate need to be measured to calculate mixing energy. A multi-blade blender equipped with time control and a rheostat (to maintain desired blender speed) was used to mix the two-component chemical treatment. The reason for using the multi-blade blender was to achieve a uniform mix across the entire sample as opposed to a non-uniform mix of a conventional single-blade blender (if a single-blade blender was used, the fully reacted sample collected around the blender blade while non-reacted sample laid on top). An equal volume of the chemical treatment slurry (stream one) and an oil-based drilling fluid (stream two) were poured into the blender. A desired mixing time and RPM was set and the mixing process began immediately. Three different oil-based drilling fluids were tested in this study: an internal olefin-based fluid, an internal olefin/ester blend based fluid, and a diesel-based fluid. Twenty-five tests were conducted for each drilling fluid (75 total) to cover the spectrum of potential mixing energies the dual-streams could encounter downhole. After mixing, the blender stopped and the reacted product was placed in a sample bucket, compressed to let entrained air escape, and allowed to cure for 30 minutes prior to YP testing. YP testing for each sample was performed using a manual YP device that determines yield points for semi-solid materials with consistencies like that of window caulking. A normal viscometer could not be used because the reacted product had a similar stout consistency. Using Equation 3 in conjunction with the YP data, Figure 1 was created, plotting the *predicted* YP versus ISH alongside the *measured* YP versus ISH. The plot shows good alignment between the predicted values and measured values. Figure 1 was obtained for the internal olefin/ester blend based fluid and, for simplicity, all results presented in this paper are from the blend-based fluid.

ENGINEERING SIMILITUDE

The scaled physical model was designed using similitude, a proven modeling strategy in many engineering applications. Specifically, Buckingham's Pi theorem was implemented to derive dimensionless terms that could characterize different geometrical parameters. This allowed the scaled model to accurately predict actual wellbore conditions. Buckingham's Pi theorem states that "the number of dimensionless and independent quantities required to express a relationship among variables in any phenomenon is equal to the number of quantities involved minus the number of dimensions" (Murphy 1950). Typically, there are three dimensions in every modeling situation: mass, length, and time. Using these dimensions to form independent, dimensionless variables can drastically reduce the number of unknown variables, making the analysis quicker and more efficient. In this study, *nine* dimensionless terms for the scaled physical model were derived using the similitude methodology:

$$\text{Reynolds number for treatment slurry} \rightarrow \frac{\rho_{TS} V_{TS} D_N}{\mu_{\infty TS}}$$

$$\text{Reynolds number for mud} \rightarrow \frac{\rho_M V_M (D_W - D_B)}{\mu_{\infty M}}$$

$$\text{Ratio of drill bit diameter to wellbore diameter} \rightarrow \frac{D_B}{D_W}$$

$$\text{Ratio of nozzle diameter to wellbore diameter} \rightarrow \frac{D_N}{D_W}$$

$$\text{Ratio of mud yield point to treatment slurry yield point} \rightarrow \frac{\tau_{oM}}{\tau_{oTS}}$$

$$\text{Ratio of mud density to treatment slurry density} \rightarrow \frac{\rho_M}{\rho_{TS}}$$

$$\text{Hedstrom number for mud} \rightarrow \frac{\rho_M \tau_{oM} D_W^2}{\mu_{\infty M}^2}$$

$$\text{Hedstrom number for treatment slurry} \rightarrow \frac{\rho_{TS} \tau_{oTS} D_N^2}{\mu_{\infty TS}^2}$$

$$\text{PI mixing number} \rightarrow PI_{mix} = \frac{\rho_{TS} V_{TS}^2}{2\tau_{oTS}}$$

where ρ_{TS} is the density treatment slurry (pumped down the drillpipe), ρ_M is the density mud (pumped down the annulus), D_B is the diameter drill bit, D_W is the diameter wellbore, D_N is the diameter jet nozzle, V_{TS} is the velocity treatment slurry, V_M is the velocity mud, $\mu_{\infty TS}$ is the plastic viscosity treatment slurry, $\mu_{\infty M}$ is the plastic viscosity mud, τ_{oTS} is the yield point treatment slurry, τ_{oM} is the yield point mud. All of these terms have meaning to actual well conditions and the scaled physical model. Usually, in a modeling scheme, at least one term represents the core of the analysis. In this case, the most important term, the Pi mixing number (PI_{mix}), has significant influence on the data analysis to quantify mixing energy. A computational tool was created to enable the user to design the scaled physical model using PI_{mix} and the rest of the dimensionless terms as indicators of proper scaling. First, the desired actual well condition parameters, including well geometrics and fluid rheological values, were input into the tool. Next, the scaled physical model parameters were input in an effort to align all dimensionless terms between actual and modeled as close as possible, ensuring engineering soundness. Finally, the output dimensions were used to design and build the scaled physical model (Figure 2).

SCALED PHYSICAL MODEL

The model body was constructed of PVC tubing to allow for visual observation during mixing reactions. The model was equipped with two pumps to classify the two-stream lost circulation treatment as dual flow. The treatment slurry was pumped through the drillstring, and the mud was pumped down the annulus. Figure 2 also shows a picture of the drill bit and spray, which was placed in the interior of the outer pipe to simulate an actual drill bit location. In addition, the model was fixed with two thief zones (½" diameter outlets) and relief valves. The thief zones were present to allow sample collection, and the relief valves ensured that the model did not overpressure. Below the thief zones was a rat-hole. All distances and dimensions were designated from the similitude analysis. The wellbore was first filled with drilling fluid to best simulate actual well conditions. Next, simultaneous and equal flow of the drilling fluid and treatment slurry was initiated. The reaction was observed in the wellbore and the final product was allowed to flow through the thief zones until an adequate sample was collected for YP testing. Finally, the YP was measured for the sample after 30 minutes, the same time as the previous mechanical agitation blender mixing.

For each oil-based mud system, eight tests were completed. The test spectrum used for this procedure called for four flow rates of 5, 10, 15, and 20 gallons per minute under two conditions (hence eight data points as shown in Figures 3-6). The first condition allowed flow through open ports, simulating minimal shear (worst case with regard to product quality). The other condition placed a screen in the mouths of the thief ports, simulating any unanticipated downhole shear that could actually be encountered during a real-world placement (best case with regard to product quality). By introducing more shear to the system, the hypothesis of accumulated shear could be proven. Therefore, best-case and worst-case scenarios were created for downhole mixing.

DATA ANALYSIS—SCALED MODEL

As in the mechanical agitation blender experiments, the data for the scaled physical model tests were analyzed using the theory of integral shear history (ISH). As stated previously, this study shows that ISH is a dimensionless function of the shear rate ($\dot{\gamma}$) encountered by the two-stream system when mixed, the time (Δt) the mixture is exposed to shear, and the mixture's sensitivity to shear (p). In the case of actual well conditions, it is assumed that all shear can potentially occur at four different locations: the bit, the open hole, the thief zone entrance, and any unanticipated shear locations (represented by the screen in the scaled physical model). Therefore, the ISH for the scaled physical model was a summation of these four:

$$ISH = \dot{\gamma}_{Bit}^{p} \Delta t_{Bit} + \dot{\gamma}_{OpenHole} \Delta t_{OpenHole} + \dot{\gamma}_{Thief}^{p} \Delta t_{Thief} + \dot{\gamma}_{Screen}^{p} \Delta t_{Screen} \quad (4)$$

The shear rate in each of the sections was calculated using Equation 5:

$$\dot{\gamma} = \frac{4\dot{Q}}{\pi R^3} \qquad (5)$$

where $\dot{Q}$ is the flow rate and R is the radius of the geometry the flow is traveling through. The time the material was exposed to shear was determined by iteration and the material's sensitivity to shear was held constant. Note that Equation 5 shows shear rate is dependent on flow rate, which is dependent on velocity. Figure 3 shows this velocity versus ISH. The plot proves the hypothesis of increasing YP with increasing ISH because at each velocity the YP is greater in the screened cases than in the no-screen cases. Furthermore, it can be seen from Figure 4 that ISH controls the yield point (i.e. quality) of the product.

CORRELATION BETWEEN BENCH-TOP AND ACTUAL WELL

Recall that Figure 1 shows ISH versus YP for the *bench-top mixing tests* and Figure 4 shows ISH versus YP for the *scaled physical model tests*. To correlate the two, Figure 5 (an overlap) was created. It shows that the scaled physical model is an accurate representation of the mechanical agitation blender. The methodology described in this study also shows that PI_{mix} becomes important in forecasting actual downhole mixing energy. The term is highly correlated with ISH and thus is key to relating bench-top mechanical mixing to mixing beneath the drill bit. This factor becomes critical when designing a successful lost circulation chemical treatment. Since the scaled physical model data depicts the predicted data to a high degree of accuracy, it can be assumed that the PI_{mix} for both cases is the same at a particular YP. Thus, an engineer can use a common blender to accurately predict the quality of the downhole reacted product. Once the bench-top tests are complete, the engineer can then estimate the flow rate necessary to achieve the desired YP.

To do this, the ISH that corresponds to the desired YP is read from Figure 5. The ISH value is then applied to Figure 6 to obtain a window (see the shaded region) of PI_{mix} values. Note that Figure 6 shows the ISH and PI_{mix} correlation for both the screen case (best scenario) and no-screen case (worst scenario). Finally, Figure 7 can be used to obtain the optimal range of placement flow rates. Again, worst-case and best-case scenarios are presented. The lower flow rate assumes that the only shear introduced into the system is due to jet mixing at the bit, whereas the higher flow rate assumes that unanticipated sources of shear are present downhole. For the case of the internal olefin/ester blend drilling fluid, the optimal flow rate for *each* stream (not total) in the dual-stream system can be derived from Figure 7. These flow rates reveal the minimum required speed (kinetic energy) the two streams need to be traveling to achieve sufficient energy upon mixing beneath the bit.

SAMPLE CALCULATION

To curtail confusion, a mock situation and subsequent calculation are presented. Assume that an operator is experiencing severe mud losses while drilling. He would like to remedy the situation by pumping a dual-stream chemical treatment to seal the weak zone. He would also like the final product to have yield point of at least 2000 Pa. Before running the job, he wants to know how fast to pump each stream to gain the mixing energy necessary to form a product of this quality.

> **Step 1—**Use Figure 5 to find the ISH that corresponds to a yield point of 2000 Pa. From inspection, this value equals 8.8.
>
> **Step 2—**Use Figure 6 to determine the window of Pi Mixing Numbers (PI_{mix}) necessary to achieve an ISH of 8.8. From the plot, the range is 11.5–32.5.
>
> **Step 3—**Use Figure 7 to find the range of optimal flow rates. In this case, the range looks to be from 2.9–4.8 barrel per minute.

The operator should pump each stream at a flow rate within this range to ensure a product of 2000 Pa.

CONCLUSIONS

Understanding and controlling the mixing energy involved in placing dual-stream treatments is important for their success. The mathematical analysis presented provides a scientific approach that can optimally design a dual-stream chemical treatment in an effort to successfully combat lost circulation. Regardless of the well conditions, the application of engineering similitude and its corresponding model can transform a common blender test into an accurate prediction of downhole reacted product quality. From these, optimal flow rates and a proper job design can be generated.

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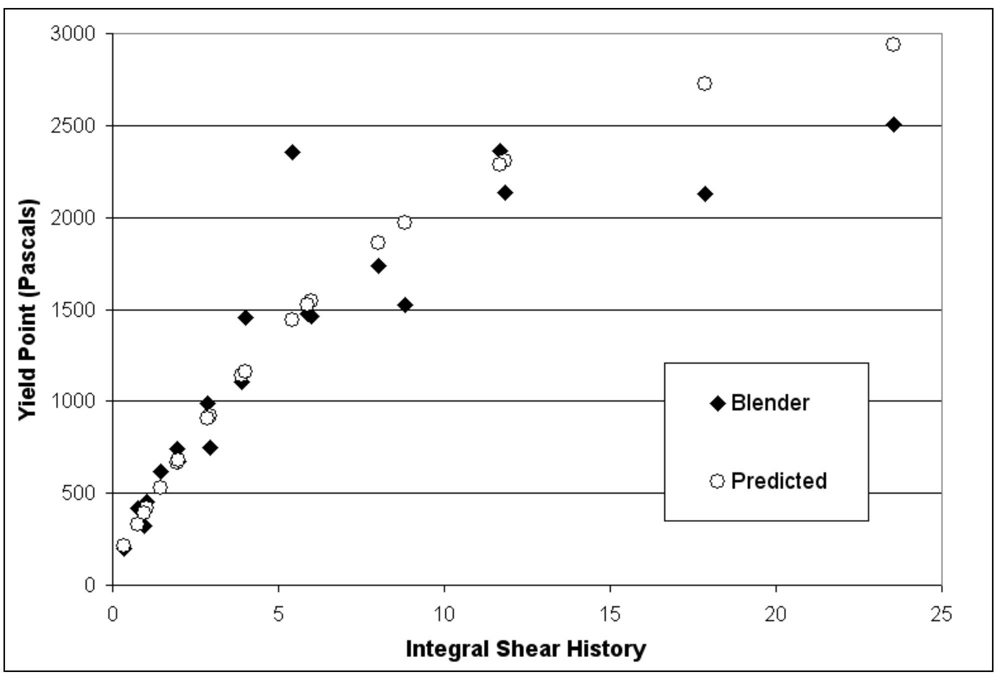

Figure 1 - Integral Shear History (ISH) versus Yield Point (YP) for Predicted Data and Mechanical Agitation Data

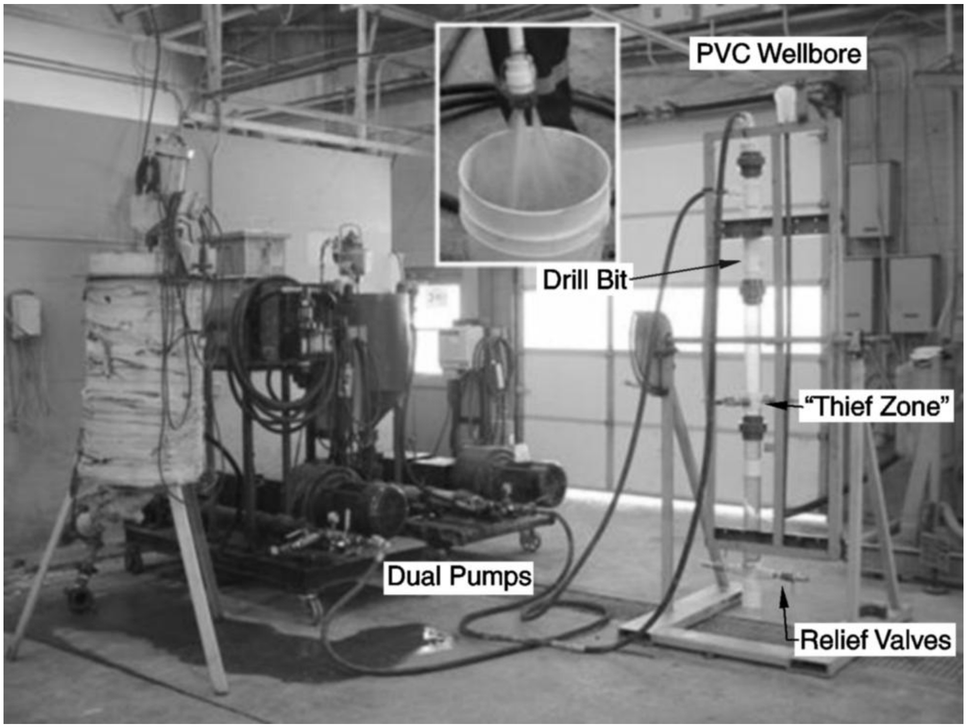

Figure 2 - Scaled Physical Model Used in Testing

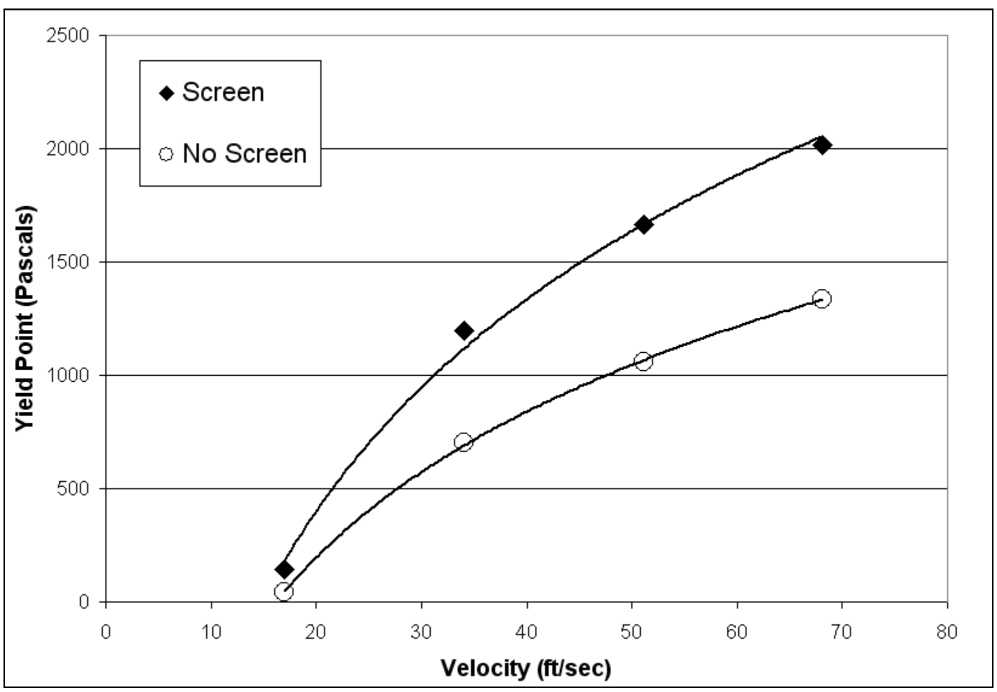

Figure 3 - Velocity versus YP for Varying Shear Exposure

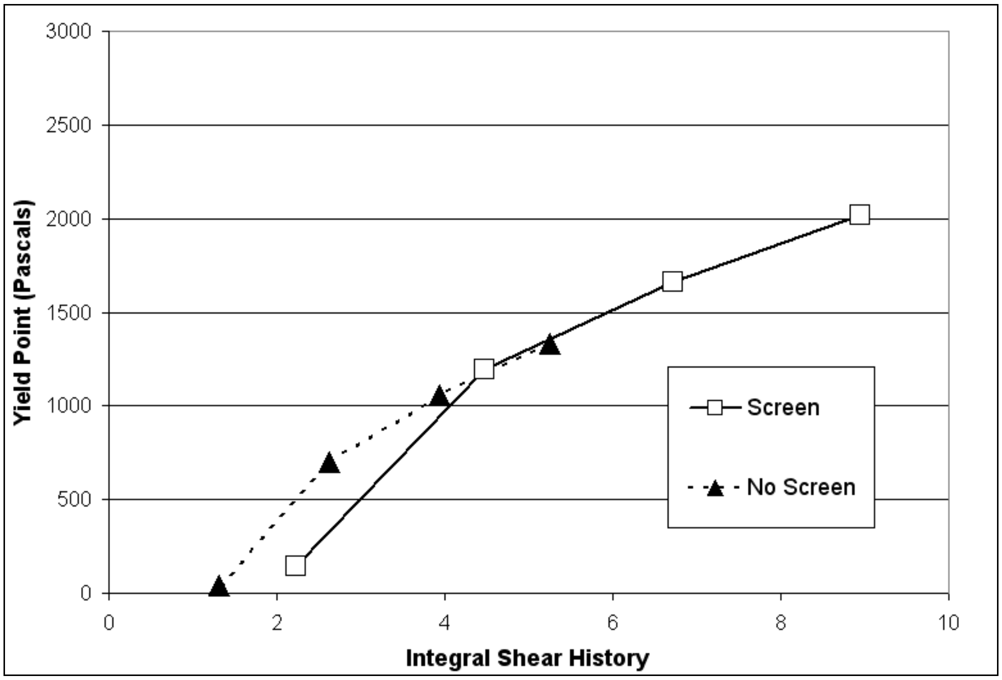

Figure 4 - ISH versus YP for Scaled Physical Model for Varying Shear Exposure

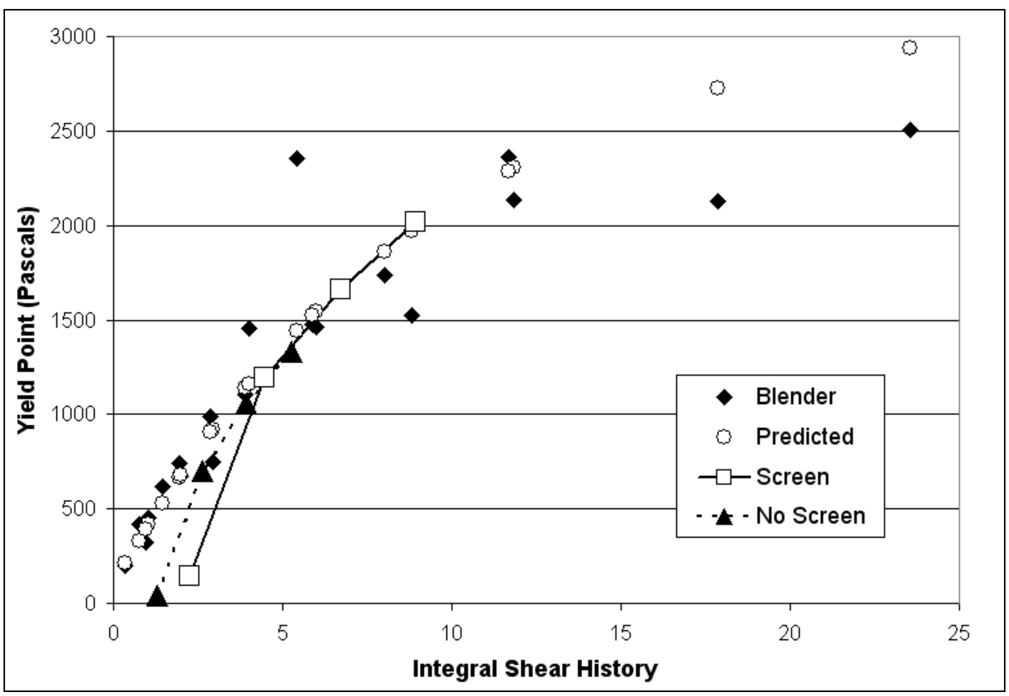

Figure 5 - Overlap Plot of ISH Versus YP for *All* Data

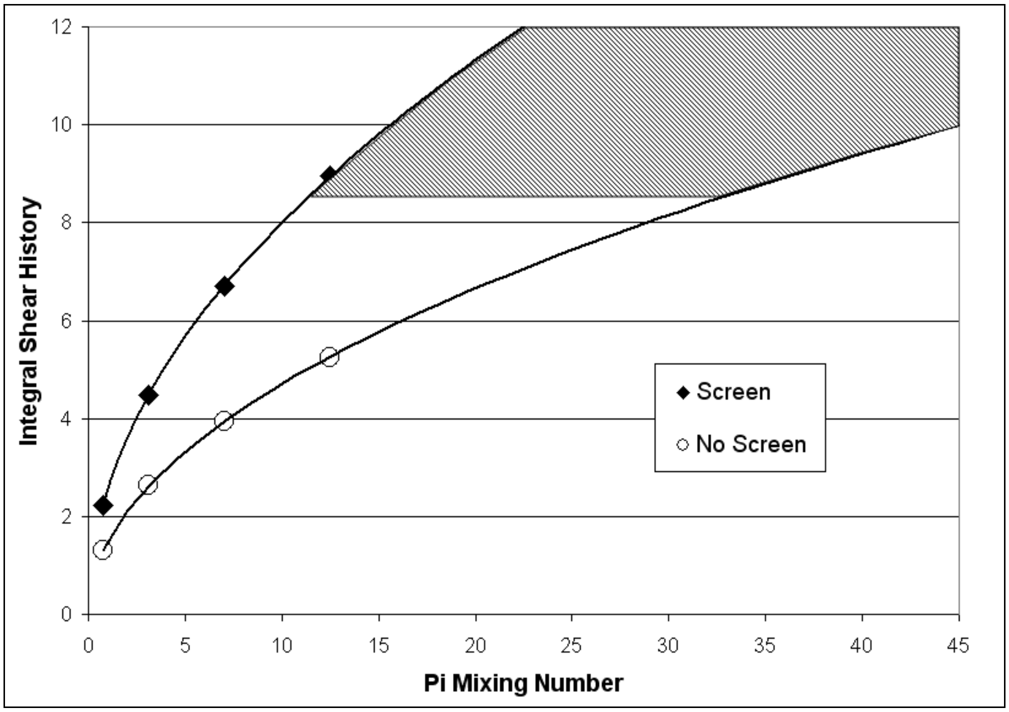

Figure 6 - Pi Mixing Number (PI_{mix}) versus ISH for Varying Shear Exposure

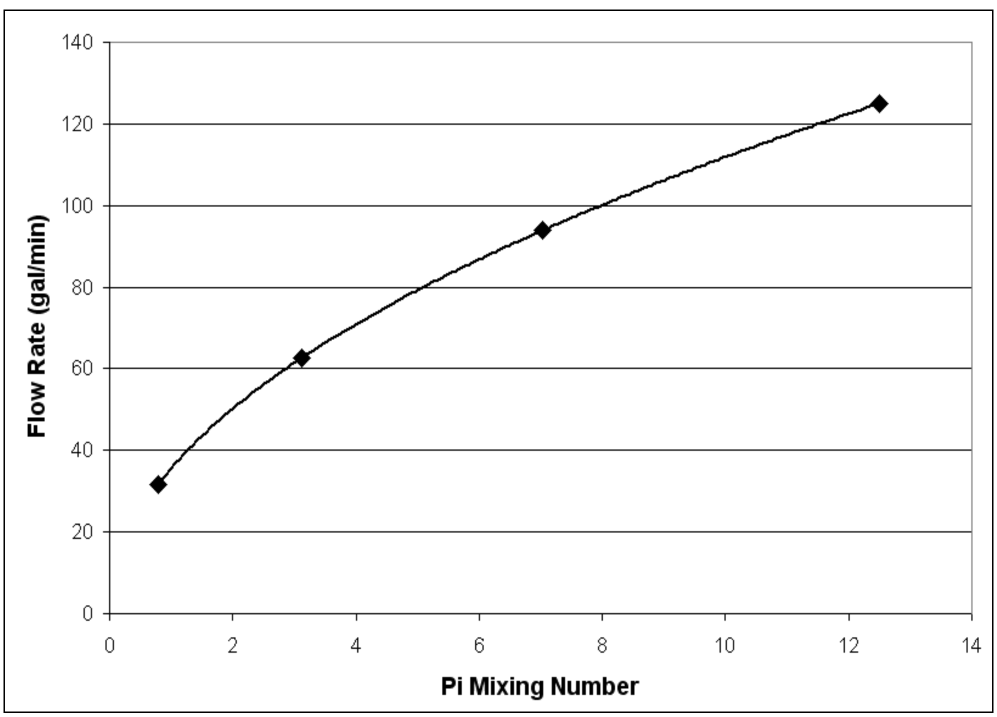

Figure 7 - PI_{mix} versus Optimal Flowrate