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INFLUENCE OF PROPPANT CONCENTRATION ON RHEOLOGICAL PARAMETERS OF SLICK WATER**

1. INTRODUCTION

Due to the high demand on world's energy resources, especially oil and gas, modern technologies were developed to get supplies to this need, which was increasing year by year. So new reservoirs were exploited, even those which were inaccessible before due to their low permeability are made feasible through advances in new technologies; for example shale gas is produced in many basins across the world. One of those technologies used today as the reservoir simulation techniques is the hydraulic fracturing, which is a process used to raise productivity of oil and gas, contained in the low permeability reservoirs, by creating high permeability path in the rocks.

Process can be described in few steps: fracturing fluid and proppant are mixed together and pumped into the formation at high pressure. That creates fractures in the rock which propagate deeply allowing production of oil and gas. Fracturing fluid is pumped back out from the fracture, allowing the outflow of the hydrocarbon. It is possible to introduce recycling because most of these fracturing fluids injected are pumped back out with groundwater and methane gas [1, 2].

Hydraulic fracturing is recognized as the most effective method for improving extraction in low permeability reservoirs. Its first experimental use was in the early 20th century, in 1940s in the USA, with an injection of gelled gasoline (as fracture fluid) and sand (as a proppant) into a gas formation. The first use of this technique lead to know that fracturing fluids required high viscosity for creating large fracture width and transporting proppant efficiently. So two decades later, guar-based fluids were introduced to replace gasoline-based gel used before. The main problem with this method was the difficult way of cleaning up gel from the fracture [2].

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In 1997, new techniques improving these methods were used for an economic extraction, the method known as “slick water fracturing”; those new technique involve the use of modern fracture fluid with different viscous properties and different chemical ingredients as proppant. Those variations have many effects on the profile of hydraulic fractures. Low viscosity fracturing fluids decrease proppant transport capability; high viscosity fracturing fluids increase pumping time, proppant transport properties and also the fracture width. Viscosity of hydraulic fracturing fluids is very important because it mainly determines the transport of proppant into a fracture and pressure distribution through flow path.

More reservoirs which were inaccessible due to their high production of water after a hydraulic fracturing are explored nowadays with this improving method [3].

2. HYDRAULIC FRACTURING FLUIDS: SLICK WATER

Hydraulic fracturing fluids were used to propagate fracture and transport proppant into a created fracture width, allowing a high flow out of oil and gas contained in the reservoir.

Many parameters were used to design, characterize and describe a hydraulic fracturing fluid, but all of those parameters mainly depend on proppant transport capability, viscosity and viscoelasticity.

Hydraulic fracturing fluids were based on water and can be used in different forms (water foam, slick water and gelled water).

Most hydraulic fracturing systems currently use water-soluble polymers composed of guar or guar derivatives. Additional materials were used to optimize the fluid characteristics for the application and also to degrade this fracturing fluid to make it easier to recover from the well prior to production.

Water-based polymers and guar have been the main choice of fracturing to their low cost and their fluid rheology, but note that most of these fracturing fluids cause a dramatic loss in fracture conductivity (10% of fracture conductivity was not achieved) [5].

Recent innovation of hydraulic fracturing fluids with no polymer and guar was developed; those one generate high well productivity with small fracture stimulation treatments such as slick water.

Slick water fracturing is a technique of hydraulic fracturing which involves special type of fluid for increasing the flow rate. Water-based fluid and proppant combination are used; it has been successfully performed in shale’s and tight gas reservoirs using low viscosity fluid. Slick water fracturing has the advantage of reducing formation damage and generally being less expensive than conventional gel [3]. It can be pumped down the well-bore as fast as 100 bbl/min to fracture the shale (while with high viscosity, the top speed of pumping is around 60 bbl/min). Water is the most common base fluid.

3. PROPPANT

Proppant is material used during hydraulic fracturing process to prevent fractures created in the shale rock from closing up after the taking place of the process. The producing formation is fractured using hydraulic pressure and then proppant is pumped into the well with fracturing fluid to hold the fissures opened so that the natural gas or crude oil can flow up the well. The materials used for proppant were generally sand grains and ceramic materials. Usually Sand was used when the net fracture closure stress is below 6000 psi, and ceramics when the net fracture closure stress is more than 6000 psi. The proppant size, shape, and mechanical strength keeps open the newly created fractures, and therefore the flow of oil and gas out of the well is possible.

The properties of proppant transport and its performance in hydraulic fracturing fluid depend mainly on: fluid specific gravity, fluid viscosity, proppant size, and proppant specific gravity.

If the fluid is not sufficiently viscous, the proppant will not be effectively transported throughout the fracture. If the slurry is too viscous, the fluid will not flow properly.

Typical proppant mesh sizes are presented in Table 1.

Table 1

Range of proppant mesh

Proppant size [mesh]
16–30
20–40
30–50
40–70
70–140

This table represents the common used size range of proppant mesh in hydraulic fracturing process; proppant size has a significant impact on the rock permeability. Typically, a larger proppant size will lead to the achievement of high permeability even applying a low stress closure. Even though that this large size of proppant is the key factor of a acquiring high conductivity, it requires enough large fracture width to be transported during the process.

4. MEASUREMENT OF THE RHEOLOGICAL PARAMETERS

To measure change of rheological parameters of slick water ($\mu < 10$ cP) was used the rotational viscometer Chan. Slick water usually is described by the Bingham model represented by the linear shear stress/shear strain. Relationship Bingham model is described by equation (1):

$$\tau = YP + PV(\gamma) \tag{1}$$

where:

PV – plastic viscosity,
YP – yield point,
γ – Shear rate,
τ – shear stress.

For chosen slick water Bingham rheological model is characterized by:

– yield point (YP) = 0, 6014;
– plastic viscosity (PV) = 0, 0038.

Table 2

Description of proppant concentration

Slick water SW	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12	SW13	SW14	SW15
Proppant concen-tration [g/L]	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750

Different proppant concentrations in slick water used during experiments are shown in Table 2. Proppant concentration vary from 50 g/L to 750 g/L. For low concentration of proppant (50–400 g/L), Bingham model was the best fitted as the shear stress is proportio-nal to shear rate behavior.

Table 3

Description of rheological parameters obtained with Bingham model for low concentration

Slick water	Bingham model: $\tau = YP + PV(\gamma)$		
	R^2	YP	PV
SW1	0.9878	1.1818	0.0070
SW2	0.9839	1.1973	0.0069
SW3	0.9861	1.3031	0.0072
SW4	0.9861	1.3031	0.0072
SW5	0.9861	1.2752	0.0071
SW6	0.9861	1.2752	0.0071
SW7	0.9913	1.2319	0.0071
SW8	0.9852	1.2940	0.0068

Table 3 describes the different rheological parameters of slick water with proppant concentration range from 50 g/L to 400 g/L, obtained by calculation with Bingham model, where:

PV – plastic viscosity, in poise [P],
YP – yield point, in pascal [Pa],
R – Pearson coefficient which measure the correlation between the shear rate and the shear stress, the linear dependence.

The next graphs represent the correlation between shear rate and shear stress (Figs 1–8).

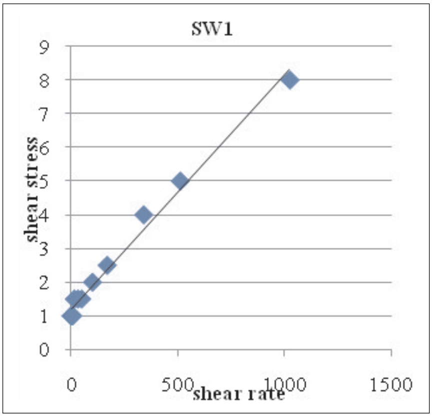

Fig. 1. Slick water SW1 (50 g/L)

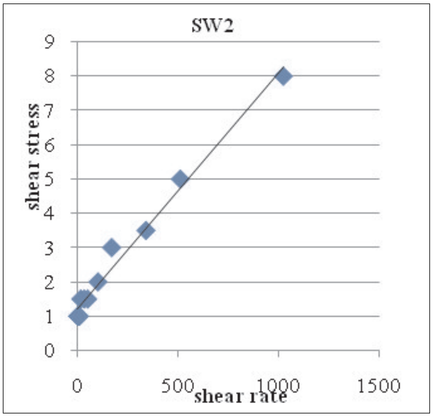

Fig. 2. Slick water SW2 (100 g/L)

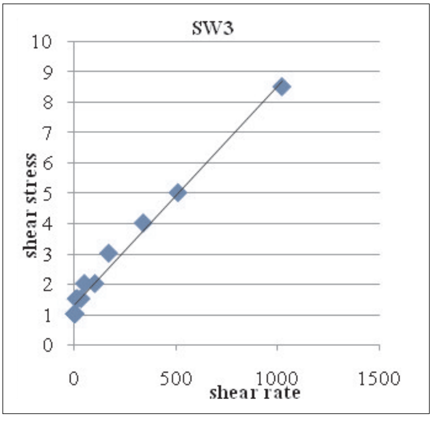

Fig. 3. Slick water SW3 (150 g/L)

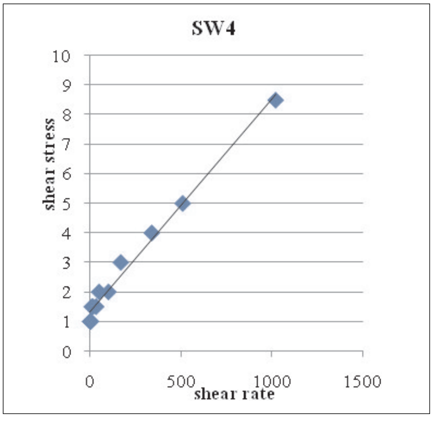

Fig. 4. Slick water SW4 (200 g/L)

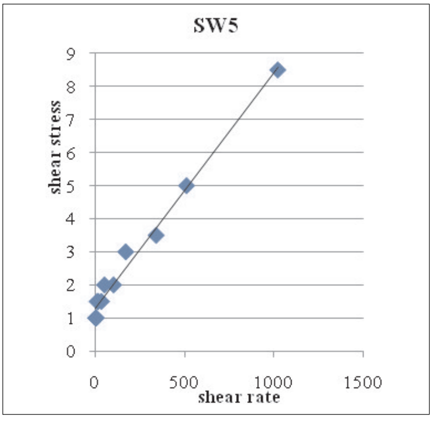

Fig. 5. Slick water SW5 (250 g/L)

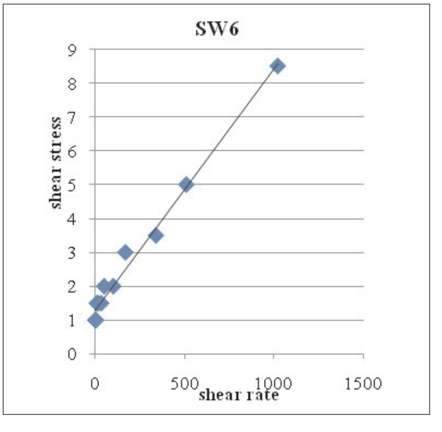

Fig. 6. Slick water SW6 (300 g/L)

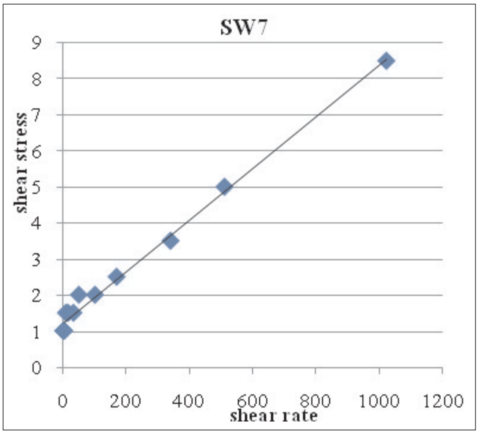

Fig. 7. Slick water SW7 (350 g/L)

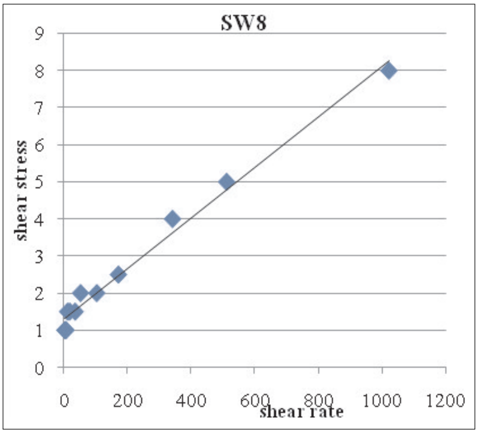

Fig. 8. Slick water SW8 (400 g/L)

Increasing the concentration of sand proppant in chosen slick water from 50 g/L to 400 g/L has few effects on rheological parameters. We have a linear shear stress/shear strain relationship with a finite yield stress. They behave like Bingham plastics, so we can use this rheological model to characterize the fracturing fluid with these concentrations as a best fitted.

For the concentration of proppant range from 450 g/L to 750 g/L, we use different models to describe rheological parameters.

Correlation with the Bingham model, as described on the previous experiments is shown in Table 4. Because of Pearson coefficient fitting, we developed a new model to compare with Bingham model, as this one doesn't describe well the correlation between shear stress and shear rate in those fracturing fluids with high proppant concentration.

Table 4

Description of rheological parameters obtained with Bingham model for high concentration of sand proppant

Slick water	Bingham model $\tau = YP + PV(\gamma)$		
	R^2	YP	PV
SW9	0.9950	0.5046	0.0054
SW10	0.9866	0.4982	0.0063
SW11	0.9925	0.5124	0.0063
SW12	0.9873	0.4995	0.0067
SW13	0.9606	0.3370	0.0084
SW14	0.9534	0.3020	0.0088
SW15	0.9385	0.4571	0.0090

Table 4 describes the different rheological parameters of slick water with proppant concentration range from 450 g/L to 750 g/L, obtained by calculation with Bingham model.

Graphs in Figures 9–15 describe the correlation between shear rate and shear stress.

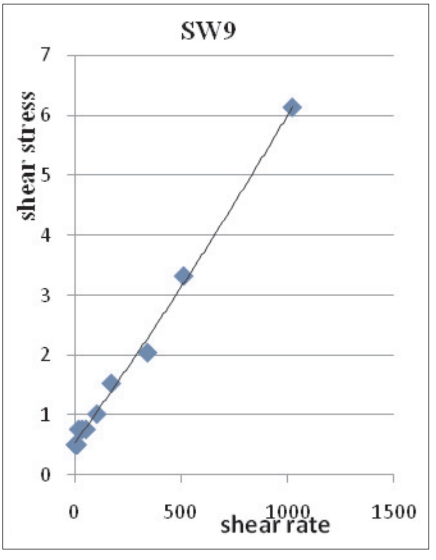

Fig. 9. Slick water SW9 (450 g/L)

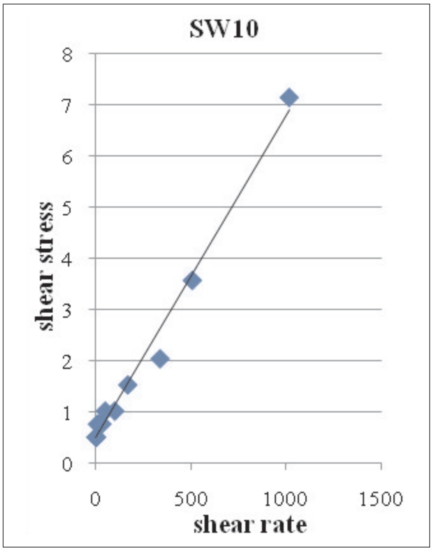

Fig. 10. Slick water SW10 (500 g/L)

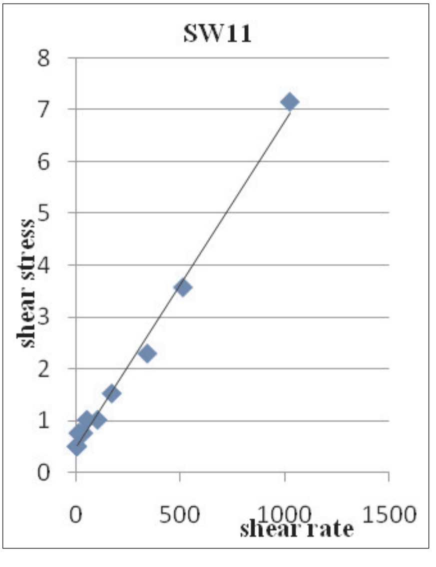

Fig. 11. Slick water SW11 (550 g/L)

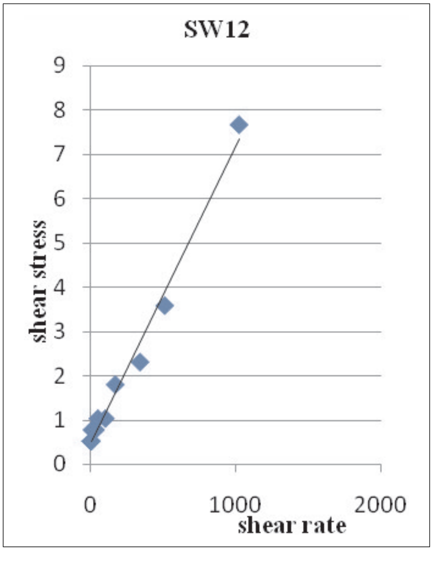

Fig. 12. Slick water SW12 (600 g/L)

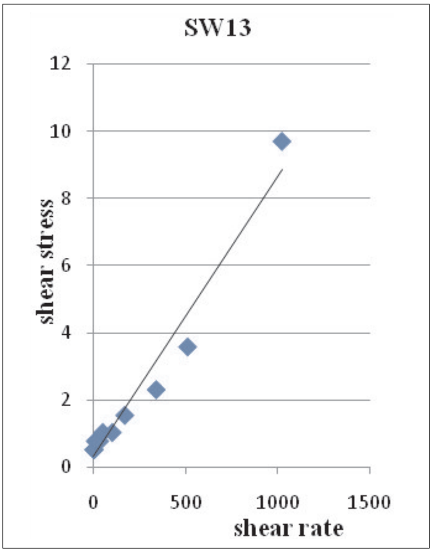

Fig. 13. Slick water SW13 (650 g/L)

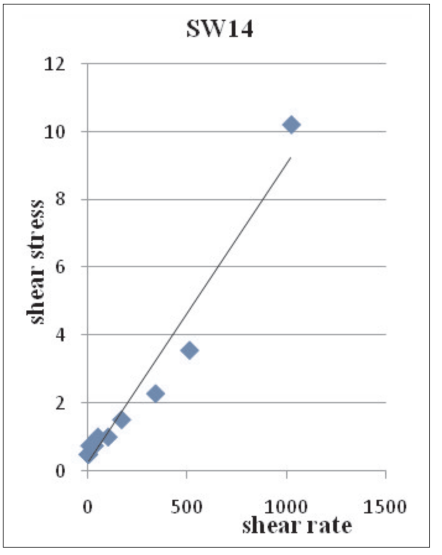

Fig. 14. Slick water SW14 (700 g/L)

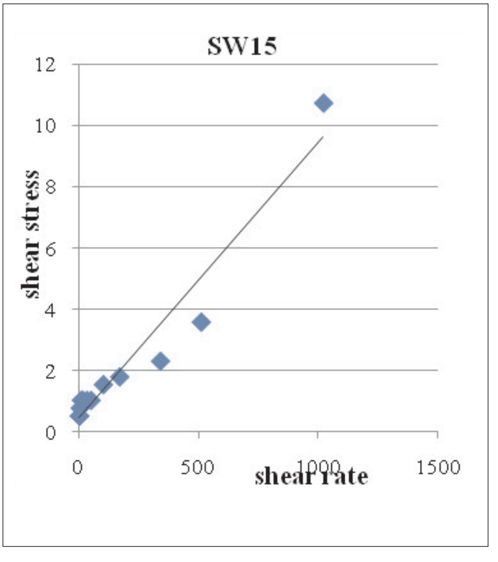

Fig. 15. Slick water SW15 (750 g/L)

Increasing the concentration of sand proppant from 450 g/L to 750 g/L increases also the rheological measurements; and by the way the shear stress. all the fracturing fluid gotten with these concentration do not have a straight linear shear stress/shear rate relationship; so Bingham model which use a linear regression doesn't describe them well.

A polonominal equation best describe this shear stress/shear rate relationship. So the viscosity can be calculated with the new model:

$$\tau = \mathrm{YP} + F_1\gamma + F_2\gamma^2 \tag{2}$$

where:

- YP – yield point,
- F_1 – factor 1,
- F_2 – factor 2,
- γ – shear rate.

5. CALCULATION FOR NEW MODEL

Table 5 describes the different rheological parameters of slick water with proppant concentration range from 450 g/L to 750 g/L, obtained by calculation with new model, where:

- YP – yield point,
- F_1 – factor 1,
- F_2 – factor 2,
- γ – shear rate,
- R – Pearson coefficient.

Table 5

Description of rheological parameters obtained with "New" model for slick water with high concentration

Slick water	New model			
	R^2	$\tau = \mathrm{YP} + F_1(\gamma) + F_2(\gamma^2)$		
		YP	F_1	F_2
SW9	0.9958	0.5346	0.0049	0.0000005
SW10	0.9943	0.6024	0.0045	0.0000020
SW11	0.9971	0.5930	0.0049	0.0000010
SW12	0.9954	0.6138	0.0048	0.0000020
SW13	0.9977	0.6465	0.0031	0.0000060
SW14	0.9975	0.6572	0.0027	0.0000060
SW15	0.9924	0.8616	0.0020	0.0000007

The following graphs describe the correlation between shear rate and shear stress.

The Figures 16–22 describe the relationship between shear stress and shear rate. The graphs are obtained with the new model.

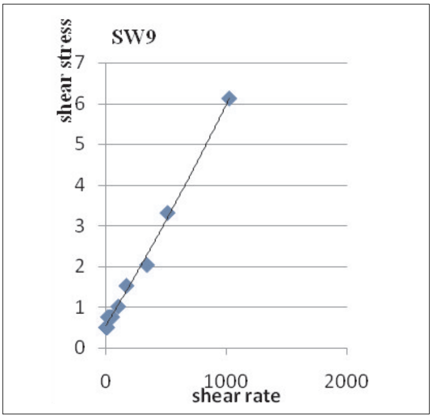

Fig. 16. Slick water SW9 (450 g/L)

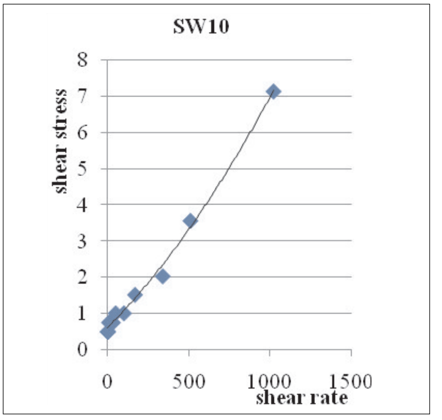

Fig. 17. Slick water SW10 (500 g/L)

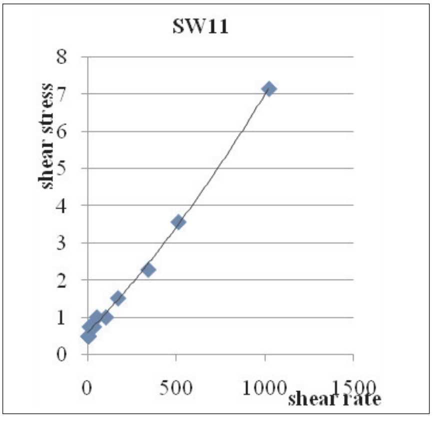

Fig. 18. Slick water SW11 (550 g/L)

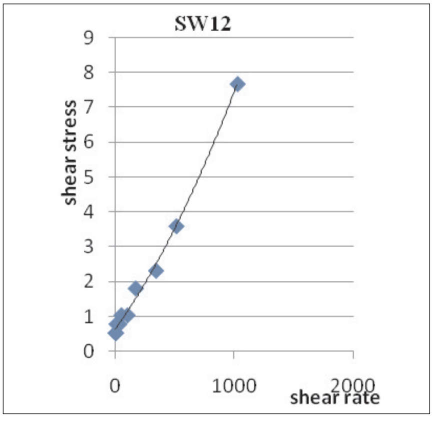

Fig. 19. Slick water SW12 (600 g/L)

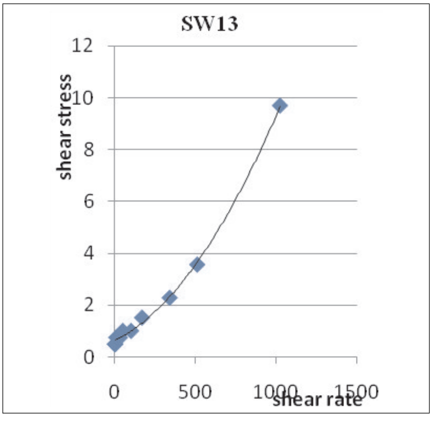

Fig. 20. Slick water SW13 (650 g/L)

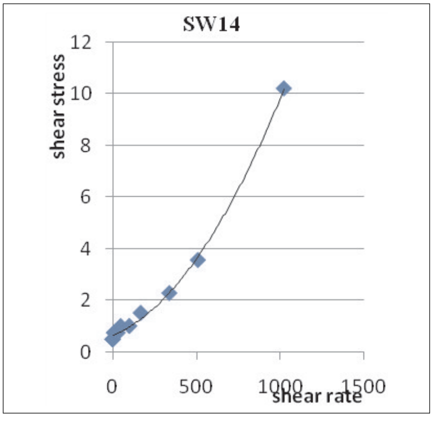

Fig. 21. Slick water SW14 (700 g/L)

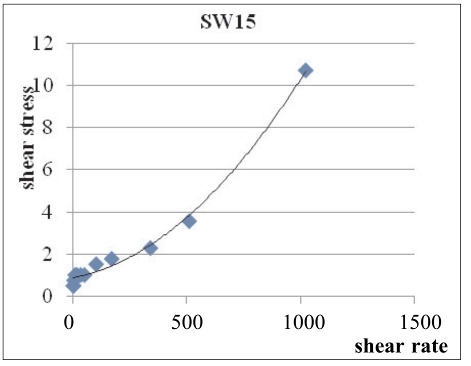

Fig. 22. Slick water SW15 (750 g/L)

6. COMPARISON OF BINGHAM MODEL WITH NEW MODEL (Tab. 6)

Table 6

Comparison of rheological parameters obtained with "New" model and Bingham model for slick water with high proppant concentration

Slick water	Coefficient of Pearson R^2	
	Bingham τ = YP + PV (γ)	New model τ = YP + $PV_1(\gamma)$ + PV_2 (γ^2)
SW9	0.9950	0.9958
SW10	0.9866	0.9943
SW11	0.9925	0.9971
SW12	0.9873	0.9954
SW13	0.9606	0.9977
SW14	0.9534	0.9975
SW15	0.9385	0.9924

By comparing the Pearson coefficient of these two models (for slick with high concentration), new model has a Pearson coefficient bigger than Bingham, its value is near to 1, that means it better describes the linear relation between the shear rate and shear stress.

7. CONCLUSION

1. Slick water solutions with concentration of proppant chosen in research paper (50–400 g/L) have approximately the same rheological parameters due to the approximately the same shear stress measured. They have a linear shear stress/shear strain relationship with a finite yield stress before they begin to flow. They behave like Bingham plastics, so their viscosity can be calculated with Bingham model.

2. Slick water solutions with high concentration of proppant chosen in research paper (450–750 g/L) have different rheological measurements due to the different shear stress measured (which is increasing rapidly). All the fracturing fluid gotten with these concentration do not have a linear shear stress/shear strain relationship; Bingham model cannot well describe it, so we can use a new model to determine the viscosity. Viscosity can be calculated with the new model which will be in the form of equation (2).
3. By comparing the Pearson's coefficient of Bingham model with the "new" model developed for slick water with high concentration of proppant, the "new" developed model has a Pearson coefficient bigger than Bingham, its value is near to 1, that means it better describes the linear relation between the shear rate and shear stress.

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