RHEOLOGICAL ANALYSIS OF A BLOOD MIMICKING

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Abstract: *One of the challenges found on analysis of mechanical systems that simulate the human circulatory system is the use of a blood-mimicking fluid with the same properties of natural blood. For this paper many* ***phantons*** *were made and had their reological properties checked at 36 C of temperature changing their composition, based on Machado et al. (2008) and Ramnarine et al. (1998), focusing overcome this lack. This mimicking fluid is composed of destilated water, P.A. Glycerin, Polivinilpirrolidone (PVP-K30), commercial detergent (Cottoclarin MJ), PVC (particle) and pure or graphite powder mixed with silicon dioxide. Because of the lack of PVP-360, PVP-K30 was used instead, which has the same properties of PVP-360 and was also used by Machado et al. (2008). Each ingredient is responsible of certain characteristic in a mimicking-fluid. It follows from Ramnarine et al. (1998) that Zero Cal® sweetener, which was replaced by PVP-K30 because of its inefficiency, also cited by Machado et al. (2008), is responsible for the kinematic viscosity, detergent avoids particle agglutination, glycerin interferes the viscosity and ultra-sound propagation speed, particulate PVC imitates erythrocyte and graphite powder approximate the thermal conduction values of* ***phantom*** *to the real ones. After making the mimicking-fluid, the Brookfield Coaxial R/S Geometry Rheometer was used to analyze the mimicking-fluid's rheological properties and it was concluded that the phantom containing graphite powder with silicon dioxide shows the behavior and the viscosity close to those of real blood, however, the phantom containing only graphite did not show results close to those of the literature.*

Keywords: *Composition, Blood-mimicking, Rheometer, Rheological properties, Silicon dioxide.*

1. INTRODUCTION

The use of a fluid alike blood in a device that imitates the human body is very important for theses mechanisms analysis because we create the possibility of getting more realistic results. For a blood-mimicking is efficiency it is necessary to have physical properties similar of real blood.

Authors as Machado et al. (2008), Ramnarine et al. (1998) and Coiado and Costa (2008) created *phantons* willing to get similarity to real blood and easiness in making them. These fluids have characteristics as thermal diffusely, viscosity, density, conductivity, ultra propagation speed, attenuation coefficient and particle size (erythrocyte) similar of real blood.

Pure water is not able to perfectly reproduce blood and it is not reliable for such experiments but it was largely used in the past. Another easily made fluid that's used nowadays is composed of water and glycerin in the proportion of 80% to 20%, respectively. Despite the fact of reaching real blood viscosity, this composition does not have the particles that simulate the erythrocytes so its curve deflects of the curve obtained by Fournier (2007), an experimental data at 37 C.

Ramnarine et al. (1998) proposed the application of destilated water, orgasol, simpheronic N (surfactant), dextrose, glycerin and graphite powder, reaching satisfactory results. Machado et al. (2008) replaced dextrose by Zero Cal® sweetener but did not get good viscosity results.

Because of time issues, availability and price, Machado et al. (2008) replaced orgasol by PVC powder, simpheronic N by commercial detergents and dextrose by PVP-360. This mixture had higher viscosity than what Suleyman et al. (2004) and Ferreira and Yanagihara (1999) mentioned, who provide data over natural blood.

Due to the main importance of this segment in bioengineering, the behavior research of these mimicking-fluids is very relevant for the development of this area and to get this gauging it is good to use precision instruments, like rheometers, which provide not only the fluid's viscosity, but also its characteristic curve and a rheological model approximation.

The rheological model used for the analysis must be considered because of the existence of many models for different kinds of fluid. Natural blood, according to Calafati et al. (2010) and Glasgow (2010), fits better the Casson model, a pseudoplastic fluid model that considerate a minimal flow tension to start the flow. Other models, such as Power-Law and Newtonian, fit specific deformation rate ranges. Newtonian model shows to be a good rheological model for deformation rate values above 200 s^{-1}. On the other hand, Power-Law model is better fitted for lower deformation rate values.

This work is due to make and studies the rheological properties, viscosity and curve behavior of a *phantoms* changing its composition. In order to measure those characteristics the Brookfield Coaxial R/S Geometry Rheometer with Rheo2000 software analyze the fluid and calculate the characteristics according with the chosen model.

The software uses the Casson equation, Eq. (1).

$$\sqrt{Y} = \sqrt{\tau_0} + \sqrt{\mu \cdot D} \tag{1}$$

In the equation Y refers to apparent viscosity (Pa.s), D is the deformation rate (s^{-1}), μ is the Casson Viscosity (Pa.s) and τ_0 is the yield strength (Pa).

To measure how much the obtained curve is close to the rheological model the software gives us the determination coefficient (R^2), whose equation is given by the Eq. (2)

$$R^2 = \frac{SQR}{SQT} = \pm \frac{\sum \left(y_{pred} - \bar{y} \right)^2}{\sum \left(y_{obs} - \bar{y} \right)^2} \tag{2}$$

Where SQR is the quadratic sum because of the regression, SQT is the total quadratic sum, y_{pred} is model predicted value, y_{obs} is the experimental value and $\bar{y}$ is the sample mean.

With the results obtained by this software it is possible to study the influence of some substances that compound this new mimicking-fluid, also innovating and making it, if possible, more effective.

2. PROCEDURE AND MATERIALS

In order to make this *phantoms*, Machado et al. (2008) composition was taken as base, which uses destilated water, P.A. Glycerin, Polivinilpirrolidone (PVP-360), neutral commercial detergent (Cottoclarin MJ), graphite powder and particulate PVC. Because of the absence of PVP-360 in the market it was replaced by PVP-K30, which has the same function of PVP-360.

There are two kinds of graphite sold, graphite powder concentrated and graphite powder with silicon dioxide. Both kinds were used for this experiment to analyze the influence of each of them.

PVC in particles was added in this mimicking-fluid with 63um of granulometry approximately. This material is commercially called Norvic P72HA. It is recommended to wear a gas mask to handle it because of the particle size and the pulmonary impregnation.

The mimicking-fluid's composition varies whether pure graphite or silicon dioxide graphite graphite was used and also in the amount of glycerin in each sample. Ten *phantoms* samples were made composed of water and glycerin on Tab. 1 and Tab. 2

Table 1. Composition of the *phantons* with pure graphite.

Substances	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Distillate Water (g)	93.8	96.2	95.6	95.0	94.4
Glycerin P.A. (g)	2.4	0.0	0.6	1.2	1.8
Graphite Powder (g)	0.2	0.2	0.2	0.2	0.2
Neutral detergent (g)	1.2	1.2	1.2	1.2	1.2
PVP- K30 (g)	2.0	2.0	2.0	2.0	2.0
PVC Particulate (g)	0.4	0.4	0.4	0.4	0.4

Table 2. Composition of the *phantons* with graphite and silicon dioxide.

Substances	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Distillate Water (g)	93.8	96.2	95.6	95.0	94.4
Glycerin P.A. (g)	2.4	0.0	0.6	1.2	1.8
Graphite Powder (g)	0.2	0.2	0.2	0.2	0.2
Neutral detergent (g)	1.2	1.2	1.2	1.2	1.2
PVP- K30 (g)	2.0	2.0	2.0	2.0	2.0
PVC Particulate (g)	0.4	0.4	0.4	0.4	0.4

The following steps were observed to make the samples:

1. Detergent in its own quantity was added in a bottle;
2. A previously amount of water was added to the bottle and mixed;
3. A certain amount of glycerin was added in another bottle;
4. The water and detergent was poured in the glycerin bottle;
5. PVP-K30, particulate PVC and graphite powder were added to the bottle containing water, detergent and glycerin;
6. It was mixed a little bit because it is not supposed to dissolve the whole mix this step;
7. It was left to rest while other samples were made;
8. After finishing the making following these steps, the samples have to be shaken observing the order they were made. In this step it is easier to achieve the total dissolution of the ingredients.

The mimicking-fluid is a suspension, Fig, 1 and Fig. 2, because of that it has to be mixed very well before collecting the data. The components were scaled through the Shimadzu AY220 precision scale, showed on Fig. 3, which has the specifications of 220 g of maximum load, 0.01 g minimum reading capacity, 0.001 g of error and 0.0001 g of deviation.

Figure 1. Sample with decantation.

Figure 2. Sample after mixed.

Figure 3. Precision Balance Shimadzu AY220.

With the samples ready, was heated the thermal bath of the rheometer, shown in the Fig. 4, at 36 ºC, that is normal temperature of the human body according with the site http://www.tubalivre.com/2009/05/g001-temperatura-do-corpo-humano-e.html.

Figure 4. Thermal bath of rheometer.

After reached the wanted temperature, the bottle with the sample was left in contact with the refrigerant of the bath until it reaches the required temperature. The sample's rest time in bath was about 17 minutes.

The rest time passed and the Brookfield Coaxial R/S Geometry Rheometer, showed on Fig. 5, was used along with the CC-45 geometry "Spindle", showed on Fig. 6, for the mimicking-fluids' rheological analysis.

Figure 5. Brookfield R/S Coaxial Geometry Rheometer.

Figure 6. "Spindle" of geometry CC- 45.

The rheometer was set to control the tension changing from zero to about 7 Pa, in relation of time, 300 seconds, making 300 measurements, being ready for the experiment. However, not all measured points were considered, only points whose the rheometer is rotation was between 50 and 150 rpm. It was done to ensure similarity to the work made by Machado et al. (2008), and then it is possible to get a better visualization of comparison and also because of the range of work of real blood, that hardly exceed this range of angular velocity.

3. Results and Discussion

The results of viscosity, determination coefficient and yield strength were obtained using Rheo2000 software attached to the rheometer through the Eq. (1) and Eq. (2), which are on the Tab. 3 and Tab. 4.

Table 3. Data of the samples with pure graphite at 36 ºC compared with literature.

Properties	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Machado (1)	Ramnarine (2)	Real blood(3)
Viscosity (Pa. s)	0.0028	0.0023	0.0027	0.0030	0.0030	0.00451± 0.00012	0.0041	0.003 ~ 0.004
Yield stress (Pa)	0.0283	0.0610	0.0349	0.0259	0.0257	-	-	0.0002 ~ 0.04
Coefficient of determination (R^2)	0.9992	0.9997	0.9993	0.9992	0.9984	-	-	-

(1): measured at 25°C
(2): measured at 22°C
(3): data of yield stress concerning the Formagia et al. (2009)

Table 4. Data of the samples with graphite with silicon dioxide at 36 ºC compared with literature.

Properties	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Machado (1)	Ramnarine (2)	Real blood(3)
Viscosity (Pa. s)	0.0039	0.0032	0.0038	0.0039	0.0039	0.00451± 0.00012	0.0041	0.003 ~ 0.004
Yield stress (Pa)	0.0000	0.0076	0.0006	0.0000	0.0000	-	-	0.0002 ~ 0.04
Coefficient of determination (R^2)	0.9959	0.9962	0.9967	0.9964	0.9971	-	-	-

(1): measured at 25°C
(2): measured at 22°C
(3): data of yield stress concerning the Formagia et al. (2009)

It is possible to see the presence of silicon dioxide increased the viscosity of the *phantoms*, setting putting all samples carrying this component within the viscosity range of real blood. But this component affects the mimicking-fluids' minimal yield strength, making its values equal to zero for the three higher glycerin amount samples.

The obtained data was used to calculate a mean error of 8% for the viscosity of pure graphite samples related to this property in real blood, 0.003 Pa.s.

The charts were built using points in which the rotation was between 50 and 150 rpm on Excel software and then they were compared to the deformation rate by viscosity charts with the curve obtained by Calafati et al. (2010), showed on Fig 7 and Fig. 8.

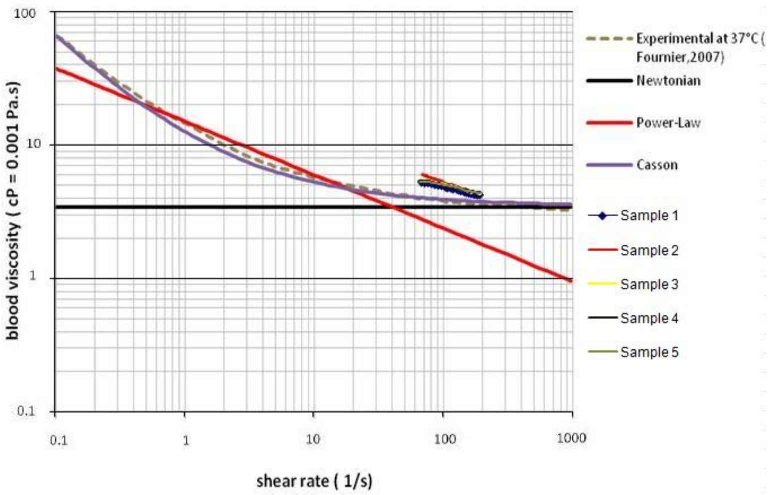

Figure 7. Graphics of the samples of *phantoms* with pure graphite compared to the graphic obtained by Calafati et al. (2010).

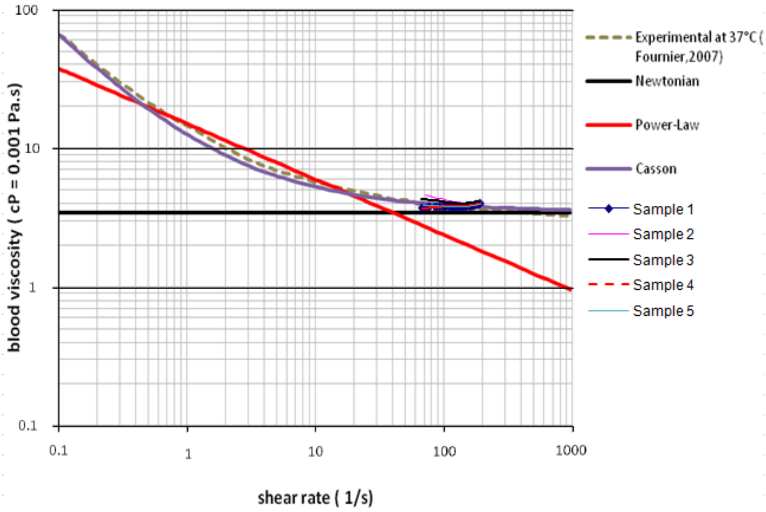

Figure 8. Graphics of the samples of *phantoms* using graphite with silicon dioxide compared to the graphic obtained by Calafati et al. (2010).

The curve's analysis shows the samples with silicon dioxide behave clearly more like real blood than the samples without this component. Yield strength, which depends on the erythrocyte, was not calculated in this experiment and has less consideration than the similarity with real blood curve.

The curves obtained by Machado et al. (2008) were also compared to the curves of *phantoms* changing the analysis temperature, showed on Fig. 9 and Fig. 10.

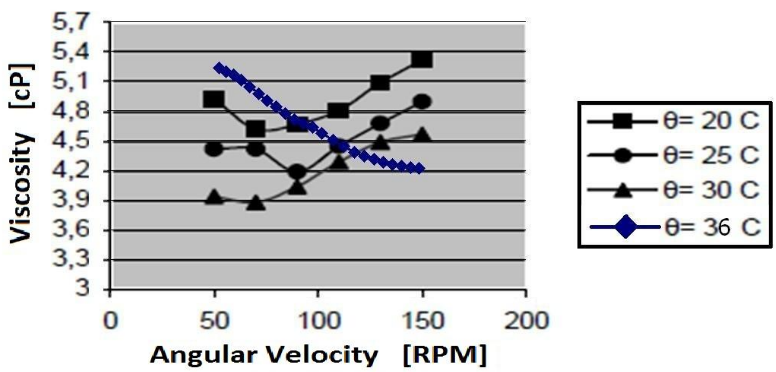

Figure 9. Comparison of the sample 1 with pure graphite at 36 ºC with graphic obtained by Machado et al. (2008), angular velocity per viscosity.

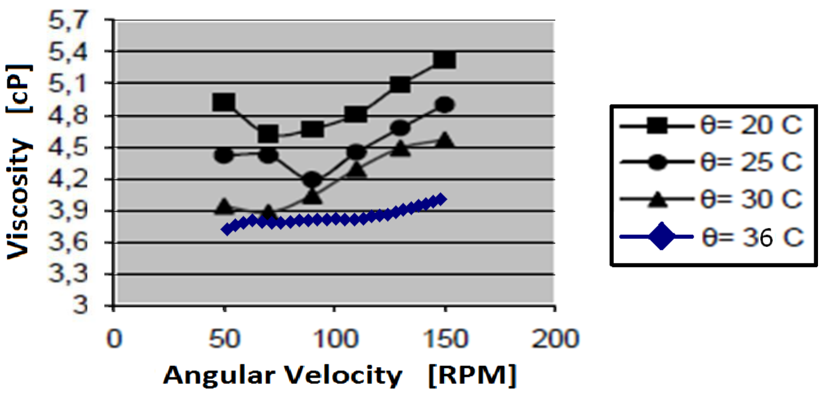

Figure 10. Comparison of the sample 1 graphite and silicon dioxide at 36 ºC with graphic obtained by Machado et al. (2008), angular velocity per viscosity.

It is clearly possible to notice an analogy between Machado et al. (2008) and the *phantoms* containing silicon dioxide, what is not true for the pure graphite sample. In a certain way, silicon dioxide interfered positively the mimicking-fluid in case, making its characteristics closer to those of real human blood and closer to other refered authors´ analyzed fluids.

4. CONCLUSION

It was possible to analyze the influence of glycerin and silicon dioxide in the focused mimicking-fluid through this study. It is concluded that glycerin was responsible for the increase of viscosity and decrease of yield strength on both pure graphite and silicon dioxide added samples. Fluids without silicon dioxide showed results of viscosity below of those of real blood related in the literatures and related to other *phantoms* already studied by other authors. This same fluid composition was able to reach yield strength values within the range of real blood. The specific value of this property, however, depends on the presence of erythrocyte in the fluid, which was not calculated in this experiment. The silicon dioxide with graphite *phantoms* reached values of viscosity close to real blood, making it more efficient over this characteristic. However, the yield strength was equal to zero for the three higher glycerin amount samples. Despite of this problem, this *phantoms* is more efficient than the one containing pure graphite because its deformation rate by viscosity curves show us its better representation of real blood. It is important to remember that the curves are more influent than the yield strength in this study because of the absence of erythrocytes. Other properties as thermal diffusivity, density, conductivity, ultra-sound propagation speed and attenuation coefficient are physical characteristics that were not studied on this present work but will be analyzed in the future.

5. ACKNOWLEDGEMENTS

I thank God for providing all this bless in my work and to put each brother and friend in my way willing to help me. I thank too my parents for the unconditional support.

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