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A STUDY ON THE EFFECT OF SLURRY TEMPERATURE, SLURRY pH AND PARTICLE DEGRADATION ON RHEOLOGY AND PRESSURE DROP OF COAL WATER SLURRIES

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The effects of temperature and pH on rheological characteristics of coal-water slurry (CWS) were investigated. With regard to effect of temperature, the experiments were carried out using a thermal cup at different temperatures in the range from 100 to 200 ^oF (37.8 to 93.3^oC). The studied pH range of slurry was from pH 2 to pH 12. The apparent viscosity and non-Newtonian properties based on power-law model were investigated using a Chandler Engineering viscometer Model 3500LS+. It was found that the apparent viscosity and degree of pseudoplasticity sharply decrease with increasing slurry temperature. At temperatures greater than 180 ^oF (82^oC) the coal slurry showed a Newtonian fluid behavior. The apparent viscosity increased with pH increase over all studied pH range. On other hand, the degree of pseudoplasticity sharply decreased with increasing pH to pH 6 and then increased. At pH equals 6 the slurry exhibited Newtonian fluid behavior. During transportation of coal water slurry, it was observed that the apparent viscosity increases with increasing number of pumping cycles. This was attributed to changes in particle size distribution as a result of particle degradation which, in turn, increase pressure drop along the pipeline. Hence, taking into account the effect of particle degradation in design of pipeline transportation of slurries is recommended.

INTRODUCTION

The use of coal–water slurries (CWS) as a fuel is regarded as a technology by which favorable economics could be realized, in comparison with the gasification or liquefaction technologies. The idea of utilizing highly loaded CWS as a substitute fuel for oil has received world wide attention since the late 1970s. Highly loaded (CWS) are of interest because of their promise as coal-based fuels possessing liquid-fuel attributes. Numerous studies have been made to improve the rheological properties of coal slurries over the past decade in an effort to obtain acceptable fluidity while maintaining sufficient stability against sedimentation. Boylu, F. et al.[1] studied the rheological properties of CWS in relation to particle size /size distribution and pulp density (solid concentration). It was found that the apparent viscosity decreases with increasing coal particle size of the slurry and increases with increasing solid concentration. This result was found in a good agreement with findings obtained by Mosa, E. S. et al.[2]. In this work, the results showed that the slurry exhibited shear thinning, i. e, pseudoplastic behavior and the degree of pseudoplasticity increases with increasing coal feed mean size. Other investigators [3,4,5] mentioned the importance of mixing the solid fraction of slurry of coarse and fine sizes. The obtained results showed that the CWS prepared with an appropriate blending ratio of two types of coal particles of different fineness is much lower in viscosity than one prepared with homogenous particle sizes. Few studies took account of the effect of slurry temperature and slurry pH on the viscosity of coal slurry. Shirley, C. T. et. al.[6] illustrated the effect of temperature on the high shear rheology of the utility grind coal water slurries which contains 71.5 and 70.4 wt. % coal. An increase in temperature from 54.7 to 109.45 ^{o}F (25 to 50^{o}C) in both slurries reduces the apparent viscosity, but has no effect on the pseudoplasticity. Further increase in temperature above 109.45 ^{o}F (50 ^{o}C) resulted in enhanced pseudoplasticity. The increase in pseudoplasticity with temperature is less pronounced for the second slurry which contains 1.1 wt% less coal content. Mingzhao, H. et. al.[7] obtained similar results with industrial mineral slurries. They concluded that temperature is another important factor that strongly affects the apparent viscosity and yield stress of the slurries. Huynh, L. et. al.[8] illustrated the effect of pH on the rheological properties of the copper concentrate slurries. The obtained results showed that the yield stress and apparent viscosity of the considered slurries decrease with pH decrease. Daniel, W. and Moncef, B.[9]. Mentioned that the viscosity is an important property in fluid dynamics because it is a key factor in determining the amount of fluid that can be transported in a pipeline during a specific period of time.

THEORETICAL BACKGROUND:

Dynamic viscosity not only describes the nature of the fluid but also is useful in predicting the behavior of the shear stress with respect to the shear rate during angular deformation of the fluid. Reynolds number, which is based on the viscosity, is an important quantity used to determine if the flow is laminar or turbulent. Mathematically, Reynolds number (R) is expressed as: [10,11]

$$R_e = \frac{\rho \ VD}{\mu} \tag{1}$$

Where: D = diameter of the pipe, V = mean velocity of the flow, μ = viscosity of the fluid. and ρ = liquid density. The flow rate of fluid or slurry (Q), is directly proportional to the pressure gradient, (ΔP/L), and may be expressed as:

$$Q = \frac{\pi r^4 \Delta P}{8 \mu L} \quad (2)$$

Where:, ΔP = pressure drop (P_2-P_1), r = radius of the pipe and L = pipe length. Hence, the head loss (h_f) in a straight circular pipe is given by the Darcy-Weisbach equation (equ.3). In this equation, (f) is the friction factor and g is force of gravity.

$$h_f = \frac{4 fLV^2}{2 gD} \quad (3)$$

Several rheological models were suggested to estimate the apparent or plastic viscosity for nonlinear fluids. Among these models, power law model was widely applied [12]. In this model, the relationship between shear stress and shear rate, (plotted on double logarithmic coordinates), for a shear-thinning fluid can often be approximated by a straight line. Mathematically, this model is expressed as

$$\tau = k \gamma^n \quad (4)$$

The apparent viscosity can be then derived from this model and expressed as,

$$\mu_a = \tau / \gamma = k (\gamma)^{n-1} \quad (5)$$

Where , μ is dynamic viscosity , τ is shear stress , γ is shear rate, k is consistency coefficient of fluid, the higher the value of *k*, the more viscous the fluid and n is the flow behaviour index which is a measure of the degree of departure from the Newtonian behaviour . According to the value of n, the power law describes three flow regimes,

(a) Pseudoplastic, $n < 1.0$, the effective viscosity decreases with shear rate,
(b) Newtonian, $n = 1$ the viscosity does not change with shear rate and
(c) Dilatant, $n > 1.0$, the effective viscosity increases with shear rate.

Abd El-Hafeez, G.m.[13] studied the factors affecting coal degradation during coal-water slurries transportation in pipelines at 20% by wt solid concentration. This study showed that most occurred degradation resulted from the agitator compared to pipeline and pump. The above mentioned study does not take into account the effect of such degradation on rheology of transported slurry. Also, temperature of slurry and slurry pH may change, to a large extent, during slurry pumping. Hence, a study that considers such effects as well as particle degradation on slurry flow rheology is of a great interest.

EXPERIMENTAL WORK

Material

The material used is a low rank coal. It was obtained from the main coal seam of El – Maghara coal mine, Northern Sinai, Egypt. The chemical analysis of the head sample is shown in table (1).

Table (1) Chemical analysis of the head sample

Test	Value
Moisture content %	3.9
Volatile matter %	43.1
Ash %	20.76
Fixed carbon %	32.24

COAL WATER SLURRY SAMPLES PREPARATION

The particle size of raw coal was initially reduced to less than 3 cm using laboratory-size crusher and then ground in a disc mill. The disc mill product was tested to obtain the maximum size of whole particle size of -250 µm.

The procedure of preparation of CWS was standardized for all tested samples. Weighed amount of tap water was transferred into a 500 ml glass beaker, and then the weighed coal sample was slowly poured into the beaker. The contents were stirred by magnetic stirrer for about 20-30 minutes. The CWS was then allowed to stand in the beaker for about 10 hrs to ensure release of entrapped air. Before testing, the considered slurry was thoroughly mixed by hand shaking and stirred to ensure homogeneity. In the tests designed to illustrate the effect of temperature and pH on slurry rheology, the solid concentration is fixed at 40% by wt.. The range of studied temperature was from 100 to 200 ^{o}F (37.8 to 93.3^{o}C) at fixed pH value of 7. The temperature was measured and controlled using a thermal cup. The effect of pH range was from 2 to 12 at room temperature. It was controlled by sodium hydroxide (NaOH) and sulphuric acid (H_2SO_4).

Viscometer

Laboratory rheological data were obtained with Chandler Engineering viscometer Model 3500LS+ which measures the rheological properties of tested slurries by measuring shear stress at specific shear rates. This Model is a concentric cylinder rotational viscometer with a wide shear rate range from 0.17 to 1022 S^{-1}. [14]

Pipeline Transportation Procedure

This section aimed to study the effect of transportation of coal water slurry on the coal degradation and hence on rheology of coal slurry and pressure drop of transportation system. The test conditions were fixed at coal concentration of 10% solids by wt., room temperature and pH = 7. The carried out procedure includes,the sample characterized by whole particle size of -250µm was prepared. The weighed amount of coal sample was added to the calibrated amount of tap water in the mixing tank. The slurry sample was agitated for about 20-30 min at constant speed of 35 rpm to obtain homogeneous slurry. The CWS sample was then pumped through the pipeline using submerged slurry pump. The used closed circuit pipeline was 41m. total length (one cycle) and 63 mm. diameter. The degradation of coal particles and the slurry viscosity were estimated by collecting slurry samples after specified pumping cycles and determining its size distribution. The pressure in pipeline was measured throughout the pumping cycle by pressure gauges which are fixed on the pipeline, at different distances from the pump.

Transportation System

The experimental set up of the transportation system is schematically represented in Fig. (1-a) and Fig. (1-b). The discharge rate of used pump was 126 liter/min. and the time per one cycle is equal to 5 sec. (i.e. 125 sec. for 25 cycles (1000 m distance)).

RESULTS AND DISCUSSION

Effect of Temperature

Fig (2) shows the relationship between shear stress and shear rate at different temperatures. The effect of temperature on apparent viscosity, and power law constants k, and n are shown in Figure (3). These data clearly indicate that the apparent viscosity (η) and consistency index (k) sharply decrease with the increase of temperature. The degree of pseudoplasticity sharply decreases with temperature increase. At temperature higher than 180 ^oF (82.2^oC), the coal slurry exhibits nearly a Newtonian fluid behavior. The reduction in apparent viscosity with increasing temperature is consistent with the mechanism of momentum transfer in liquid by molecular collision, i.e., the resistance of the carrier fluid (water) decreases with temperature increase.

Figure (4) illustrates the effect of temperature on apparent viscosity at different shear rates. It can be seen that, the apparent viscosity decreases with increasing shear rate. The apparent viscosity at high temperatures is almost constant, i.e., it does not change with shear rate increase and the coal slurry exhibits Newtonian behaviour.

Effect of Hydrogen Ion Concentration (pH)

Figure (5) shows the relationship between shear stress and shear rate at different pH. values. Fig. (6) Illustrates the effect of pH on rheological parameters, i.e, apparent viscosity and power law constants n and k. It can be seen from these figures that the apparent viscosity increases rapidly with pH increase At higher pH values (>pH6), the degree of pseudoplasticity sharply decreases with pH increase. The lowest viscosity is observed at pH = 2 -3. This may be related to hydrophobicity of coal particles. It is well known that the more hydrophobic coal particles can give a lower viscosity. This can be explained as: the internal surface and pores of hydrophobic coal can hardly be penetrated by water and water-soluble adsorbate, so that much more water remains outside the particles, lowering the slurry viscosity and improving slurry ability. Fig (7) shows the effect of pH on apparent viscosity at different shear rates. It seems like that the apparent viscosity is, more or less, constant (Newtonian behavior) at high shear rates greater than 102 S^{-1} for all tested pH values.

1- V- belt 2- Impeller

3- Slurry 4- Cast iron

5- Drainage 6- Plastic

7- 80*80*85 cm

8-

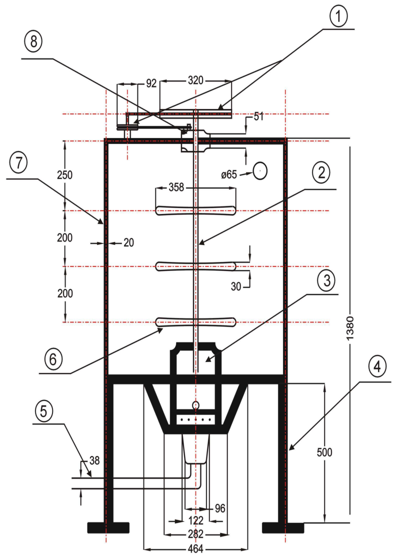

Figure (1-a) Agitation tank

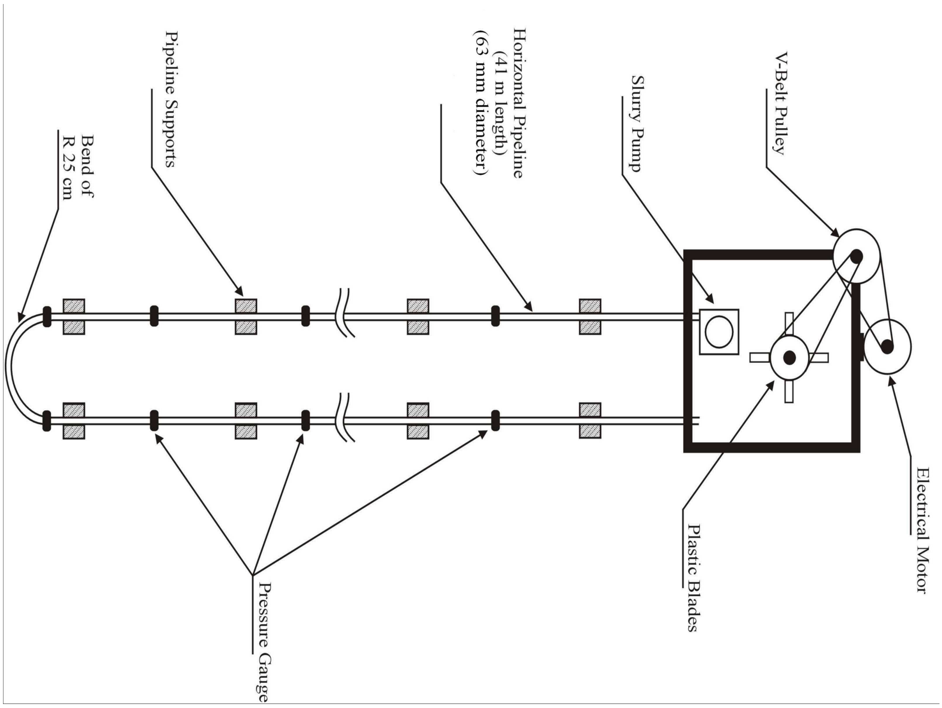

Figure (1-b) Transportation system.

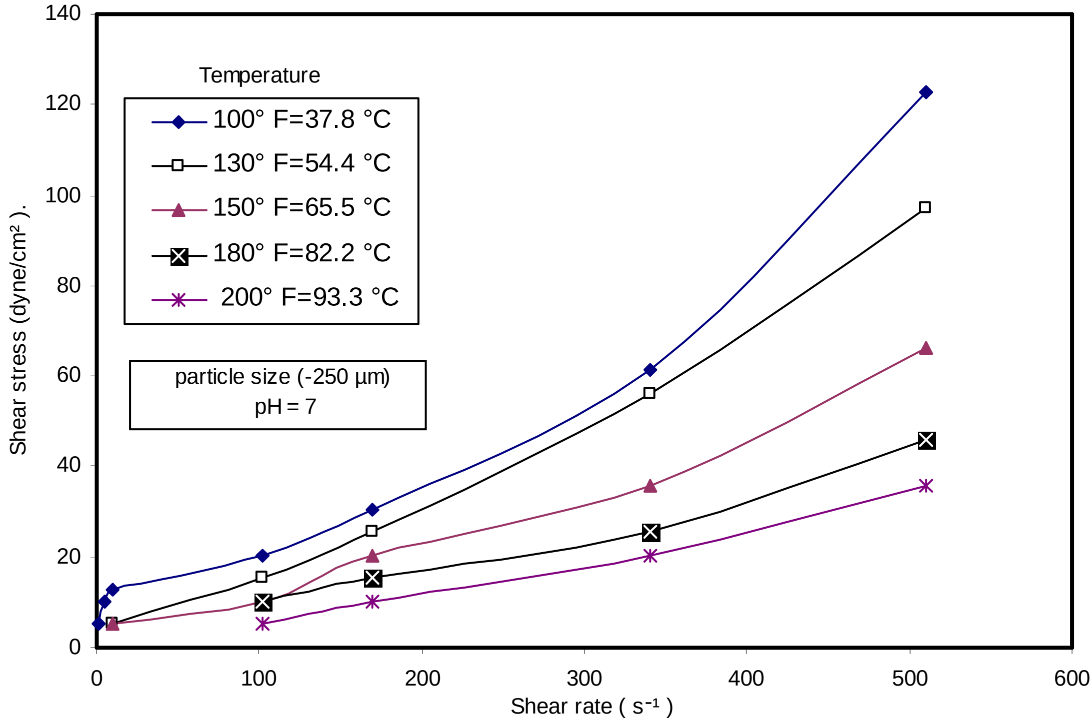

Fig.(2) Relation between shear stress and shear rate for (-250 µm) particle size sample at different temperatures and constant solid concentration of 40 %by wt.

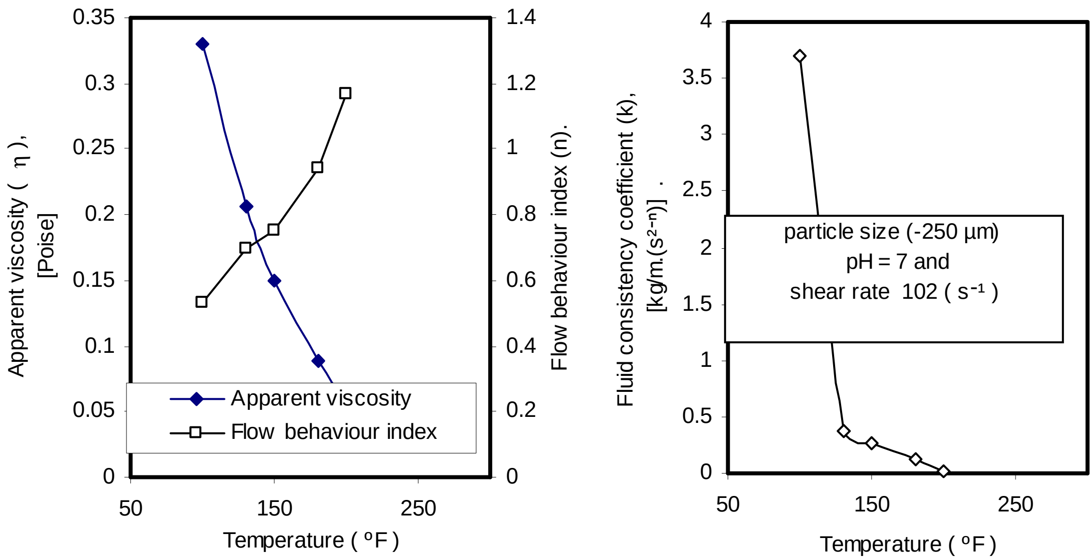

Fig. (3) Effect of temperature on apparent viscosity and non-Newtonian parameters for (-250 µm) particle size sample at 40% solid concentration by wt. pH = 7 and shear rate 102 (s^{-1})

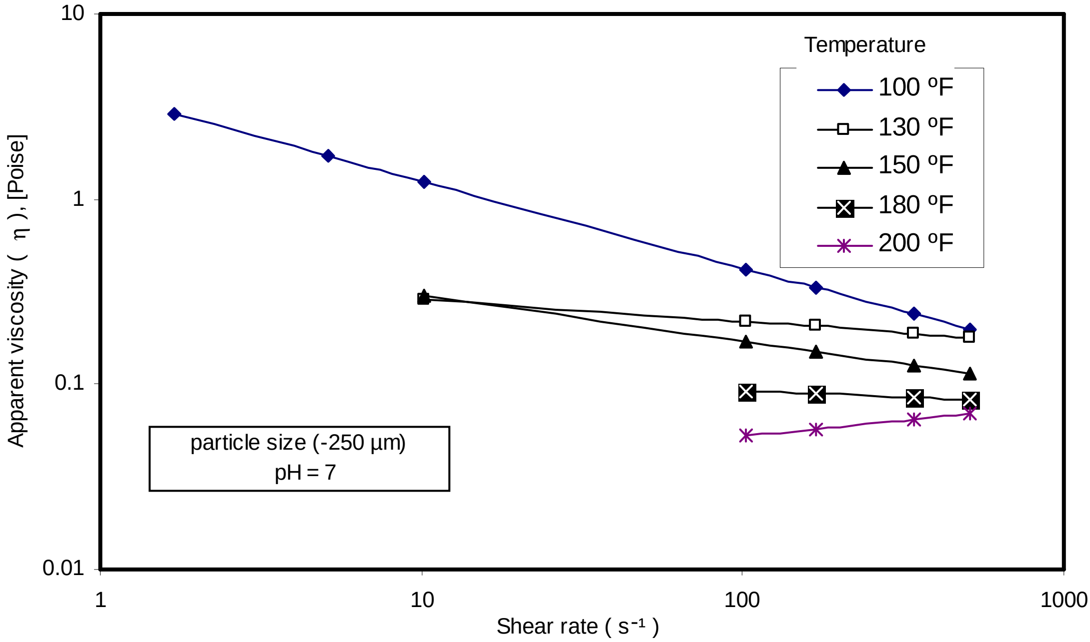

Fig. (4) Effect of trmperature on apparent viscosity for (-250 µm) particle size sample at 40% solid concentration by wt.

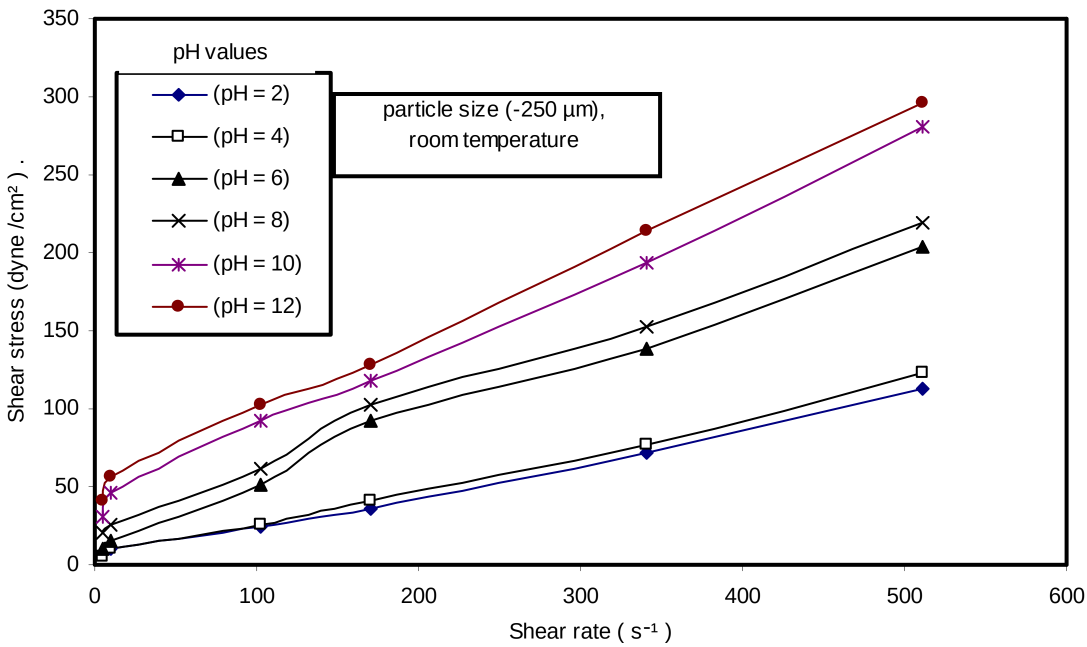

Fig. (5) Relation between shear stress and shear rate for (-250 µm) particle size sample at different pH, and constant solid concentration of 40 % by wt.

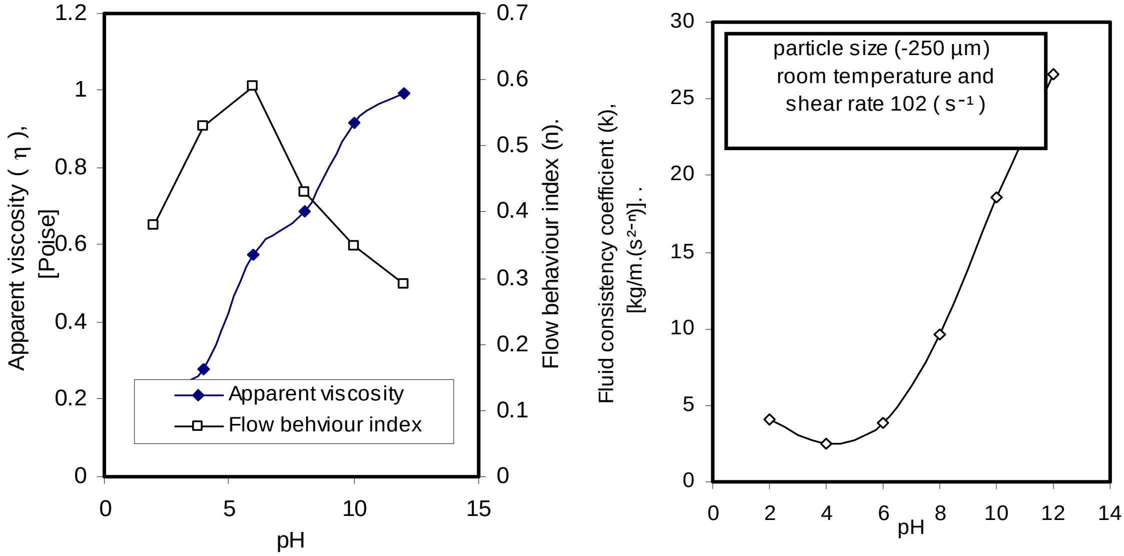

Fig. (6) Effect of pH on apparent viscosity and non-Newtonian parameters for (-250 µm) particle size sample at constant solid concentration of 40% by wt. at shear rate 102 (s^{-1}) and room temperature

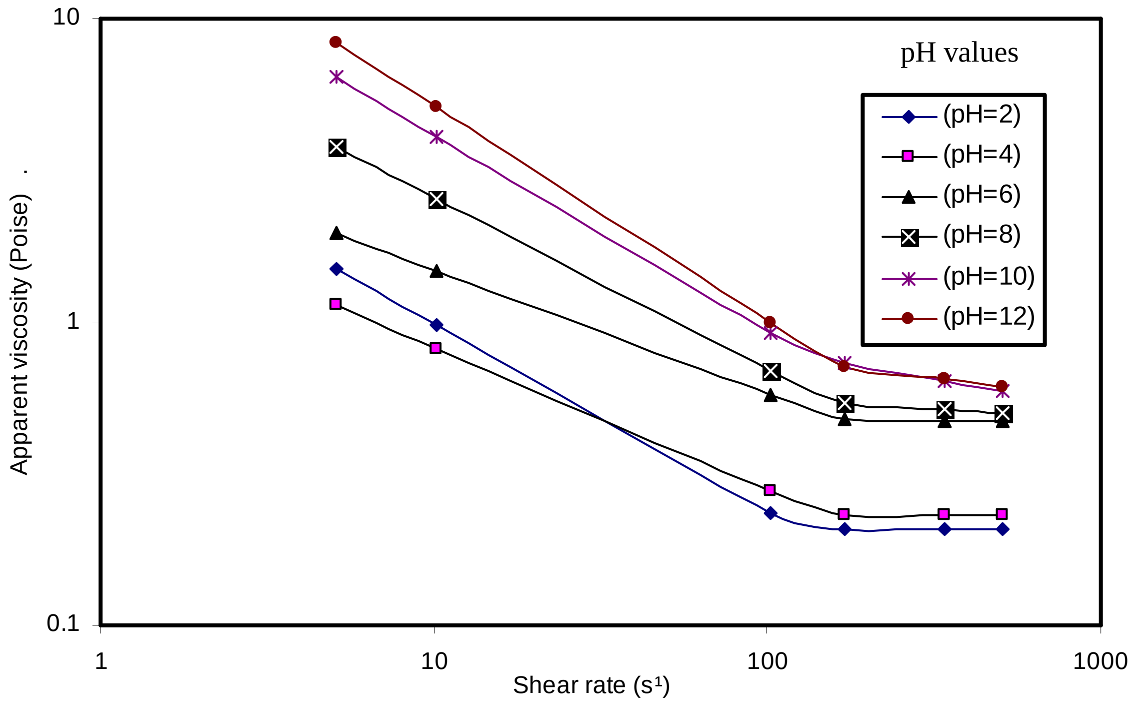

Fig. (7) Effect of pH on apparent viscosity for (-250 micron)coal slurry sample at different shear rates and at constant solid concentration of 40% by wt.

Effect of Coal Degradation

The transportation of solids by liquids in pipelines is applied nowadays throughout the world on a large scale. It includes long distance handling of coal, minerals, ore and solid commodities as well as collection and disposal of solid waste materials. It is often required to pump slurry over long distances through pipelines from storage to various processing units and / or from one plant site to another. The particle size distribution changes, to a large extent, during transportation of the slurry. Such change may result not only from impeller, pump and pipeline erosion but also from interparticle friction or collision between the solid particles. This will lead to change in the viscosity of slurry and cause a head loss.

It is interesting to illustrate the effect of transportation of coal water slurry in pipeline on the particle degradation and hence on rheology and pressure gradient. Experiments were carried out at constant coal concentration of 10% by wt., at room temperature and at pH = 7.

Figure (8) shows the particle size distribution for the coal water slurry before and after transportation. The considered transportation cycles were in the range 5-25 with each cycle has 41 m. total length. From this figure, it can be seen that, the particle size distribution changes with increasing transportation cycles (distance). The degradation % of coal particles was determined from the following relation.

Where d_{50} is the median size of sample, the median size d_{50} can be determined from the sample size distribution graph at 50% cumulative passing.

$$\text{Degradation \%} = \frac{d_{50}\text{ of original sample} - d_{50}\text{ of considerd sample}}{d_{50}\text{ of original sample}} * 100$$

Figure (9) shows the relation between degradation % and number of transportation cycles. The degradation % is very low and may be neglected up to 5 cycles and becomes significant at larger transportation cycles. Because the coal particle size becomes very small after 25 cycles, the energy required to break it is very high and hence the recorded degradation is negligible.

The shear stress / shear rate and viscosity of coal water slurry at different number of pumping cycles were studied using 3500 LS^+ rotational viscometer. These results are shown in Figure (10), and Figure (11). From these figures, it is clear that the shear stress and viscosity of CWS increase with increase pumping cycles.

Figure (12) illustrates the relation between pressure head in pipeline and relative transportation distance at different pumping cycles (i.e., from 5 to 25 cycles). The relative distance was estimated as a percentage from total pipeline length. From this figure, it can be seen that, the pressure in the pipeline decreases with increase of relative transportation distance, i.e, the pressure head loss increases. This result may be attributed to change in particle size distribution of the coal particles. With increasing transportation cycles (distance traveled) the particle sizes became smaller due to particle degradation occurred through transportation as shown from Figure (8). From previous results, it can be concluded that, the viscosity of the slurry increases with increasing pumping cycles as a result of increasing degradation %. This may be attributed to the increase in specific surface area with decrease average particle size, resulting in higher interparticle friction and hence higher viscosity.

Insignificant increases in pressure loss as a result of increasing degradation and viscosity with increasing pumping cycles are observed. The mathematical equations that relate viscosity, Reynolds number, head loss, flow rate and friction factor for Newtonian fluids in smooth pipes under laminar flow are previously mentioned. More detailed information about the subject is found elsewhere [10]. The transportation operations affect the particle size of transported slurry and consequently increase the value of slurry viscosity. Therefore, it is necessary to take into consideration in design of transportation pipeline systems that, the energy required to achieve this process should be higher than the theoretical value calculated from slurry properties before transportation. The pipeline designer should take into account this effect when choosing the system components, especially pumps. Pumps must be selected with high sufficient power to compensate such changes in the properties of slurry.

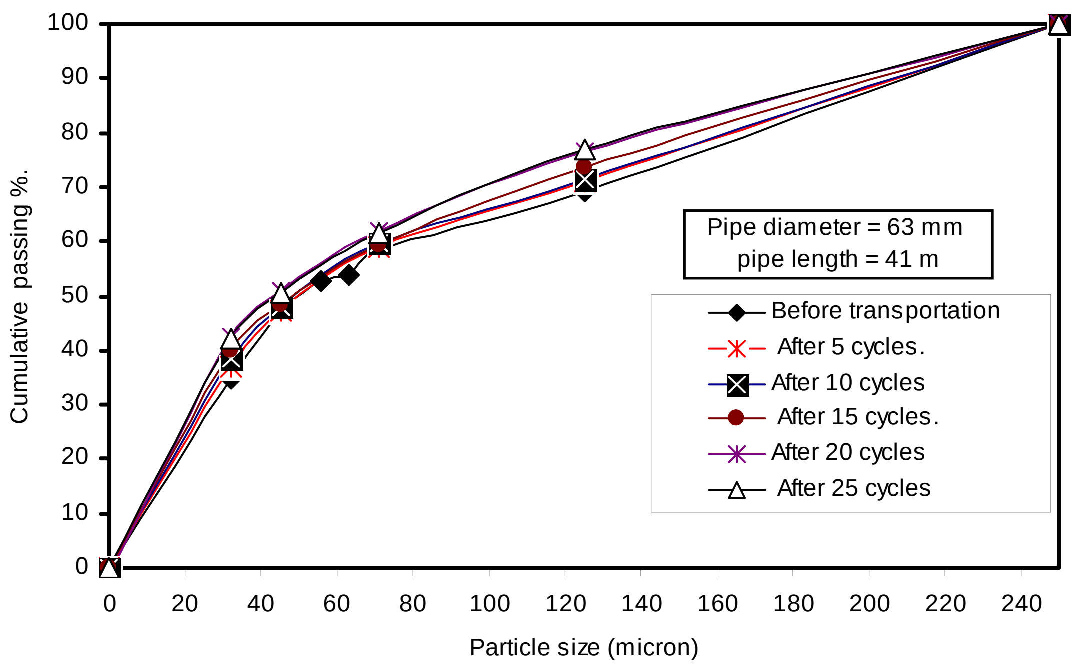

Fig. (8) Particle size distribution for (-250 μm particle size) CWS before and after transportation.

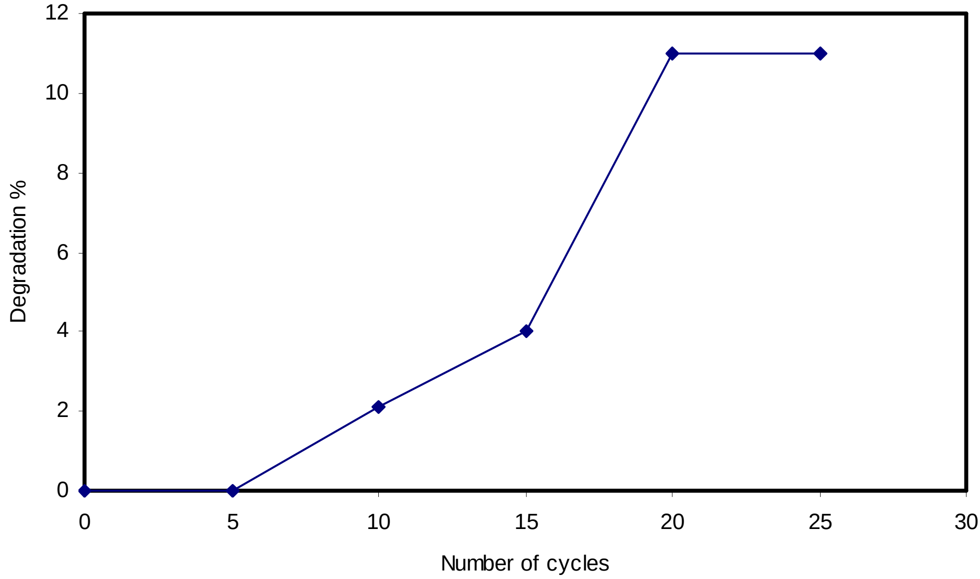

Fig. (9) Relation between number of cycles and degradation % for -250 micron particle size of coal at 10 % solid concentration by wt..

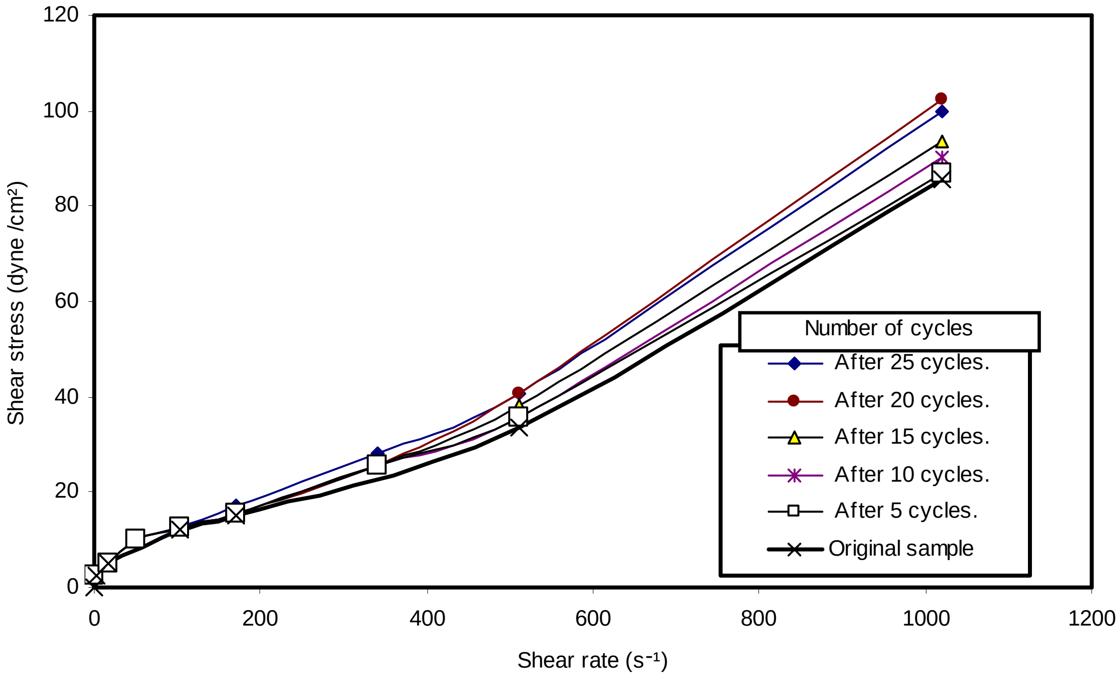

Fig. (10) Relation between shear stress and shear rate for -250 micron sample at differant number of pumping cycles (distance).

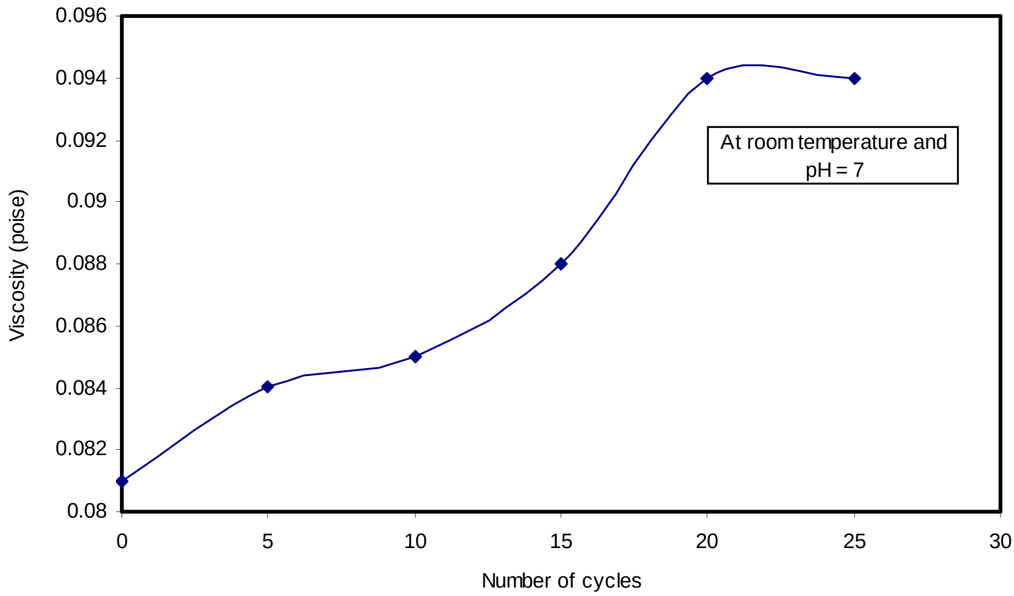

Fig. (11) Effect of number of cycles on viscosity of -250 µm particle size sample at 10% solid concentration by wt..

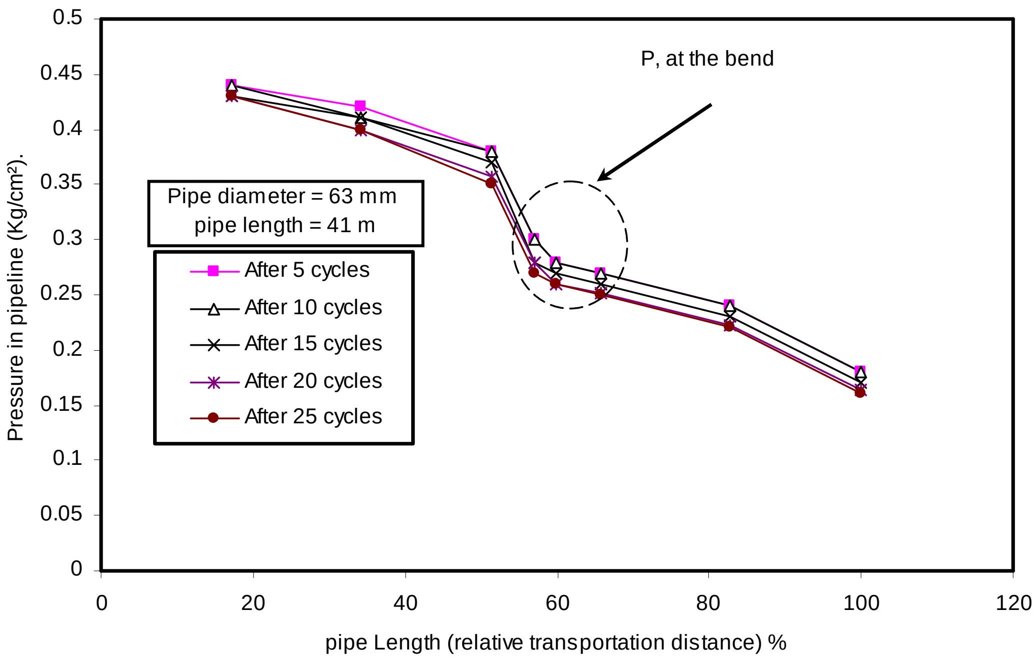

Fig. (12) Effect of transportation distance on pressure drop at different numper of cycles for (-250 micron particle size) at 10 % solids by wt.

CONCLUSIONS

The results of this study can give the following conclusions,

1. The apparent viscosity and degree of pseudoplasticity are sharply decreased with the increase of temperature. At temperature more than 180°F (≈ 82°C) the coal slurry exhibits Newtonian fluid behavior.
2. The apparent viscosity increases with the increase of pH. The degree of pseudoplasticity sharply decreases with the increase of pH in the range from 2 to 6, and sharply increases in the range from 6 to 12. At pH equals to 6, the coal slurry may be considered as a Newtonian fluid.
3. During coal slurry transportation, the size distribution of its solid component changes which, in turn, changes the slurry properties.
4. Coal degradation during coal slurry transportation must take into account. In this context, it was found that the viscosity of slurry and pressure drop increase with increasing degradation %. Therefore, it is necessary to take this effect into consideration in design of transportation pipeline systems. Applying energy higher than the theoretical value calculated from properties of slurry before transportation is highly recommended. The effect of particle degradation on rheology of mineral slurries, in particular, at coarse particle sizes must be investigated in future studies.

REFERENCES

1. Boylu, F. Dincer, H. anSd Atesok, G. "Effect of coal particle size distribution, volume fraction and rank on the Rheology of coal–water slurries". Fuel Processing Technology, 85 (2004), pp(241– 250).
2. Mosa E. S., Saleh. A.M., Taha. A.T. and El-Mola, A. M. "Effect of particle size and solid concentration on Rheology of coal-water slurries". Al Azhar Engineering ninth international conference, April 12-14, 2007, Vol. 2, No. 6 , pp (60-73).
3. Slaczka, A., and Piszczynski, Z., "The rheology of concentrated coal- water slurries" Al-Azhar Engineering Fourth Int. Conf., Dec. 16-19, 1995, pp (174-180).
4. Nam-Sun, R., Dea-Hyun, S., Dong-Chan, K. and Jong-Duk, K., "Rheological behaviour of coal-water mixtures" 1.Effects of coal type, loading and particle size", Fuel, vol.74, No. 8, 1995, pp (1220-1225).
5. Mosa E. S., Saleh. A.M., Taha. A.T. and El-Mola, A. M. "Effect of Bimodal/Trimodal size distribution on flow characteristics of coal-water Mixtures (CWM) ". Al Azhar Engineering ninth international Conference April 12-14, 2007, Vol. 2, No. 6, pp (45-59)
6. Shirley, C. T. and Everett, W. K., "Viscometry and rheology of coal water slurry" Fuel, Vol. 65, April 1986, pp (566-571).
7. Mingzhao, H., Yanmin, W. and Forssberg, E. "Slurry rheology in wet ultrafine grinding of industrial minerals: a review , Powder technology,. Vol. 147, November 2004, pp (94-112).
8. Huynh, L., Paul, J. and John, R. "The rheological properties of copper concentrate slurry: from surface chemistry to pipeline transport" 2001.

9. Daniel, W.. and Moncef, B. “The importance of online viscosity measurement for leak detection and other simulation application” Proceedings of IPC 2004 International Pipeline Conference, October 4 – 8 , 2004 , Calgary, Alberta, Canada.
10. Lester, C. B., “ Hydraulics for pipeliners ” Vol. 1, Fundamentals, Second Edition 1994, Chapter 3,4 (Newtonian viscosity and non-Newtonian).
11. Byron, R. B., Warren, E. S. and Edwin, N. L., “Transport phenomena” published by John Wiley Sons Inc., New York and London. 1960.
12. George R., Darley, H and Walter F. , Book in, “Composition and properties of Oil well drilling fluids”, Fourth Edition, 1984, Chapter (1, 2. introduction, 3. Evaluating drilling fluid performance, and 5. The rheology of drilling fluids), pp (3-239)
13. Abd El-Hafeez, G. , “Factors affecting coal degradation on transportation of coal-water slurries in pipelines” Msc. Thesis, Mining Engineering, Mining and Petroleum Department ,.Faculty of Engineering, Al-Azhar University, 1999.
14. Chandler engineering, L.L.C., 3500LS Direct indicating viscometer 2003/03/20 www.chandlereng.com

دراسة تأثير درجة الحرارة والأس الهيدروجيني و درجة التحتت على لزوجة أخلاط الفحم والماء

في هذا البحث تم دراسة تأثير درجة الحرارة والأس الهيدروجيني على لزوجة أخلاط الفحم والماء وذلك باستخدام الوعاء الحراري الملحق بجهاز الزوجة المستخدم وذلك عند درجات حرارة تتراوح بين 100 إلى 200 درجة فهرنهيت (37.8 إلى 93.3 درجة مئوية) وعند أس هيدروجيني يتراوح من 2 إلى 12 وتم قياس اللزوجة للأخلاط باستخدام جهاز قياس اللزوجة الدوار.

وقد وجد أن اللزوجة تقل بزيادة درجة حرارة الأخلاط. وقد لوحظ أنه عند درجات الحرارة العالية، أعلى من 180 درجة فهرنهيت (82.2 درجة مئوية) أن الأخلاط تتبع في سلوكها قانون نيوتن للزوجة. وقد وجد أيضا أن اللزوجة تزداد بزيادة الأس الهيدروجيني وعند أس هيدروجيني يساوى 6 وجد أن الأخلاط تتبع في سلوكها أيضاً قانون نيوتن للزوجة.

وقد امتدت الدراسة لتشمل تأثير نقل الأخلاط في خطوط الأنابيب على اللزوجة. وقد وجد أن لزوجة أخلاط الفحم والماء تزداد بزيادة مسافة النقل (أي بزيادة عدد دورات الضخ). ويعتقد أن يكون ذلك نتيجة زيادة المساحة السطحية للجزيئات والناشئ من تحتت هذه الجزيئات والذي يؤدى بدوره إلى زيادة الفقد في الضغط.

وعلى ذلك يوصى بأخذ درجة تحتت الجزيئات في الاعتبار عند تصميم أنظمة النقل الهيدروليكي للأخلاط.