

# The Effects of Particle Size on the Wettability of Akwuke Coal Using Continuous Flow Technique

Gbasouzor Austin Ikechuku

**Abstract** – An investigation of the displacement of air by de-ionized water in a packed bed of Akwuke coal powder was studied using seven powder size ranges at ten liquid flow rates. The external liquid pressure heads,  $h$  were measured as a function of time, therefore, the maximum capillary pressure heads,  $h_c$  at which liquid penetration into the powder bed occurred were determined from the graphs of capillary pressure head against time. Using the values of  $h_c$  and the corresponding flow rates,  $q$ , for each of the samples, graphs of  $h_c$  against  $q$ , were also plotted by method of regression analysis, the lines were produced to cut the maximum capillary pressure heads,  $h_c$ , axis. The corresponding values of  $h_c$  at zero liquid flow rates were respectively determined and taken as the breakthrough pressure heads,  $h_{bc}$ . Using the  $h_{bc}$  and the other measurable quantities the contact angles of water on the beds of the particles was calculated. The corresponding values of the interface free energies (surface tension) were determined from the standard tables of contact angle/surface tension. The result shows that there is a strong dependence of the wettability of the coal particles on particle size.

**Keywords:** Wettability of coal particles, capillary pressure head, particle size, surface tension, contact angle.

## I. INTRODUCTION

The wetting behaviour of any substance depends largely on its forces of adhesion and cohesion. These forces have to do with the surface tension as well as the contact angles of the wetting liquid. On the whole, the term wettability simply refers to the ability of any given liquid to soak or moisten a known solid substance. Any liquid whose forces of cohesion are greater than the adhesive force will remain non-wetting (hydrophobic) on the solid. The difference in the wetting characteristics of different substances partly calls for the wettability study of various liquids on some solid substances.

Usually the degree of wetting explained as change in free surface energy of a unit area of a solid, which occurs when it comes into contact with a specific liquid, depends on the liquid used. It is common practice to talk of interfacial energy in wettability study. In reality what is meant and measured by experiment is the interfacial free energy,  $Y$ . The free energy of a system containing an interface of area  $A$  and free energy per unit area may be taken as for example.

$$G = G_o + AY \quad (1)$$

Here  $G_o$  represents the free energy of the system assuming that all materials in the system have the properties of the bulk.  $Y$  is, therefore, the excess free energy arising from the fact that some material lies in or close to the interface. It is also the work that must be done at constant temperature and pressure to create unit area of interface [2].

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It is known that surface tension, the force tending to reduce the area of liquid at the interface to a minimum, only acts at the interface. By definition, the surface tension is a name given to the force acting on unit length of the perimeter of the area, this force being normal to the perimeter and tangent to the interface [3].

In this wettability study, a lot of factors upon which wettability depends come into play. These factors include the porosity of the material, specific surface area, the contact angle  $\theta$  and the corresponding interfacial free energy,  $\gamma_{LV}$  read off from the standard table of contact angle/surface tension [4].

The continuous flow (C.F) technique is adopted for the study of fluid displacement process in porous media of Enugu Coal particles. The primary object of the study is actually to determine whether particulate sizes have any effect on wettability and on the surface tension values. In the course of the experiment, water is constantly admitted into an inter-connected metering set of apparatus at predetermined steady flow rates. The advancing liquid is diligently monitored as soon as contact with the packed coal powder bed is established. The pressure needed for the liquid to penetrate the powder is noted at intervals. Worthy of note is the fact that the pressure head ( $h$ ) increases with the hydrophobic (non-wetting) fluid until the liquid commences its penetration into the powder bed, the said pressure shortly becomes steady after the de-ionized water first permeates through the powder bed of each of the particle (powder) sizes. It is however, this steady pressure that is interpreted in terms of the wettability of the coal powder used.

### A. Industrial Benefits of the Wettability Study

In coal industries, coal fines (particles) are usually generated during the transportation (in the conveyors) and also in company of undesirable gang materials associated with the coal mined. Not only are the generated coal fines wasted since no attention is paid with respect to finding a means of recovering them but they also constitute industrial pollution and hazard to people. It is, however, of interest to note that these fines can be of considerable use in our various industries and companies. By studying the wettability of coal at varying liquid media, factors such as the breakthrough pressure, contact angle and the interfacial free energy that could lead to the regaining of the fines are brought to limelight. This helps to determine the liquid that will be used in recovering the coal fines at cheaper rate since the energy required for the recovery is different for different liquids.

The stringent environmental regulations on pollution, the increasing coal demand and its subsequent price increases, and of course other economics challenges have made the recovery of coal particles and their usage absolutely necessary in the developing countries. In advanced countries, efforts are usually geared towards the recovery and continuous use of coal fines and fuel oils in

burners of their metallurgical furnaces. Worthy of note is the fact that coal oil and coal dispersion always remain in suspension under different storage and transportation conditions, and also during utilization. Knowledge of this study can as well be employed in beneficiation of materials.

The wettability study of Akwuke coal will, in brief, afford the corporation the opportunity of recovering the coal fines as well as using the result of the process for coal powder, coal oil and of course coal water dispersion in burners of their furnaces. It is, however, no gainsaying that the idea could be sold to other corporations and allied industries where burners are used to generate heat for the furnace. The introduction and subsequent use of the coal fines in heating will no doubt, reduce the coast of heating in the industries to the barest minimum, and in the end step up the finance. This is because the cost of transporting the coal fines to the industries where they are utilized is much less than that of the actual coal lumps which occupy a lot of space. Owing to the competences of the coal fines, the size of the burner will also be cheaper than that used for coal lumps.

In this study the relationship between the particle size and the surface tension were looked at to determine the effect of the particle size of the coal to be recovered on the wettability.

## II. REVIEW OF CONTACT ANGLE MEASURING TECHNIQUES OF POWDER FOR IRREGULAR PARTICLES

### A. Qualitative Methods

The measurements of the contact angle of irregular particles are extremely tedious. To this end, the measurement is qualitatively tested.

To carry out this test, the powder is dusted on the surface of the liquid medium used. One or two things are noticed: the time interval required for the powder to sink is related to the contact angle; the smaller the time when the powder sinks, the smaller the contact angle while the longer the times, the larger the contact angle. However, if care is not taken, the particle probably gets to the liquid surface as aggregates or as small loose pile.

Sinking of the powder assumes a different trend when loose piles are formed. Here the sinking process is usually the capillary penetration of the liquid into the pile. That is the liquid gradually permeates through the powder until finally the powder sinks. If the contact angle is relatively small, the powder pile sinks easily whereas if the contact angle is large, it becomes difficult for the powder to sink. Owing to the difference in the rate at which the powder sinks as a result of the difference in the contact angle of the powders, it becomes necessary to compare the mobility of different powders in a stream of air directed obliquely at the surface of the liquid. This comparison being done, it is always found that the larger the contact angle, the higher the mobility since with larger contact angles, the powder particles are less deeply immersed, and less work done also against the viscous drag of the liquid. On the other hand, if the contact angle is small, the movement of the particles on the liquid surface becomes very small and slow. In this case the powder particle becomes deeply immersed in the liquid at relatively short interval: the work done against the viscous drag of the liquid here being very large.

### B. Quantitative Method

Some other methods other than the qualitative method can be used in measuring and testing the wetting behaviour of a substance. This method, the quantitative method, border on four basic systems of approach, these are the application of: Pressure of displacement, rate of capillary penetration, direct measurement of compressed powders and liquid intrusion.

### C. Pressure Of Displacement

The contact angle,  $\theta$  can be determined when the pressure required to balance the Laplace pressure that is responsible for driving liquid into a capillary bed is measured. It is this pressure that is charged with the actual penetration of liquid, knowing the effective pore radius,  $r$  and the surface tension of the liquid used, the equation below is used for determining  $\theta$ , [7]

$$\Delta P = \frac{2\gamma_{LV}}{r} \cos\theta \quad (2)$$

One of the limitation of this method stems from the fact that the effective pore radius,  $r$  is not constant from point to point in the packed powder bed.

### D. Rate of Capillary Penetration

In this method, use is made of the capillary driving force for a cylindrical tube having radius,  $r$  in conjunction with the equation of viscous drag under conditions of steady flow for the determination of the contact angle,  $\theta$ . This method however, uses the unopposed penetration of a liquid into the powder.

However, where the capillary tube is vertical, that is erect, gravity opposed the liquid flow and the effect of gravity is also considered. According to [11], the equation for the rate of penetration,  $dh/dt$  becomes,

$$\frac{dh}{dt} = \frac{r^2}{8\mu h} x(2\gamma_{LV} \cos\theta - \Delta\rho gh) \quad (3)$$

Where  $\mu$  is the Viscosity,  $\Delta\rho$  is the difference in density between the liquid and the surrounding medium and  $h$  is the height of penetration at time,  $t$  the effective capillary radius used in determining  $\theta$  is usually obtained by making the same measurement above with a liquid that has a zero contact angle ( $\theta = 0$ ), taking the penetration process and the pore structure to be same in the runs with varying liquids.

It is of interest to note that when capillary tube or the powder bed is horizontal, that gravitational force has no influence on the flow. Consequently, the gravity term in equation (3) becomes zero ( $\Delta\rho gh = 0$ ). Another case where this gravity term can be neglected even though the powder bed may be vertical is when the pore radius is very small. In both cases when  $\Delta\rho gh$  is assumed zero, then equation (3) reduces to

$$\frac{dh}{dt} = \frac{\gamma_{LV} \cos\theta}{4h\mu} \quad (4)$$

Worthy of note once again is the fact that the dependence of the rate of penetration,  $dh/dt$  on  $r$  is not the same for equations (3) and (4). This difference in the dependence on  $r$  simply indicated that whenever the two terms in the parenthesis in equation (3) that is

$$\frac{(2\gamma_{LV} \cos\theta - \Delta\rho gh)}{r}$$

are of about the same value, it then becomes necessary to employ a combination of measurements with the horizontal and

vertical powder beds in the determination of the contact angles.

However, since  $r$  changes from point to point in the powder bed the rate of penetration  $dh/dt$  has to correspond to the average value of  $r$  instead of representing this, [4] substituted a "tortuosity constant"  $k$  in equation (4). Hence

$$\frac{dh}{dt} = \frac{K\gamma_{LV} \cos\theta}{r} \quad (5)$$

Here  $K = \frac{r}{4M}$

From the equation (2) and (5), re-arranging therefore,

$$\theta = \cos^{-1} \left[ \frac{4h\mu}{r\gamma_{LV}} - \frac{dh}{dt} \right] = \cos^{-1} \left[ k \frac{h}{\gamma_{LV}} - \frac{dh}{dt} \right] \quad (6)$$

*E. Direct Measurement On Compressed Powders*

Direct measurement of contact angle on compressed powders involves the use of compressed powder cake with a flat upper surface. A liquid whose contact angle is sought is deposited slowly on the cake, the rate at which the liquid is absorbed is noted. This gives the indication of the magnitude of the contact angle. If the contact angle is high, the liquid drops on the compressed powder cake remain stable; on the other hand, if the contact angle is low, the liquid instantly begins to penetrate into the powder.

The essence of measuring the contact angles on powder is chiefly to predict and control the penetration of the liquid into the powder bed or alternatively to predict and control as well the dispersion of the powder in the liquid.

III. THEORY OF CONTINUOUS FLOW TECHNIQUE

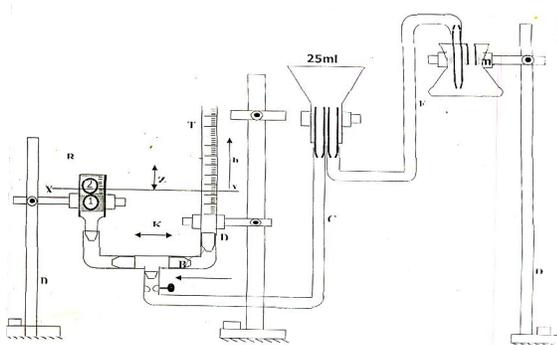


Fig. 1: Apparatus for Continuous Flow Technique

The diagram above (fig. 1) in the experimental set-up of a fluid/fluid displacement process for the continuous flow method, with the data generated by the use of the apparatus and some other materials, the contact angles and their corresponding surface tension are determined.

The set-up consists of a glass tube R, a Tee-capillary tube k, a capillary tube T, transparent flexible rubber hoses C,D,F a screw clip B two conical flasks U, a plastic plunger.

The glass tube R and a glass capillary tube T are connected at both ends of the Tee-capillary glass K by the use of flexible rubber hoses D. The tube R and capillary tube T both held firmly upright using retort stands, at the tall end of the tee-glass tube is connected a long transparent flexible rubber hose C. the other end being connected to one

inverted conical flask through a short capillary glass, N fitted to the flask rubber-cork. The two conical flasks are respectively held strongly in position with two retort stands, the feeder flask (receiver) being clamped erect, little above the inverted one.

*A. Loading of Powder/Fluid Flow*

A measured quantity (mass)  $m$  of the coal powder is fed into the glass tube R of uniform cross-sectional area, A; and compressed with the perforated plastic plunger to a thickness L. the de-ionized water (1), and incompressible fluid and still immiscible with air (fluid (2)), is allowed to advanced towards the bottom end of the powder bed at a pre-determined, steady flow rate  $q$  (ml/min). the bottom end of the powder bed in tube R is aligned with the zero mark on the capillary glass tube T such that at time  $t = 0$ , the water level in both tubes is at x-x level. At this point, contact is made between the liquid front and the bottom end of the powder bed.

*B. Determination of Liquid Flow Rate*

After each run of the experiment, a suitable fluid flow rate, each,  $q$  is re-determined by adjusting the screw-clip S, the volume (discharge) Q that passed the flexible hose section in a given time,  $t$  is collected with a graduated measuring cylinder, the time,  $t$  is taken using a stopwatch, the flow rate is ,then evaluated using the equation

$$q = \frac{Q}{t} = \frac{(ML)}{(\text{min})} \quad (7)$$

*C. The trend of fluid behaviour in contact with the powder bed*

It is of interest to state that at times, when contact is established between the liquid front and the powder bed at the x-x level, liquid penetration into the powder does not occur immediately as one would expect. This behaviour is evident when the displacing fluid (water) does not wet the saturated powder bed. In this circumstance, the pressure needed to counter-balance the pressure due to capillary and to subsequently cause initial fluid penetration into the porous medium (the compressed coal powder). This being the case, the de-ionized water flows preferentially into tube I pending when a pressure head  $h$  sufficient to initiate liquid penetration into the powder bed is reached.

When the fluid (1) permeates the powder bed, fluid (2), air, within the pores is displaced upwards against gravitational pull. The reason for the upward displacement  $f$  air is that capillary forces are no longer enough to sustain the pores laden with air (fluid (2)) at the bottom end of the powder bed. As a result of the imbalance in pressure, the fluid/fluid front advances through a distance  $z$  into the compressed powder in time  $t$ .

The aforementioned is just the one characteristic trend of liquid penetration into the, powder bed. In the second case, liquid penetration into the powder bed is spontaneous. When the liquid level is at x-x level, at zero time interval ( $t = 0$ ) the negative capillary pressure induces a sudden liquid suction, triggering a reversal of the usual liquid front into tube T. as a result of this fluid (2) is displaced upwards a distance  $z$  in time  $t$ / its position being filled with the liquid. While this happens, the liquid level in tube T falls a distances  $h$  below x-x in the same time interval, the upward movement of the liquid and the subsequent displacement of air continues until the capillary pressure responsible for the

movement of the fluid/fluid interface is counter-balanced by an external pressure head in tube T. at this point, the liquid level in tube T reverses and starts to rise.

#### D. Assumptions made:

Given below are some of the basic assumptions made prior to the derivation of the macroscopic equations of motion of fluid/fluid interface.

- The particles are randomly distributed.
- The packing geometry is not displaced by the penetrating
- The wetting fluid is uniformly and steadily displaced by the non-wetting fluid.
- No mixing occurs at the fluid/fluid interface.

It is of interest to note that all the four basic assumptions given are not rest assured [8].

#### E. Equation of Motion of Fluid/Fluid Interface

By employing Darcy's law to both sides of the fluid/fluid interface, the pressure drop due to the fluid flow is given by

$$\Delta P_d = \Delta P_1 + \Delta P_2 \quad (8)$$

Where

$$\Delta P_1 = \frac{-\mu_1}{k_1} \xi S_1 z \cdot \frac{dz}{dt} \quad (9)$$

$$\Delta P_2 = \frac{-\mu_1}{k_2} \xi S_1 (L - z) \frac{dz}{dt} \quad (10)$$

Equations (9) and (10) are never stated without some basic assumption made. They assume,

- That Reynolds number is small
- That energy given out at the entrance to the porous powder bed as well as at the fluid interface is negligible;
- That there is no fluid circulation in the porous medium.

Similarly the pressure drop,  $P_g$  due to the gravitational forces on either side of the interface is given by

$$\Delta P_g = \xi S_1 g P_1 z + \xi S_2 g P_2 (L - z) \quad (11)$$

Where  $\xi$  = porosity of particle  $S_1$  and  $S_2$  = specific surface area of fluid (1) and (2)  $z$  = Distance moved by fluid in tube R.

In a similar vain, the external pressure and the capillary pressure are respectively given by

$$P_e = \xi S_0 g p \quad (12)$$

$$P_c = S_1 S_2 (1 - \xi) \gamma_2 \text{Cos} \theta \quad (13)$$

The sum of all the resultant pressure drops stated above equals the rate of change of momentum (inertia force). This implies that, for force balance:

$$\Delta P_g + \Delta P_d + \Delta P_c - \Delta P_e = \xi S_1 P_1 (z + e) + \xi S_2 P_2 \left[ (L - z) \frac{d^2 z}{dt^2} \right] \quad (14)$$

Where  $L$  = compressed powder thickness

$$e \approx \frac{D}{5}$$

Which takes care of the initial wetting of the bottom of the powder bed [9].

$D$  = the particle diameter.

The pressure drops across the capillary tube, the valve B, the perforated disc and filter papers are neglected.

Considering the above, therefore, the equation for mass balance in the tube R and T and the valve B is given by (13b)

$$\frac{dh}{dt} = \frac{q}{a} - \frac{\xi SA}{a} \cdot \frac{dz}{dt} \quad (15)$$

Nevertheless, where the breakthrough pressure head  $h_o$  is experimentally obtained, the equation below

$$h = P_1 g h_d s_0 \left[ \frac{(1 - \xi)}{\xi} \right] \gamma_{12} \text{Cos} \theta \quad (16)$$

is used to determine the wetting characteristic of particulate materials. This simply gives the indication that since other variables in the equation, viz  $\gamma_{12} \rho \cdot S \cdot \xi$  can be quantified, and  $h_o$  determined experimentally, the contact angle,  $\theta$  can as well be found from equation (16). The specific surface areas,  $S_o$  is obtained from the equation

$$S_o = \frac{6}{D} \quad (17)$$

Where  $D$  is the powder particle diameter in microns

$$\xi = \frac{A_z - \frac{m}{P}}{A_7} \quad (18)$$

#### F. Experimental

The Akwuke coal sample was chosen for this wettability study. The sample was washed, air-dried in an oven at an average temperature of 80°C for two days, the essence being to eliminate the moisture content of the coal. The sample was of varying size ranges of 55µm, 63µm, 71µm, 100µm, 125µm, 160µm, and 200µm. Table 1 is the chemical analysis of the washed coal sample of the coal preparation plant (CPP) Enugu.

Prior to the experiments, the inner wall of tube R was coated with thin film of candle wax to prevent preferential wetting of the glass tube walls and hence of the powder particles nearest to the tube wall. A perforated plastic disc, covered with a filter paper was inserted at the bottom end of the tube R.

This order was continuously repeated each time the experiment was to be performed. Then, a known sample mass,  $m$ , was diligently added while the tube was gently and continuously tapped by the sides. Using a flat ended perforated plastic plunger, the powder was gently compressed to form a stable particle bed of height,  $Z_o$ .

The tube was then put in place, vertically, as shown in the set up, Fig. 1 with the two perforated plastic discs consisting constraints at both ends of the powder bed. A stop watch was used for the timing of the fluid flow in the capillary tube.

The liquid height (otherwise referred to as the external pressure head)  $h$  was read off from the graduation on the capillary tube. On each of the experiments, the external pressure head,  $h$ , was measured as a function of time,  $t$ , for each flow rate.

The generated data are shown in the appendix for the seven coal particle size ranges at ten liquid flow rates. On the whole, seventy experiments were performed.

Table 1: Chemical Analysis of Washed Akwuke Coal

Proximate Analysis (%W)

	As Received	Dry	Dry Ash Free
Total moisture	9.0	-	-
Ash	8.5	9.5	-
Volatile	37.6	41.3	45.6
Fixed carbon	44.8	49.2	54.4

Ultimate Analysis (%w)

	As Received	Dry	Dry Ash Free
Carbon	65.4	71.9	79.4
Sulphur	1.6	-	-
Hydrogen	-	0.68	0.75
Nitrogen	0.52	1.8	1.9
Oxygen	-	-	-
Phosphorus	0.007	0.008	0.008
Chlorine	0.03	0.03	0.04
Carbon Dioxide	0.35	0.038	0.042
Mineral matter	9.5	10.4	11.5

Gross Calorific Value

	As Received	Dry	Dry Ash Free
Kcal/kg	6480	7120	7860
KJ/kg	27130	29810	32910

Net Calorific Value

Kcal/kg	6480
KJ/kg	16000
BTU/lb	11180

Ash Analysis (%W)

S <sub>1</sub> O <sub>2</sub>	62.5
Al <sub>2</sub> O <sub>3</sub>	29.0
FeO <sub>3</sub>	3.5
T <sub>1</sub> O <sub>2</sub>	2.1
CaO	0.3
K <sub>2</sub> O	0.6
Na <sub>2</sub> O	0.1
BaO	0.1
MnO	0.05
P <sub>2</sub> O <sub>5</sub>	0.1
SO <sub>3</sub>	0.05

Fusibility of Ash (°C)

Deformation Temperature	1400
Hemisphere	++
Flow	+

Petrographic Analysis

Vitrinite	%	52
Exinite	%	7
Inertinite	%	41
Mean maximum reflectance of vitrinite		0.5

Coking Characteristic

B.S swelling Index	1
Cray-king coke type	C

Dilatometric Properties

Softening Point °C	365
Reconsolidation point °C	475
Softening range °C	115
Contraction %	20
Dilation %	0
Plasticity from °C to °C	Not measurable
Max fluidity Div/min	0.5
Temperature (°C)	380

Other Properties

Specific gravity	1.3
Hardgrove Grindability Index	39
Rank (NCB)	802

Table 2: Properties of Materials

Coal particles size (µm)	Density, ρ (kg/m <sup>3</sup> )	Height of powder Z(cm)	Specific surface areas S <sub>v</sub>	Mass M(g)	Surface Tension N/m	Viscosity μ (poise)	Porosity Σ
55µm	1300	1.49	109090.91	6	-	-	0.4198
63µm	1300	1.49	95238.10	6	-	-	0.4184
71µm	1300	1.49	84507.04	6	-	-	0.4199
100µm	1300	1.50	60000	6	-	-	0.4202
125µm	1300	1.50	48000	6	-	-	0.4201
160µm	1300	1.50	37500	6	-	-	0.4203
200µm	1300	1.50	30000	6	-	-	0.420
Distilled water	100	-	-	-	72	0.00895	-

## IV. RESULTS AND DISCUSSIONS

### A. Experimental results

The results generated from the seventy experiments performed are shown in Figures 2 to 8 in the graphs of the capillary rise,  $h$ , against time ( $t$ ). In a similar vein, figure 9 to 15 show the graphs of maximum capillary pressure ( $h_c$ ) against the liquid flow rate  $q$  for the seven particulate size ranges of sample.

It is interesting to note that the breakthrough pressure head,  $h_0$ , the pressure at which the liquid penetration into the powder bed first occurred, was got by linear regression analysis. The regression line was extrapolated until it cut the maximum capillary rise,  $h_c$ , axis at liquid flow rate  $q = 0$ .

The results for the displacement of air by de-ionized water in a bed of Enugu coal particles are shown in figures 2 to 8 for ten liquid flow rates namely,  $q = 0.27, 0.33, 0.42, 0.47, 0.53, 0.58, 0.6, 0.72, 0.80, \text{ and } 0.92$  ml/min. the said figures revealed that, as contact was made between the bottom of the particle bed and the on coming liquid front, no liquid penetration into the powder bed took place. Rather than penetrate the particle bed, the liquid flowed into the capillary tube,  $T$ , the external pressure head,  $h$ , continued to rise until equaled the critical (maximum) pressure head,  $h_c$ , that is  $h = h_c$  at time  $t = t_c$ , at which time the pressure head was adequate to cause fluid penetration through the pores within the first layers of the powder bed at the bottom end of the powder bed. The water in the capillary tube then displaced the air in the packed bed upwards against gravity. The reason for the upward displacement of the air was that the forces of capillary were no more enough to sustain the pores at the bottom end of the powder bed saturated with air.

### B. Wettability of Particles

For the wettability investigations on coal particles, consider the results for coal/de-ionized water system shown figures 2 to 8. from the figures, the maximum values of the external pressure head ( $h_0$ ) at which liquid penetration occurred into

the powder bed were determined and taken as corresponding to the breakthrough pressure head and plotted as a function of liquid flow rate in figures 9 to 15 by mere extrapolation, the values of  $h_c$  at zero liquid flow rate given as  $h_o$  as shown were obtained by linear regression analysis.

Using equation 17 and 18, the specific surface area,  $S_o$ , and the porosity,  $\Sigma$  were respectively obtained for the seven particulates sizes of the coal. The value corresponding to the capillary pressure for each particulate sizes was used in conjunction with equation 16 to calculate the contact angle,  $\theta$  of water on the individual particle.

The contact angle data obtained for all the particle sizes and their corresponding surface tension values read off from standard table of surface tension/contact angle [4] for comparison with values quoted by Vargha-Butter et al [10].

Determination of the Breakthrough Pressure ( $H_o$ ) and Its Coefficient of Correlation (Reliability)

The breakthrough pressure  $h_o$  is determined by getting the maximum capillary pressure head ( $h_o$ ) at which liquid penetration occurred into the powder bed from the graphs of  $h_c$  against liquid flow rate  $q$  (Figs 2 to 8).

Using the linear regression equations, the constants 'a' and 'b' are determined and thereafter substituted back into equation 19.

$$h_c = a + bq \quad (19)$$

By mere use of equation 19, a straight line graph is produced. See figures 9 to 15. This line is then extrapolated to cut the  $h_c$  axis at zero liquid flow rate ( $q = 0$ ). The point at which the regression line cuts the  $h_c$  axis is taken to be the breakthrough pressure head  $h_o$ . It is worthy of note that the constant 'a' at zero liquid flows rate (equation 19), that is

$$h_{o_c} = a = h_o \text{ at } q = 0.$$

The least square method otherwise known as the regression analysis is employed to eliminate the need for individual judgment in obtaining the line of best fit for the given set of experimental data points plotted for each particulate sizes.

The correlation factor ( $r$ ) of the data points generated and hence the straight line obtained for each particulate size is determined using the linear correlation equation. On the whole, the points are seen to have very good correlation coefficients and are, therefore, reliable. Of the coal particle sizes, the 100 $\mu$ m size has the best correlation coefficient of 0.984 with 50.44mm breakthrough pressure head, followed by the 200 $\mu$ m particle size which has 0.957 correlation coefficient and 31.3mm breakthrough pressure head.

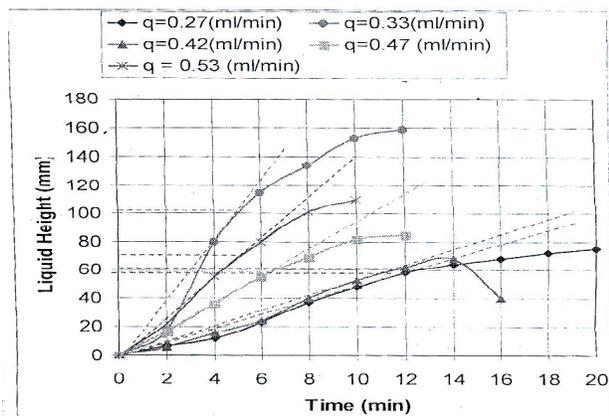


Fig. 2: 55 $\mu$ m coal particle/de-ionized water

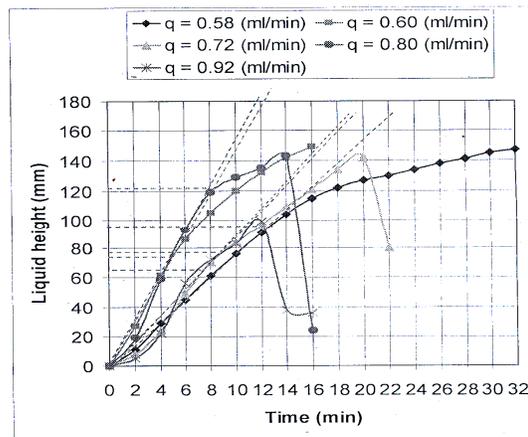


Fig. 3: 55 $\mu$ m coal particle/de-ionized water

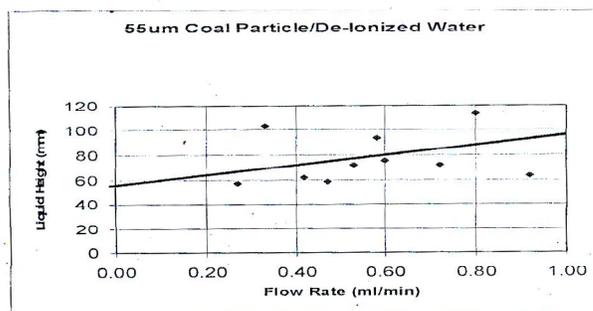


Fig. 4: 55 $\mu$ m coal particle/de-ionized water

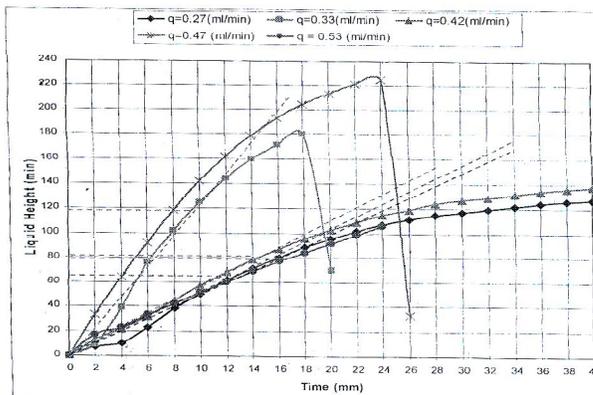


Fig. 5: 63 $\mu$ m coal particle/de-ionized water

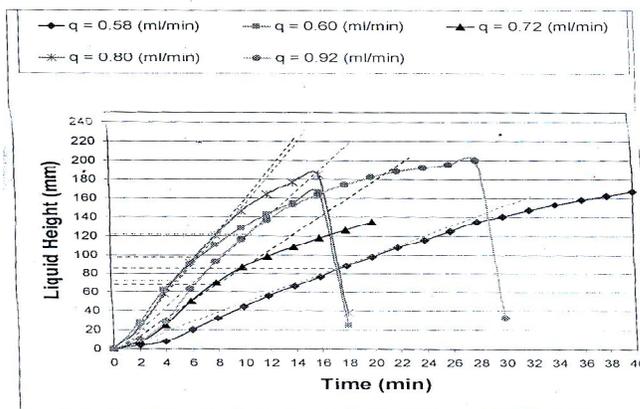


Fig. 6: 63 $\mu$ m coal particle/de-ionized water

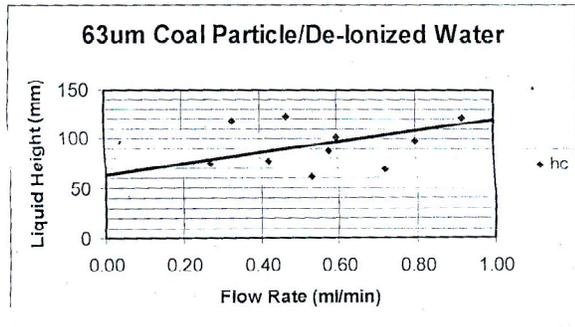


Fig. 7: 63µm coal particle/de-ionized water

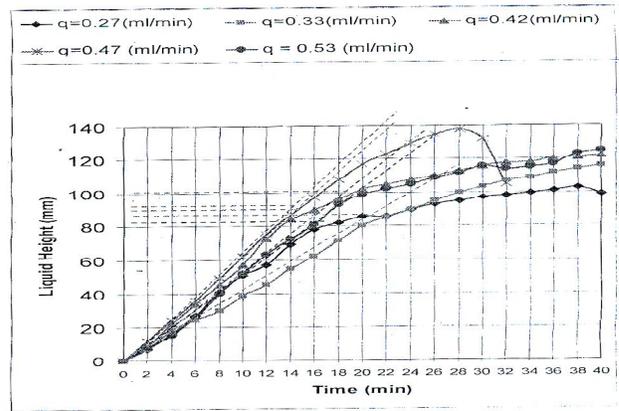


Fig. 11: 100µm coal particle/de-ionized water

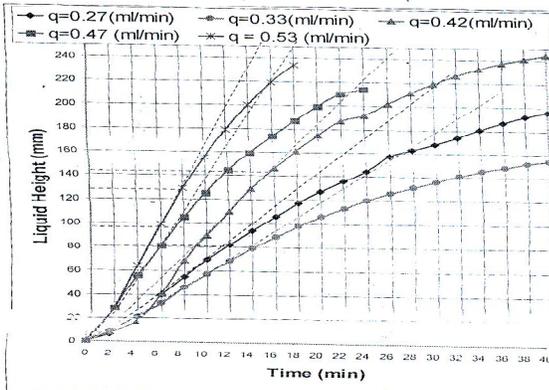


Fig. 8: 71µm coal particle/de-ionized water

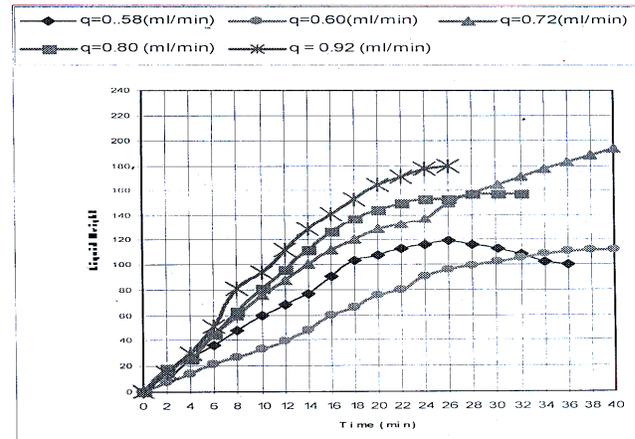


Fig. 12: 100µm coal particle/de-ionized water

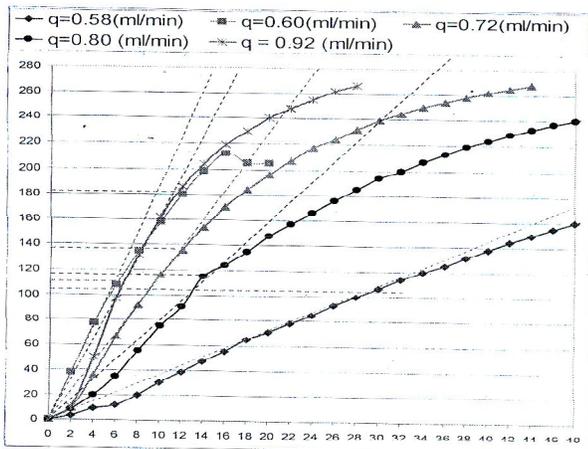


Fig. 9: 71µm coal particle/de-ionized water

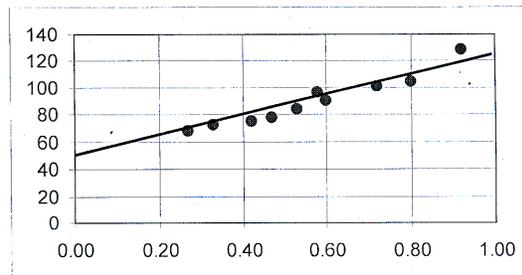


Fig. 13: 100µm coal particle/de-ionized water

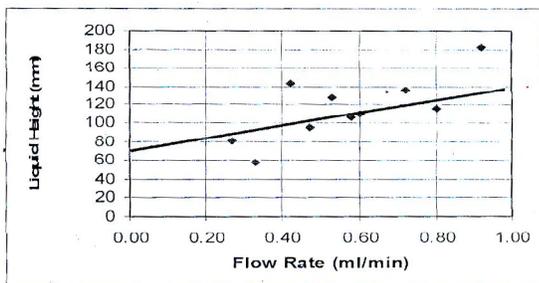


Fig. 10: 71µm coal particle/de-ionized water

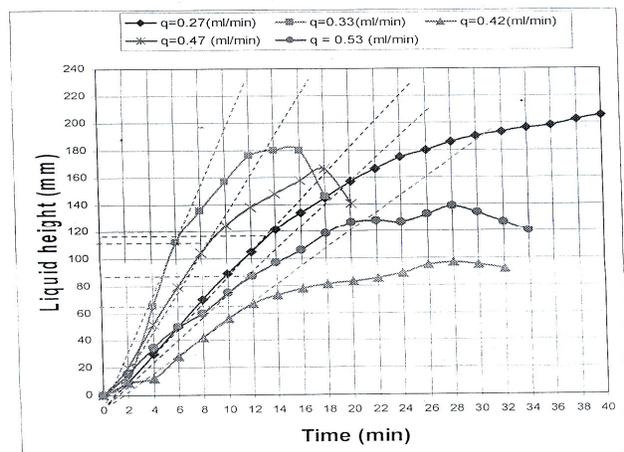


Fig. 14: 125µm coal particle/de-ionized water

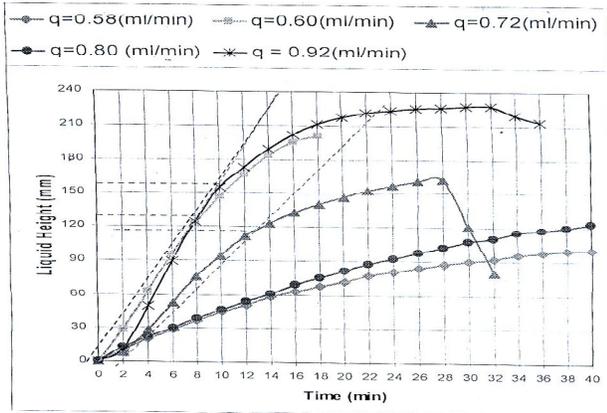


Fig. 15: 125µm coal particle/de-ionized water

### V. OBSERVATION

*The implication of the relationship that exist between particle size and surface tension  $\gamma_{sv}$  of solid*

Experimentally, it has been clearly shown that particle size of the coal used has some relationship with the surface tension,  $\gamma_{sv}$ , of the solid.

This relationship shows that as particle size diameter increases, its surface tension also increases whereas the surface tension decreases when the particle size decreases. This phenomenon/observation depicts that the smaller the particle size the closer, the actual/original material of the coal is approached. Since the coal lump has some inclusions (or unwanted gang materials) from the earth crust as mined, when crushed, ground and sieved to varying size ranges, the smaller the particle size, the smaller the inclusion, and the larger the particle size, the larger the inclusions (for unwanted gang material). It is an axiom that, the larger the particle size, the further the actual material of the particle is approached due to the included gang materials, which assume a large proportion of the particle in this case.

It is of interest to state emphatically that it is the inclusion, otherwise called the unwanted gang material, which steps up the interfacial free energy (surface tension) of the solid when in contact with a liquid, say distilled water.

From this work, It was noted the smaller the particle sizes:

- The smaller the inclusions in the particle the closer the original material of the particle is approached by the liquid in contact with it, and
- The smaller the interfacial free energy (or surface tension,  $\gamma_{sv}$  of the solid)

Similarly, the larger the particle size:

- The larger the unwanted gang materials in the particles.
- The less closely the actual material of the particle is approached by the liquid in contact with it, and
- The larger the interfacial free energy (or surface tension,  $\gamma_{sv}$  of the solid).

The resume, therefore, is that inclusions in samples (solids) are contributory factors to the fluctuations in surface tension values of solids.

The final result of the experiment on the Akwuke coal powder, therefore, revealed that particle size has influence on the wettability of the Akwuke Coal and on the surface tension values.

### VI. CONCLUSION

The wettability of Akwuke Coal powder was analyzed using the continuous flow technique using seven particle size ranges. During the experiment, air was displaced by the de-ionized water used, the external pressure head,  $h$ , was measured as a function of time and as a function of flow rates.

Based on the analysis of the generated data, it was completely inferred among other things that:

- Particle (grain) size has influence or effect on the wettability of Akwuke Coal. In other words, the wetting characteristics of the Coal depends on the particulate sizes,
- Particle size has effect on the surface tension values of the-Coal.

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