Mechanism of Atomization of Non-Newtonian Suspensions using Hydraulic Spray Nozzles

Addo-Yobo, F*, Kutsanedzie, F., Amevi Acakpovi, Anthony Woode, Edwin Mends Brew
Research & Innovation Centre, Accra Polytechnic, Barnes Road, Box GP 1070, Accra, Ghana.

Abstract

A high-speed photographic technique has been used to record the break-up of sheets of suspensions, of Glass particles and Attapulgite particles to form a network of ligaments and nodes and the subsequent disintegration of the network to form droplets. Thirteen types of the break-up of the ligaments are postulated although from the analysis of the photographs, five are observed for Glass suspension and nine for the Attapulgite suspensions. The droplets formed from the above can be grouped into three: nodal droplet, mid section droplet, satellite droplets. The perforations which lead to the formation of the above network and from which drops are formed, attain different growth times prior to secondary disintegration, and therefore the ligaments have different thicknesses, giving rise to the possibility of the formation of multimodal distribution of drop sizes. The analysis of the two dimensional images of the drops formed, at long distances from the nozzle, indicate that multi-modal distributions of drops could result from this type of secondary disintegration.

Introduction

Atomization is widely used to form droplets from suspensions of solids in liquids in diverse industries including: combustion of solid fuels in rocketry and power generation, spray drying of foods and pharmaceuticals. However, the mechanisms by which sheets of liquids containing particles break up to form droplets is not well understood. The conventional theory for the break-up of liquid jets proposed by Rayleigh and later modified by Squire [1], Fraser and Dombrowski [2], to describe the break-up of freely moving sheets of liquids while applicable to pure liquids cannot be applied directly to suspensions or two phase systems[3]. Quite apart from the above problems with understanding the mechanisms, further complication arise when the solids used in forming the suspensions are such that the rheology of the suspensions are non-Newtonian. In this work we have used glass particles to produce suspensions that are Newtonian and clay particles to produce suspensions that are shear thinning. This paper characterizes the primary and secondary processes of disintegration of sheets of aqueous suspensions to form droplets using photographic techniques.

Experimental

The glass particles of mean size 26micron and known size distribution, were used for preparing the suspensions. Particles of Attapulgite clay comprising needle like fibres of submicron diameter and about five microns long were dispersed in water with shearing action to form a thick suspension. Thereafter the suspensions were stirred vigorously to enhance dispersion. The particles absorb several times their volume water on hydration and swell to form a smooth gel. The flow curve as determined by a Haake Rotovisco viscometer, indicated that the gel (11%wt/wt) is shear thinning, with effective bulk viscosity reducing from about six centipoises, at low strain rates, to about1.5 centipoise in the higher strain rate regime.

Apparatus

The suspensions were stored in a pressure pot (upstream of the nozzle) and stirred immediately before a run. Nitrogen at preselected pressures was used to force the suspensions through the nozzles. The sprayed slurry was collected in a tank and the particles recovered. The tank was extracted with a fan to maintain a gentle breeze of ambient air downward (in the direction of the spray) to prevent sprayed droplets from impinging on the sheets. Atomizing pressures used ranged from 3 to 14 bars (see Table 1). The sheets were observed using a flash stroboscope and several photographs (at least five) were taken with a short duration (100 ns) light flash produced by an argon stabilized spark source, using focused rear illumination technique [3].

Method of Analysis of the Photographs

In analyzing the photographs, images of the networks were divided into zones and the zones examined through a graticule in order to identify ligaments and nodes. In order to further characterize the networks formed, the numbers of ligament per node were determined. On each photograph, the radial distance from the nozzle at which the networks end was recorded. The characteristic lengths of the two-dimensional images of the drops and their radial distances from the nozzle orifice were measured. The types of break-up of the ligament were also recorded. The data were recorded, and displayed as frequency and Bar charts.

Results

Figure 1 shows photographs of sheets of Glass and Attapulgite suspensions breaking up by the perforation process to form ligaments, which disintegrate to form droplets. The Glass sheet perforate in the region where the sheet thickness is less than the particle size of 26 microns, whereas the sheet containing Attapulgite breaks up in the region where the sheet thickness is about 20 microns, which is much thicker than the average size of the dry clay particles.

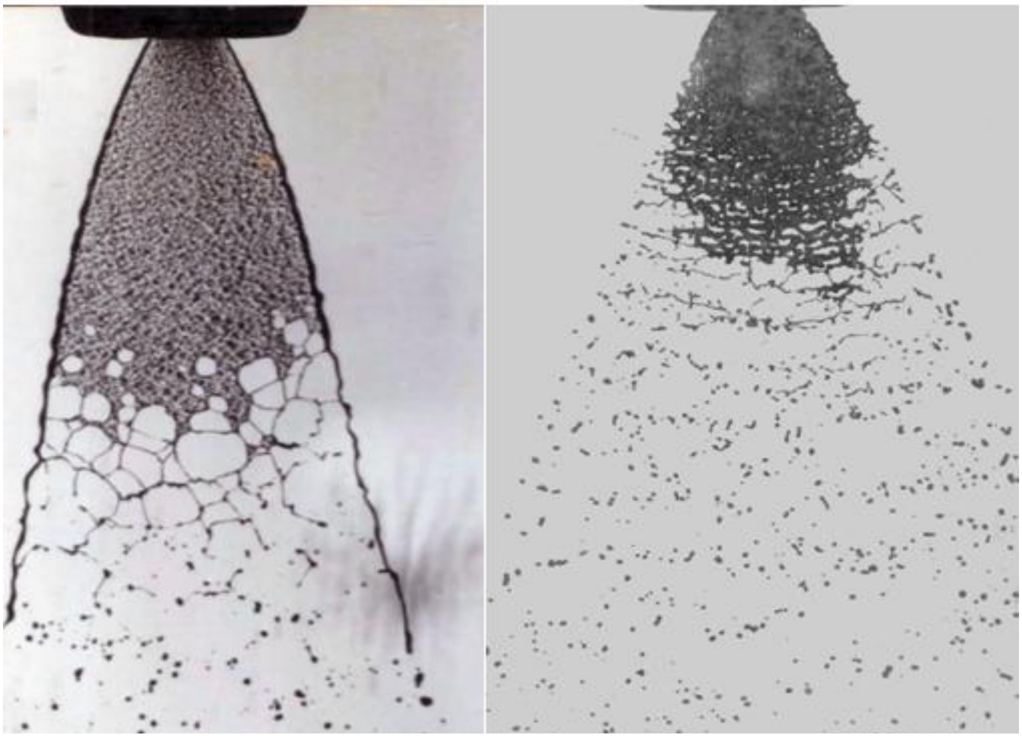

Fig. 1 : Photographs of sheets containing Attapulgite particles (left) and Glass particles (right) undergoing break-up. The Nozzle is Titan 521, Sheet velocities are ca. 22m/s

Holes, Nodes and Ligaments

The perforations grow to form holes in a network of Ligaments. Because the sheet expands with distance from the nozzle, the shape of the holes are ellipsoidal rather than circular as demonstrated in Figure 1 above. The network formed from sheets of Attapulgite suspensions persists a greater distance beyond the sheet. The rims of the sheets also persist longer. The network of Attapulgite suspensions have fewer holes or voids per unit area of the sheet compared to that of the Glass suspensions, indicating that there are fewer perforations per unit area of the sheet.

A high magnification photograph of the network formed by the Attapulgite suspension is shown in Fig 2. The material which lies along the length of adjacent holes contracts under surface tension to form ligaments. The

Ligament are connected to the network via nodes. Feature A, in the upper left side of Figure 2 shows an example material between two holes contracting to form a Ligament. The material which lies in the boundary where more than two holes share a common border contract to form nodes. The nodes were differentiated by their connectivity to the network. For example, two types of nodes labeled B & C, which are bordered by three and four ligaments and by three and four holes respectively are indicated in Fig. 2.

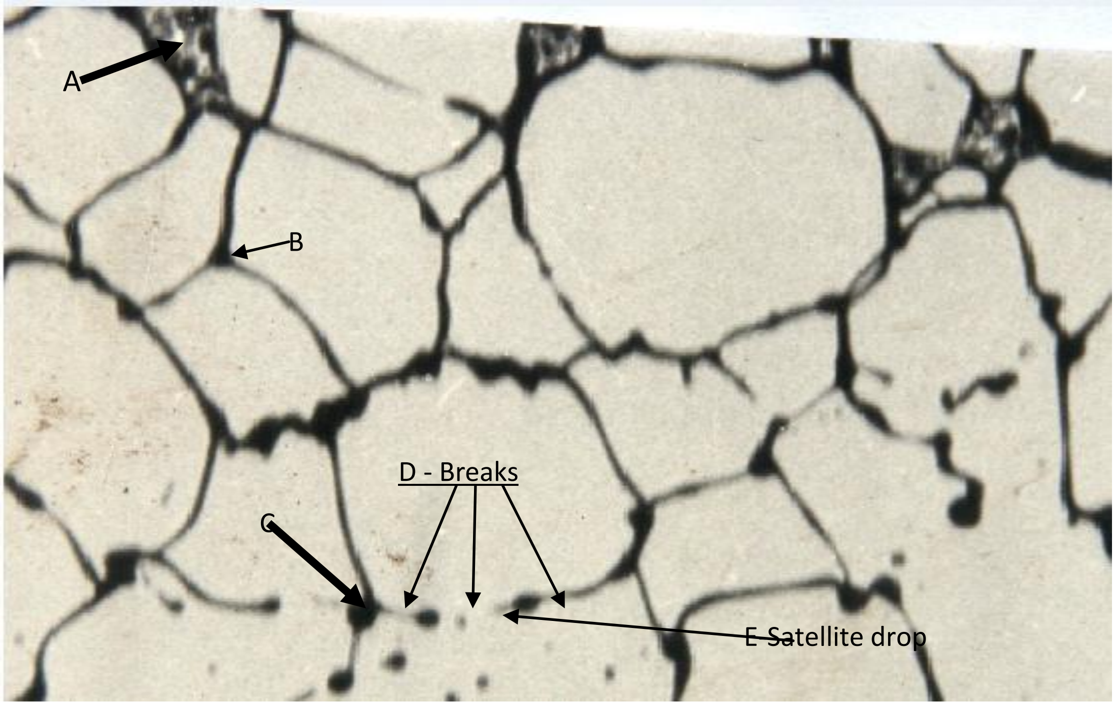

Figure 2: High magnification photograph (X 22.6) of network formed by suspension of Attapulgite clay showing fracture of ligaments.

The ligaments undergo secondary break-up at variable numbers of points to forms drops and may produce satellite drops due to pinch off as demonstrated by feature D and E respectively in the above Figure.

Glass Suspensions

The bar chart in Fig. 3 shows the connectivity of the nodes to the networks formed by the two suspensions. The majority (93%) of the nodes formed by the Glass suspensions are connected to the network by three ligaments, whereas only 7% are connected by four ligaments. Ninety-two percent (92%) of nodes in the network were bordered by three holes compared to 8% which were bordered by four holes.

Attapulgite

Figure 3 shows that 74% of nodes in the network formed by the Attapulgite suspensions are attached by 3 ligaments, 22% attached by 4 Ligaments and about 4% attached by 5 ligaments. The nodes bordered by 3, 4, and 5 holes in proportions of 77%, 19% and 4% respectively.

Age Distribution of Holes

The analyses of the sizes of the holes showed that fresh holes were formed at radials positions beyond the radial distance at which perforation first appeared on the sheets. One could observe holes of 600 microns side by side with holes of 2000 microns on the sheets of Attapulgite suspensions. Likewise, one could observe holes of size 200 microns side by side with holes of size 1400 microns on the sheets of Glass suspensions.

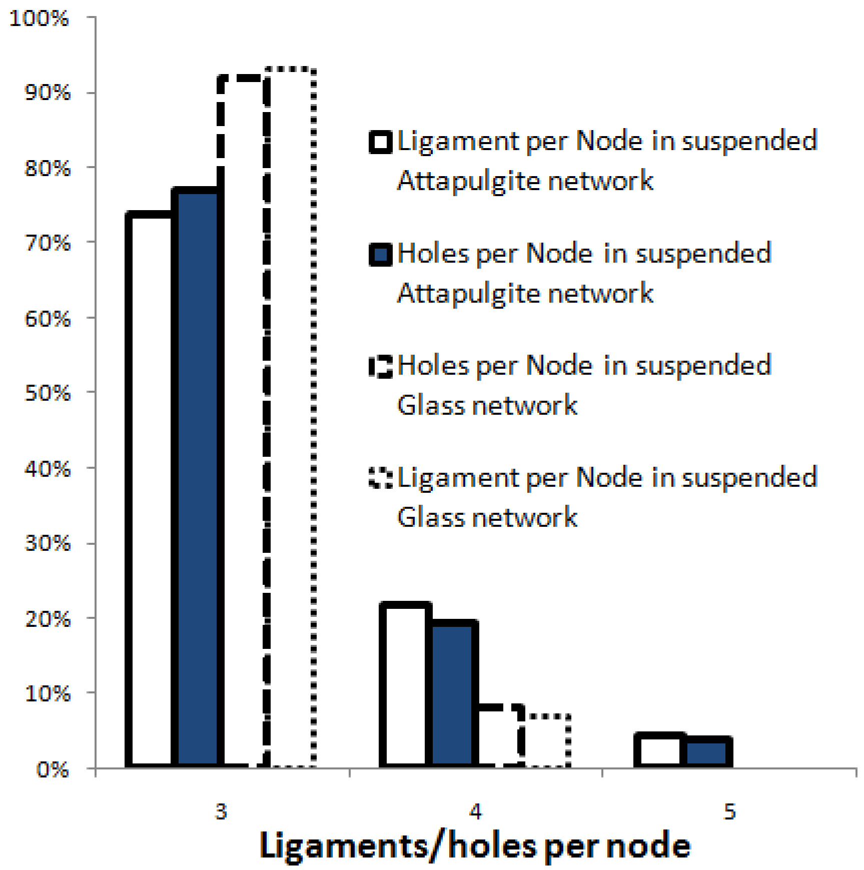

Fig. 3: Bar chart of the Distribution of Ligaments per node and Holes per node in the network formed by sheets Glass and Attapulgite Suspensions

Breakup Types	Number Satellite / Mid Section Drops	Breakup Types	Number Satellite / Mid Section Drops
Type 1a	One Break no satellite	**Type 2a**	Two breaks One mid sect drop no satellite
Type 1b	One break one satellite	**Type 2b**	Two breaks One mid sect drop one satellite
Type 1c	One break two satellite	**Type 2c**	Two breaks One mid sect drop two satellite
Type 1d	One break 3 satellite	**Type 2d**	Two breaks, One mid section drop, three satellite drops
		Type 2e	Two breaks, One mid section drop, four satellite drops
Type 3a	Three breaks, two mid section drop no satellite drops	**Type 3d**	Three breaks, two mid section drops three satellite drops
Type 3b	Three breaks, two mid section drop one satellite drop	**Type 3e**	Three breaks, two mid sect drop four satellite
Type 3c	Three breaks, two mid section drop two satellite		

Table.1. The types break-up of ligament and their corresponding number of satellite and mid section drops

Thirteen types of fracture of the network are identified Table 1, above. The digit in the nomenclature indicates the number of breaks in the ligament and the alphabet differentiates the break-up events by the number of mid-section and satellite drops which are formed. Thus break-up **type 3c** references the break-up event in which two mid section drops are formed accompanied by two satellite drops.

Secondary Disintegration of Network of Glass Suspensions
The bar chart in Fig. 4 summarizes the relative frequencies of types of break-up which account for the secondary disintegration of the network formed from sheets of the two suspensions.

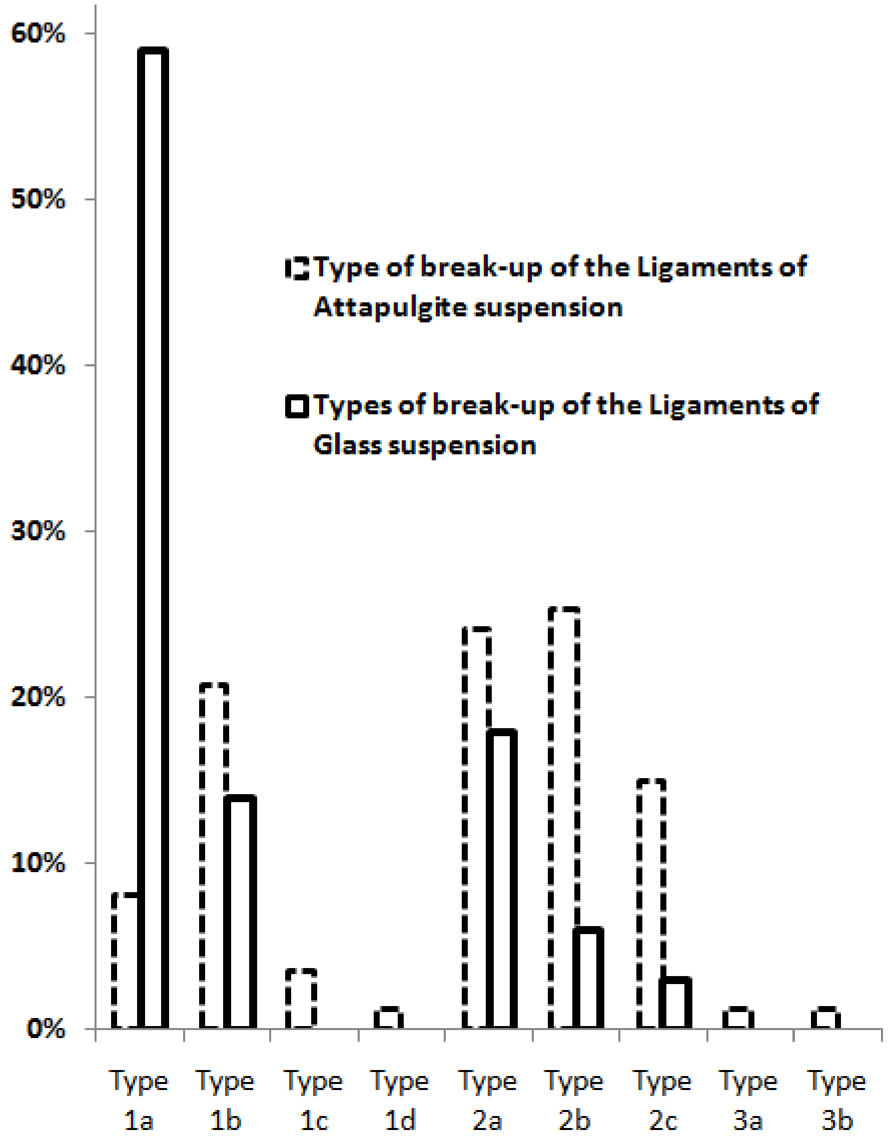

Fig. 4: Types of Break-up of network formed by sheets of suspensions of Glass and Attapulgite (Nozzle Titan 521 & 943, Velocity 22m/s)

Break-up Type 1a predominates (59%) the secondary disintegration of sheets of Glass suspension, followed by type 2a. These would indicate that the single or double breaks in the ligaments are most common. About one quarter of the fractures are accompanied by satellite drop formation.

Secondary Disintegration of Network of Attapulgite Suspensions

Compared to the break-up of ligaments of Glass particles, the secondary break-up of sheets of Attapulgite suspensions are more varied and contain more satellite particles (65% of all fractures). The majority (ca. 64%) of ligaments break-up in two places and are accompanied by satellite drop formation. About one third of the ligaments in network break-up in one place but are not accompanied by satellite droplets. A little over two percent of the ligaments break up in three places.

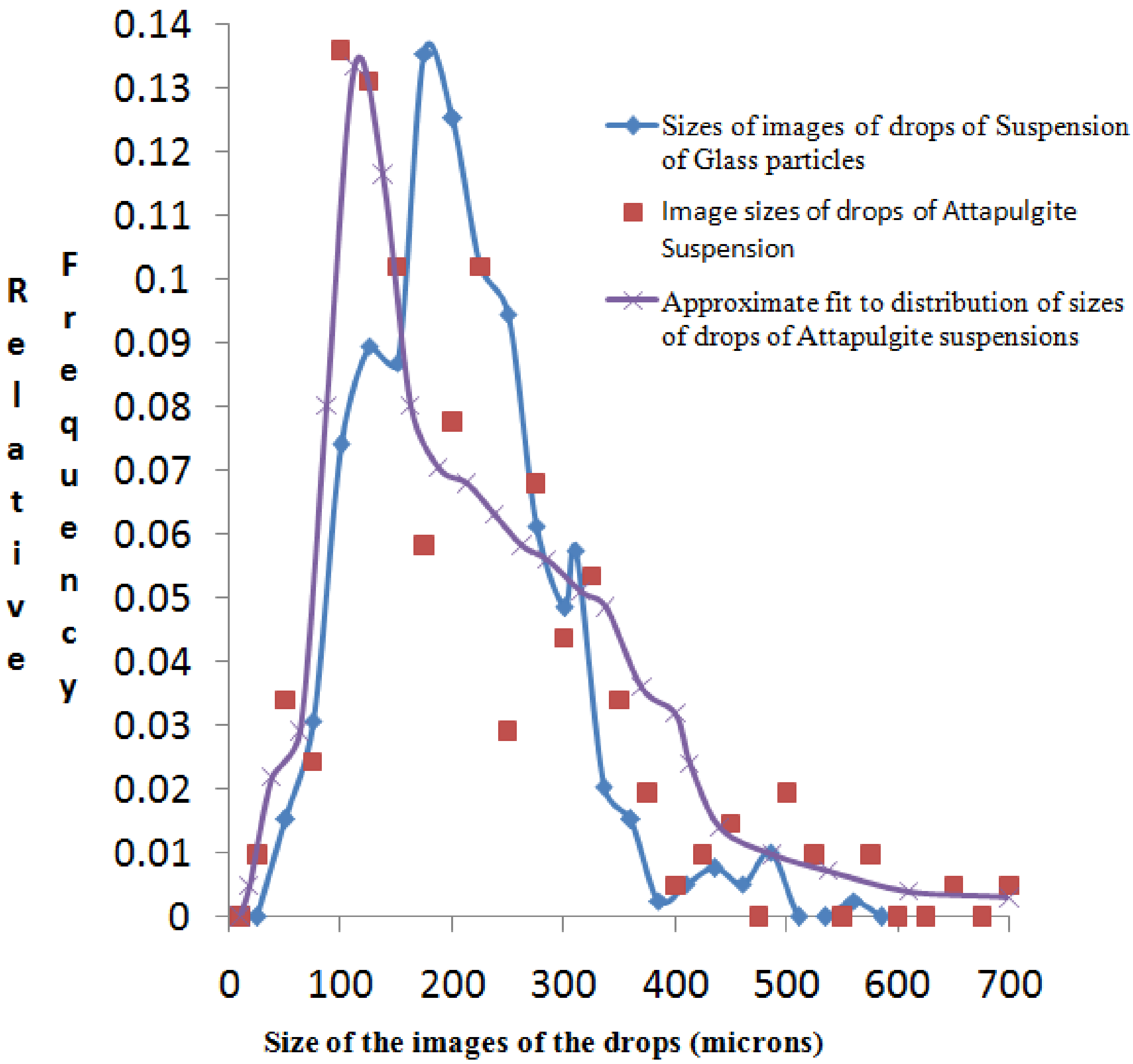

Fig. 5: Distribution of the sizes of shadowgraphs of drops of the suspensions

Distribution of Drops

In order to gain an idea of the size of drops, we identified the regions of the photographs furthest away from the nozzle where the flight times of the drops from the limit of the sheets exceeded the time for reshaping into spheroid by factor greater than five. The estimates of the sizes of drops were inferred from the images of drops in this area. Figure 5 shows that the distribution of sizes of the drops formed from the two suspensions sprayed under similar conditions are likely to be complex. The curves probably comprise composite distributions which overlap. The drops from the Attapulgite suspensions show the largest modal peak at around 120 microns and a second one at around 210 microns. There is a small but significant cusp around about 40 microns.

The drops formed from the Glass suspensions show the largest peak at about 180 microns. The other two peaks are close by but differentiated at 235 microns and 135 microns. The tail of the drop distribution from the Attapulgite suspension is longer at the higher drop sizes compared to that of the Glass suspensions.

Discussion

It is demonstrated that, shear thinning suspensions atomize as if they comprised suspensions of particles larger than the intrinsic dry size of the particles. Such behaviour can be expected because such particles form structures on hydration to become solid-like, however under the action of shear within the passages of the orifice, the structure of the suspension would break down only partially leading to the formation of a suspension of "hard agglomerates" in a viscous liquid. Similar observations have been made concerning the perforation of sheets of suspension of Titanium Dioxide, Bentonite and Fuller's Earth [4], [2]. Therefore the important question to answer for modelling purposes is what the expected fraction of the suspension under severe shear could be considered liquid and into what sizes would the remainder be shred. This information is crucial to determining the character of the atomization process. If the agglomerate sizes are fine e.g. five microns as in Titanium dioxide, then waves growth would be significant prior to perforation [5]. On the other hand suspension of Attapulgite are shred into coarse agglomerates (ca 20 microns) hence sheets perforate before significant wave growth can occur.

From the presentation above, the non-Newtonian perforate to form a network of ligament and nodes which ultimately disintegrate into drops. Thus there are three sources of droplets: nodes, mid-section and satellites. The observation that fresh perforations occur throughout the region where sheet thickness falls below the particle size would give rise to nodes and ligaments of a distribution of thickness, which the drops formed from them would inherit. The nodes may be connected by three or four ligaments and the ligaments themselves would be of varying thickness and would break at one, two or three places. Thus there are potentially three size distributions: one due to the nodal drops, a second due to midsection drops, and a third due to satellite drops.

It reasonable to expect that the degree of overlap of size distribution of the mid section drops and nodes and satellite drops depend on the distances from the nozzle orifice or the local thickness of the sheet at which perforations occur. The reason for this is that if perforations occur over a wide range of distances from the nozzle, then this will give rise to large differences in size distributions and the different modes in the distributions become distinguishable.

It is established in the literature that satellite drops may form from elongating filaments depending on the local fluid dynamics [6]. And that the pinching off process may be controlled by manipulating the fluid dynamics. Even though it was not possible to determine the size of drops formed by the use of laser diffraction techniques, the observed difference in the distribution of drops, using the crude shadow photographs is consistent with the mechanisms adduced from this work. As noted in the results section, the fracture events of Attapulgite ligaments produces a greater proportion of satellite drops hence the apparent peak at about 40 microns, which is absent in the drops produced by the network of Glass suspensions.

Summary and Conclusion

We have used shadow photography to provide evidence which is useful in the search for the mechanism by which particle laden sheets break-up into ligaments and nodes, which form a network. The network undergoes secondary disintegration to give a distribution of droplets. Very much like the break-up of non-structure forming suspension of particles, the evidence assembled support the notion that non-Newtonian sheets also give rise to multi-modal distributions for similar reasons. As the sheet elongates, the ligaments are stretched and breakage occurs due to two driving forces: surface tension acting on the well -developed shape of a node and stretching leading to the formation of capillary waves, which break the ligaments via Rayleigh mechanism. It is feasible that Non-Newtonian suspensions may be treated as particles suspended in a viscous liquid, similar to how one might treat newtonian suspensions.

Future work require thinking about how structures in the non-Newtonian suspensions formed by hydrogen-bonding and Van-der Waals forces break up partially under action of shear and turbulent flow in the nozzle orifice. On the experimental front, more work needs to be done on the statistics of the perforation process. It would be of fundamental importance to determine if the process is influenced by Brownian motion at the molecular level.

Acknowledgements

We acknowledge the help of Al-Hassan Saeed of the Department of Science Laboratory Technology of the of Accra Polytechnic in measuring the flow curves of shear thinning suspensions.

References

[1] Squire H.B., *Brit. J. Appl. Phys.4 :167-170 (1953)*
[2] Dombrowski, N. and Fraser, R.P., *Phil. Trans. R. Soc. of London 247A,101-10 (1953)*
[3] Basel Mulhem∗, Günther Schulte, Udo Fritsching, *Chemical Engineering Science, 61, 2582 – 2589 (2006)*
[4] F.O. Addo-Yobo et.al, *A.I.Ch.E.J, 57-8, 2007-2024 (2011)*
[5] Addo-Yobo, Festus & Kutsanedzie, Felix, *Proceedings of the 24th Conference of the ILASS, San Antonio, Texas, USA, May 20-23, 2012.*
[6] Xiaofeng Yang, James J. Feng, Chun Liu c, Jie Shen, *Journal of Computational Physics, 218: 417–428 (2006)*