Mathematical Model on the Effect of Viscosity of Oil Palm on Oil Quality

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ABSTRACT

Over the past few years, the quest for international competitiveness and the need for improved profit have driven organisations towards increasing their product quality. In the palm oil industry, the development of high quality, viscous, and nourishing product may attract high volume sales, and consequently, high revenues. This paper presents a mathematical model to study the effects of viscosity of oil palm on oil quality. A hypothetical case is considered in which the number of mixing atoms in palm oil is related to viscosity. This is aimed at verifying the workability of the model. Viscosity (with values ranging from 2.19 cSt and 14.56 cSt) was varied, while the quantity of heat applied was held constant at (Q = 100 KJ) and later varied between 21.86 KJ and 100 KJ. The distance of the intermediate layers was held at h = 10 mm, while the area of conductor in contact was maintained (at A = 12 mm^2). The velocity of movement of particles was V = 5 mms^{-1}, while the diameter of mixing substance atoms was made constant at D = 11.64 micro mm. The results obtained show that the number of mixing atoms of another mixing component with palm oil is much when viscosity increases. Also, the foreign atoms to fill these spaces increase. The research has helpful hints and information for molecular scientists, agricultural researchers, and managers of palm oil firms who need such information for decision making and for improved efficiency at work.

Keywords: Viscosity, palm oil, oil quality, mathematical modelling, oil molecules, Nigeria

1. INTRODUCTION

Relevant research on palm oil has indicated a continued interest by manufacturers in producing high quality, viscous and nourishing products (Sadat and Khan, 2007). Kazemi et al. (2005) noted that the quality of frying oil is a critical factor to keeping high quality fried products. Thus, the frying industry constantly seeks for new frying oils that are stable and impact desired characteristics on fried products. Consequently, efforts are made to improve the quality of palm oil, which is obtained from oil palm that is considered as the highest oil-yielding crop in the world (Hartley et al., 1998; Tandon et al., 2007).

The literature on oil palm has been limited to the problem of pest infestation of the fruits (Owolafe and Arumughan, 2007), effluent produced from palm oil mills (Okwute and Isu, 2007; Chindaprasirt et al., 2007), solid waste oil palm materials as alternative building materials (Jaturapitakkul et al., 2007; Teo et al., 2007), wear in screw press in oil palm mills (Okafor, 2007), and palm oil processing (Cintia et al., 2007; Zaidul et al., 2007; Zeba et al., 2006). Unfortunately, no documentation seem to be available on quality of palm oil as it relates to viscosity measurements. A detailed account of the reviewed studies is as follows: Owolarafe and

Arumughan (2007) reviewed oil palm fruit plantation and production in India and noted that the problem of pest infestation of the fruits is a serious threat to palm oil quality (Supeni et al., 2002, 2004, 2005). Another direction of research relates to the effect of palm oil mill effluent (POME) on the total aerobic bacterial population and ammonium oxidizers in a dumping site in Anyigba (Okwute and Isu, 2007). Jaturapitakkul et al. (2007) evaluated the effects of using palm oil fuel ash (POFA) as a new pozzolanic material on sulphate resistance in terms of expansion and loss in compressive strength of concretes exposed to 5% $MgSO_4$ solution for up to 24 months. Teo et al. (2007) determined the structural bond properties, split tensile strength, modulus and rupture and modulus of elasticity of lightweight concrete incorporating solid waste oil palm shell (OPS) as coarse aggregate. Also, in an article, Okafor (2007) investigated wear in screw press in oil palm mills. Information relevant to the current study could also be found in Marwan et al. (2007) and Partida et al. (2007).

From these reported studies, the current paper argues that apart from the problem of pest infestation of oil palm fruit, viscosity of the palm oil, which depends on the efficiency of the palm oil firm, is a strong determinant of the quality of palm oil. Thus, in order to capture high quality of palm oil, the important variable of viscosity in production should be explored. Consider a good palm oil, it seems necessary to note that a low viscous palm oil flows easily, vapourises easily and looses taste in due time. However, a high viscous palm oil retains its taste, flows less and is less volatile as it is free to shear. Thus, low viscosity of the palm oil is a setback to good quality product. The purpose of this paper is to present a mathematical model to study the effects of viscosity of oil palm on oil quality.

Since viscosity is the internal frictional resistance offered by a fluid to change its shape or relative motion of its parts, it is noted that a palm oil contains thin films arranged on top of one another, to form a large molecule of palm oil. Obviously, the films slide over one another, causing shear resistance offered by each film in order to avoid displacement. As a result of low viscosity, deformation of the palm oil surface is done with ease. Even its flow from one point is done with ease and this makes the oil easily deformed. The molecules of the palm oil are visualized as small balls which roll in layers between two plates. Palm oil molecules may stick to both the surfaces and therefore the layer of molecules in contact with the stationary plate has zero velocity. Palm oil is used for cooking where it adds flavours to food. Also, it is nutritious and serves useful purpose to the human body. It can also be used in lubrication due to some of its characteristics. Palm oil can be important in hydrodynamic lubrication where the load carrying surfaces of the bearing are separated by a relatively thick film of oil, so as to prevent metal-to-metal contact and that the stability thus obtained can be explained by the laws of fluid mechanics. Hydrodynamic lubrication does not depend upon the introduction of the lubricant under pressure, though that may occur; but it does require the existence of an adequate supply at all times. The film pressure is created by the moving surfaces itself pulling the lubricant into a wedge-shaped zone at a velocity sufficiently high to create the pressure necessary to separate the surfaces against the load on the bearing.

The paper is divided into four sections. Section 1 provides the motivation to study the viscosity problem in palm oil. This is supported by appropriate literature review to identify the important gap that the current study fills. Section 2 discusses the methodology, which explains the formulation of the model. In section 3, a case is illustrated to verify the workability of the model.

This is aided with simulated data that demonstrate the behaviours among the model parameters. Section 4 shows the concluding remarks.

2. MODEL FRAMEWORK

The notations used in the body of this paper are defined here.

2.1 Nomenclature

d	displacement of oil film
m	mass of oil film
g	acceleration due to gravity
t	thickness of oil film
μ	dynamic viscosity
m_0	mass of palm oil before heating
Q	quantity of heat applied
ρ	density of palm oil
m_i	mass of palm oil after heating
m_m	mass of metal/conductor supplying the heat
V	velocity of movement of the upper plate
h	distance of the intermediate layers from the stationary plate
T	absolute temperature
τ	shear stress due to viscosity and velocity
$\dot{Q}$	rate of heat flow
K	thermal conductivity of the metal
L	specific latent heat of vaporization of palm oil
A	area of conductor in contact
V_o	initial volumes of the palm oil
V_i	final volumes of the palm oil
G	universal gravitational constant
F	force of attraction between oil molecules
P	shear force on the oil surface
D	diameter of mixing substance atoms
N	Number of mixing substance atoms occupying the intermolecular distance

2.2 Mathematical Framework

Modelling for viscosity and its effects to the palm oil industry is built up from the elementary physical science to the effects. If a sample of palm oil with its molecules is confined within two parallel plates. The lower plate is stationary while the upper plate is moved with velocity V by means of a force, P.

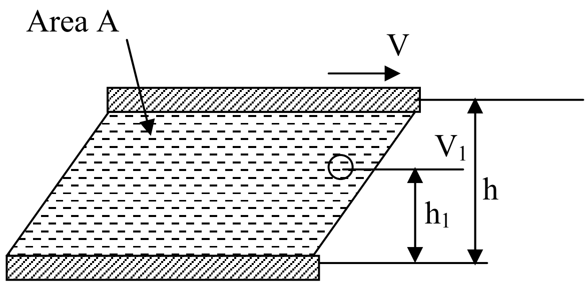

Figure 1. Molecules of palm oil confined within two parallel plates

The velocity of the layer of molecules in contact with the upper plate will move with a velocity, V (Figure 1). The intermediate layers will move with velocities, which are proportional to their distance from the stationary plate, i.e., $V \alpha h$. This is an assumption that is practically realizable. Thus, $V = Kh$ (1), and

$$K = \frac{V}{h} = \frac{V_1}{h_1} = \frac{V_2}{h_2} \qquad (2)$$

This kind of orderly movement of the palm oil molecules is called streamline, laminar or viscous flow. However, Tangential force per unit area $= \frac{P}{A}$ (3) and

$$\text{Rate of shear} = \frac{V}{h} \qquad (4)$$

From Newton's law of viscosity, the shear stress is proportional to the rate of shear at any point in the fluid, i.e., $\frac{P}{A} \; \alpha \; \frac{V}{h}$, which gives $\frac{P}{A} = \mu \frac{V}{h}$. Thus, $P = \mu A \frac{V}{h}$ (5)

When the velocity distribution is non-linear with respect to h, we have $\frac{V}{h} \approx \frac{dV}{dh}$. Therefore,

$$\frac{P}{A} = \mu \frac{dV}{dh} \text{ x } A = \mu A \frac{dV}{dh} \qquad (6)$$

Considering a thin film of palm oil, which is deformed by a force, P. If the film of oil is displaced by a distance d from its mean position and also falls a height equals to the thickness of the film. Due to sliding it moves a distance d forward and falls a thickness, t. Then,

$$P \text{ x } d = mgt \qquad (7)$$

Since mass = density x volume, therefore $m = \rho\surd$, where $\surd$ = volume. Thus, $\surd = blt$. From potential energy = work done, we have $Pd = (\rho \; b \; l \; t) \; gt = \rho \; b \; l \; t^2 \; g$ (8)

But from equation (6), $P = \mu A \frac{dV}{dh}$. By substituting for P in equation (8), we have (9).

$$\mu A \frac{dV}{dh} \cdot d = \rho\, b\, l\, t^2\, g \tag{9}$$

$$\text{But} \quad \int_0^V dV = \int_{h_1}^{h_2} \frac{\rho\, b\, l\, t^2\, g}{\mu A d}\, dh \tag{10}$$

Therefore $$V = \rho \frac{b\, l\, t^2\, g}{\mu A d} (h_2 - h_1) \tag{11}$$

The velocity of the movement of palm oil molecules is affected by the viscosity of the oil. The higher the viscosity of oil, the lower the velocity of its molecules. When heat is applied to palm oil molecules in the industry, the volume of the molecules or the volume they occupy is proportional to the absolute temperature, i.e., $V \alpha T$, and $V = CT$. Thus,

$$C = \frac{V_1}{T_1} = \frac{V_2}{T_2} \tag{12}$$

It is assumed that temperature relates to viscosity by $\mu \alpha e^{\frac{1}{T}}$. Thus, $\mu = e^{\frac{1}{T}}$. The constant here is assumed to be 1. The transformation gives $\frac{1}{T} = \ln \mu$. But a linear relation exists between the temperature of the oil and its viscosity practically. Thus, from $y = mx + c$, we note that y = y axis assigned to $\ln \mu$, and x = x axis assigned to $\frac{1}{T}$. Then $\ln \mu = \left(\frac{dV}{dh}\right)\frac{1}{T} + \rho$. Here, ρ = density of palm oil which is constant = c. Thus,

$$\mu = e^{\left[\left(\frac{dV}{dh}\right)\frac{1}{T} + \rho\right]} \tag{13}$$

Production of palm oil requires its flow through a duct or a slot. From the configuration assumed by this model, the palm oil is passed through a rectangular slot. In analysing the rectangular slot system in Figure 2, the effective pressure exerted by palm oil on surfaces, the area of slot, and the force acting on the slot could be calculated as follows:

Effective pressure = $p_i - p_o = \Delta p$
Area of slot = xb
Force on slot = pressure x Area = Δp x b

It is also known that the shear foces by the surfaces parallel to the slot could be expressed mathematically as:

$$p = \mu A \left(\frac{dV}{dh}\right) = \mu\, (2lb) \frac{dV}{dx} \tag{14a}$$

But it is known that x is equivalent to h and that the velocity reduces as height increases, so

$$p = -\mu\, (2lb) \frac{dV}{dx}, \text{ where } -\mu\, (2lb) \frac{dV}{dx} = \Delta P \times b \tag{14b}$$

Thus, by substituting for the value of $-\mu\,(2lb)\dfrac{dV}{dx}$ in equation (14b) gives

$$dV = -\frac{\Delta P \text{ x } b}{2lb\mu}dx = -\left(\frac{\Delta P}{2l\mu}\right)xdx \qquad (15)$$

By integrating equation (15), equation (16) emerges as $\int dV = -\int_{x_1}^{x_2}\left(\frac{\Delta P}{2l\mu}\right)xdx$ (16)

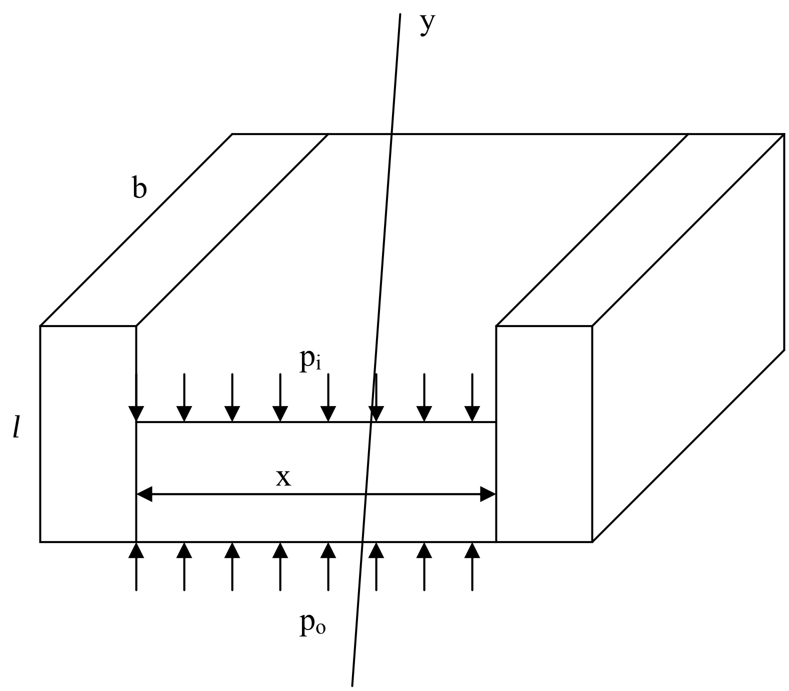

Figure 2. Rectangular slot configuration for the production of palm oil

By introducing limits, a transformation is made to equation (16) to give

$$V = -\frac{\Delta P}{2l\mu}.\frac{x^2}{2}\Big|_{x_1}^{x_2} = -\frac{\Delta P}{4\mu l}x^2\Big|_{x_1}^{x_2} = -\frac{\Delta P}{4\mu l}\left(x_2^2 - x_1^2\right) \qquad (17)$$

At this stage, it is important to study the effect of velocity on pressure variation due to viscosity on the palm oil element. Figure 3 supports this analysis.

From the analysis, it is known that $\dfrac{d}{dx}(Pdydz)dx = \left(\dfrac{dP}{dx}dx\right)dydz$ (18)

Also, the force at the other side = $Pdydz + \left(\dfrac{dP}{dx}dx\right)dydz = \left(P + \dfrac{dP}{dx}dx\right)dydz$ (19)

Thus, $\sum_{\text{forces}} = \left(P + \frac{dP}{dx}dx\right)dydz + \tau dxdz - \left(\tau + \frac{d\tau}{dy}dy\right)dxdz - Pdydz = 0$ (20)

The supporting Figure 2 is thus shown

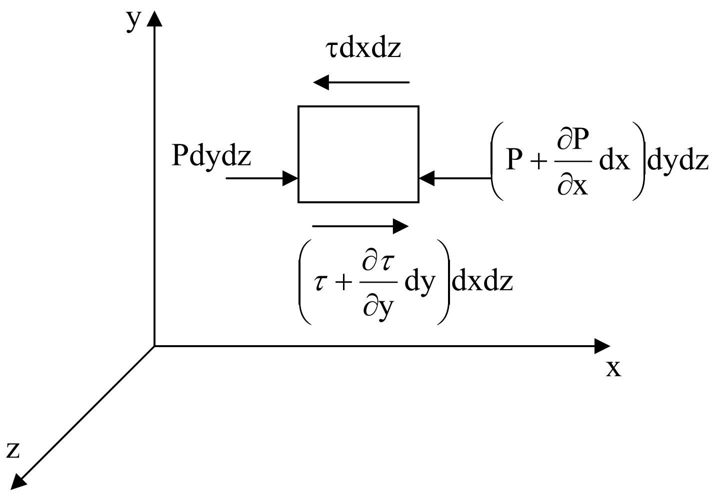

Figure 3. Effect of velocity on the pressure variation due to viscosity on palm oil element with force Pdydz moving across dx and changing with respect to dx.

Also, it is known that $\left(\frac{dP}{dx}\right)dxdydz = \left(\frac{d\tau}{dy}\right)dydxdz$ and $\tau = \mu\frac{dV}{dh}$ (21)

Thus, if the element height, dh = dy, then equation (19) could be replaced with

$$\tau = \mu\frac{dV}{dy} \tag{22}$$

However, the velocity depends on both x and y, that is $V = V(x, y)$ (23)

Therefore, $\tau = \mu\frac{\partial V}{\partial y}$ and $\frac{dP}{dx} = \frac{d\tau}{dy} = \frac{d}{dy}\left(\mu\frac{\partial V}{\partial y}\right) = \frac{\partial}{\partial y}\left(\mu\frac{\partial V}{\partial y}\right) = \mu\frac{\partial^2 V}{\partial y^2}$ (24)

It then follows that $\frac{\partial^2 V}{\partial y^2} = \frac{1}{\mu}\left(\frac{dP}{dx}\right)$. By integrating both sides of the equation with respect to y, we have $\int\frac{\partial^2 V}{\partial y^2} = \int\frac{1}{\mu}\left(\frac{dP}{dx}\right)dy$. However, $\frac{\partial V}{\partial y} = \frac{1}{\mu}\left(\frac{dP}{dx}\right)y + C_1$.

Thus, $\int\frac{\partial V}{\partial y}\partial y = \int\left(\frac{1}{\mu}\left(\frac{dP}{dx}\right)y + C_1\right)dy$ (25)

This gives $$V = \frac{1}{\mu}\left(\frac{dP}{dx}\right)\frac{y^2}{2} + C_1 y + C_2 \qquad (26)$$

However, when y = 0 , V = 0. Also, when y = h , V = -u

In order to study the effect of low viscosity of palm oil on the vaporization during heating, the principles supporting Fourier series of conduction is explored.

Thus, $\dot{Q}\,\alpha\, A\frac{dt}{dx}$, where $\frac{dt}{dx}$ = Temperature gradient. Then, $\dot{Q} = -K\,A\frac{dt}{dx}$ (27)

However, absolute temperature is considered. Then $\dot{Q} = -K\,A\frac{dT}{dx}$ (28)

Now, relating the conduction process to the vapourisation of oil, it is noted that for vaporization of the oil, $\dot{Q} = \dot{m}L$. Hence, Heat absorbed by conduction = Heat of vaporization, which gives

$$-K\,A\frac{dT}{dx} = \dot{m}\,L \qquad (29)$$

It is noted that $\dot{m} = \frac{dm}{dt} = \frac{\text{change in mass of oil}}{\text{change in time}} = \frac{m_o - m_i}{dt} = \rho\frac{(V_o - V_i)}{dt}$ (30)

Thus, $\left(\frac{dV}{dh}\right)\frac{1}{T} = \ln\mu - \rho$, and $\frac{1}{T} = \frac{\ln\mu - \rho}{\left(\frac{dV}{dh}\right)}$, which gives $T = \frac{\left(\frac{dV}{dh}\right)}{\ln\mu - \rho}$ (31)

The linkages among the expressions (29), (30), and (31) could be obtained as

$$\dot{Q} = -K\,A\frac{dT}{dx} = -K\,A\frac{d}{dx}\left(\frac{\frac{dV}{dh}}{\ln\mu - \rho}\right) \qquad (32)$$

By transforming the expression (32), the following is obtained:

$$\rho\frac{(V_o - V_i)}{dt} = -K\,A\frac{d}{dx}\left(\frac{\frac{dV}{dh}}{\ln\mu - \rho}\right) \qquad (33)$$

This could further be reviewed as $V_o - V_i = -K\,A\frac{d}{dx}\left(\frac{\frac{dV}{dh}}{\ln\mu - \rho}\right)\cdot\frac{dt}{\rho}$ (34)

where $V_o - V_i$ = volume of palm oil after vaporization due to low viscosity.

The next stage of analysis is to consider the weak mixture due to low viscosity, supported by Figure 4.

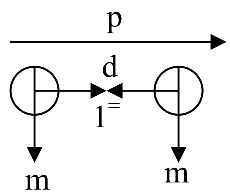

Figure 4. Interation between molecules and gravitation

The starting point is to consider the relationship F α $\frac{m^2}{d^2}$ (Law of Gravitation)

If we take mass of palm oil molecules = m_o, and $F = \frac{Gm_o^2}{d^2}$ (G & m_o are constants), while F = P,

then $$P = \mu A \frac{dV}{dh} \tag{35}$$

This transforms into $$\mu A \frac{dV}{dh} = \frac{Q}{d^2} \; (Q \equiv Gm_o^2) \tag{36}$$

Thus, $$d = \left(\frac{Q}{\mu A \frac{dV}{dh}} \right)^{1/2} \tag{37}$$

Where d = distance separating two atoms of palm oil molecules. It could be stated that

$d \; \alpha \; \left(\frac{1}{\mu} \right)^{1/2}$, and $d \; \alpha \; \frac{1}{\sqrt{\mu}}$. This implication of this is that the lower the viscosity of palm oil, the farther the intermolecular distance between the atoms. Further analysis could relate the mixture between palm oil and another substance. Let D = diameter of mixing substance atoms. Thus Figure 5 is illustrative of this.

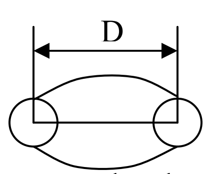

Figure 5. Intermolecular distance between two atoms

Then, $N = \frac{d}{D} = \left(\frac{D}{d}\right)^{-1} = \left(\frac{D}{\sqrt{\frac{Q}{\mu A \frac{dV}{dh}}}}\right)^{-1}$. Thus, the square of N could also be expressed in terms of D, Q, μ, A, dV, and dh as follows: $N^2 = \left(\frac{D^2}{\frac{Q}{\mu A \frac{dV}{dh}}}\right)^{-1} = \left(\frac{D^2 \mu A \frac{dV}{dh}}{Q}\right)^{-1}$

Finding the square root of N gives $N = \left(\frac{D^2 \mu A \frac{dV}{dh}}{Q}\right)^{-\frac{1}{2}} = \left(\frac{Q}{D^2 \mu A \frac{dV}{dh}}\right)^{\frac{1}{2}}$

The number of mixing atoms, N, is obtained by proportionality as $N = \frac{d}{D}$. Thus, we could safely conclude that the number of mixing atoms of another component mixing with palm oil is much when the viscosity is low because the molecular distance widens as viscosity decreases, and the foreign atoms to fill these spaces increase.

3. CASE STUDY

Dynamics Enterprises (DE) is a small-scaled industrial set-up jointly owned by three families who utilise their members for labour activities. This hypothetical business is situated in Ajibode, a village close to Ibadan in Nigeria. As a result of government policy towards industrial development, the Federal agency responsible for funding agricultural projects loaned this enterprise a large sum of money to encourage growth and business expansion. Thus, the enterprise is confronted with loan repayment and business sustainability. However, in recent times, the enterprise has observed a decreasing patronage rate from customers. After a thorough interaction with the customers, it was noted that the major complaint has been linked to unacceptable viscosity. Thus, the owners of the business were motivated at inviting an expert to advise on how to measure the viscosity of the palm oil sold. The invited expert who is a researcher at the Nigerian institute for Oil Palm research developed a relationship between the number of atoms and viscosity, and related this expression graphically to obtain the information below.

In order to demonstrate the application of the model in a practical sense, focus was given to the final equation that expresses a linkage between the number of mixing atoms (N) and other parameters. Data was simulated using a Microsoft Excel add-in called Random Generator. It is noted that the number of mixing atoms (N - unitless), is a function of the following variables: Q (quantity of heat applied - KJ), D (diameter of mixing substance atoms – micro mm), μ (dynamic velocity – Pa.s), A (area of conductor in contact – mm^2), V (velocity – mms^{-1}) and h (distance of the intermediate layers from the stationary plate - mm). The values of all the six independent parameters were randomly generated using the Random Generator. Initially, all (except μ) parameters were kept constant. In addition, D was varied and then Q was varied. Under the three different conditions (varying μ, varying D, and varying Q), the values of the number of mixing atoms (N) were computed again using the terminal equation.

The Microsoft Excel was also used to plot the values of N against μ under three different conditions. The three graphs were superimposed as shown in Figure 6. The graphs (Figure 6) show N1, N2 and N3 curves. N1 curve has only viscosity (with values ranging between 2.19 cSt and 14.56 cSt) was varied, quantity of heat applied (at Q = 100 KJ), area of conductor in contact (at A = 12 mm^2), velocity (at V = 5 mms^{-1}), distance of the intermediate layers (at h = 10 mm), and diameter of mixing substance atoms (at D = 11.64 micro mm) were kept constant. N2 graph has only viscosity (with values ranging between 2.19 cSt and 14.56 cSt) and quantity of heat applied (with values ranging between 21086 KJ and 100 KJ) were varied, area of conductor in contact (at A = 12 mm^2), velocity (V = 5 mms^{-1}), distance of the intermediate layers (at h = 10 mm), and diameter of mixing substance atoms (at D = 11.64 micro mm) were kept constant. N3 graph has only viscosity (with values ranging between 21.86 cSt and 100 cSt), diameter of mixing substance atoms (with values ranging from 5.64 to 28.44) were varied, area of conductor in contact (at A = 12 mm), velocity (at V = 5 mms^{-1}), distance of the intermediate layers (at h = 10 mm) were kept constant.

4. CONCLUSION

With the rapidly expanding food and allied manufacturing industries in small, medium-scale and giant conglomerates, the need for high quality palm oil, is important. This high grade oil, as reflected by its high viscosity, is increasingly being demanded for. In the current work, a mathematical model has been formulated to measure the viscosity of palm oil using some related factors of number of mixing atoms, quantity of heat applied, diameter of mixing substance atoms, dynamic velocity, area of conductor in contact, velocity, and distance of the intermediate layers from the stationary plate. This model has been empirically tested using simulated results to verify the application of the model. The unique attribute of this model to predict values for other parameters in relation to viscosity places a high premium on its value. The developed model presents a platform upon which future models extensions could be made. It will be a worthwhile effort to test the validity of the model, and also calibrate it for a more extensive usage. In essence, it should be noted that the current work is a preliminary investigation in the research direction reported. Subsequent investigations need to be experimental in nature, in which real precise measurements of viscosity should be made with the latest Viscometer, which are commercially available. This will lead to proper model validation, verification, state-of-the-art sensitivity test, and model modification for use by the international scientific community.

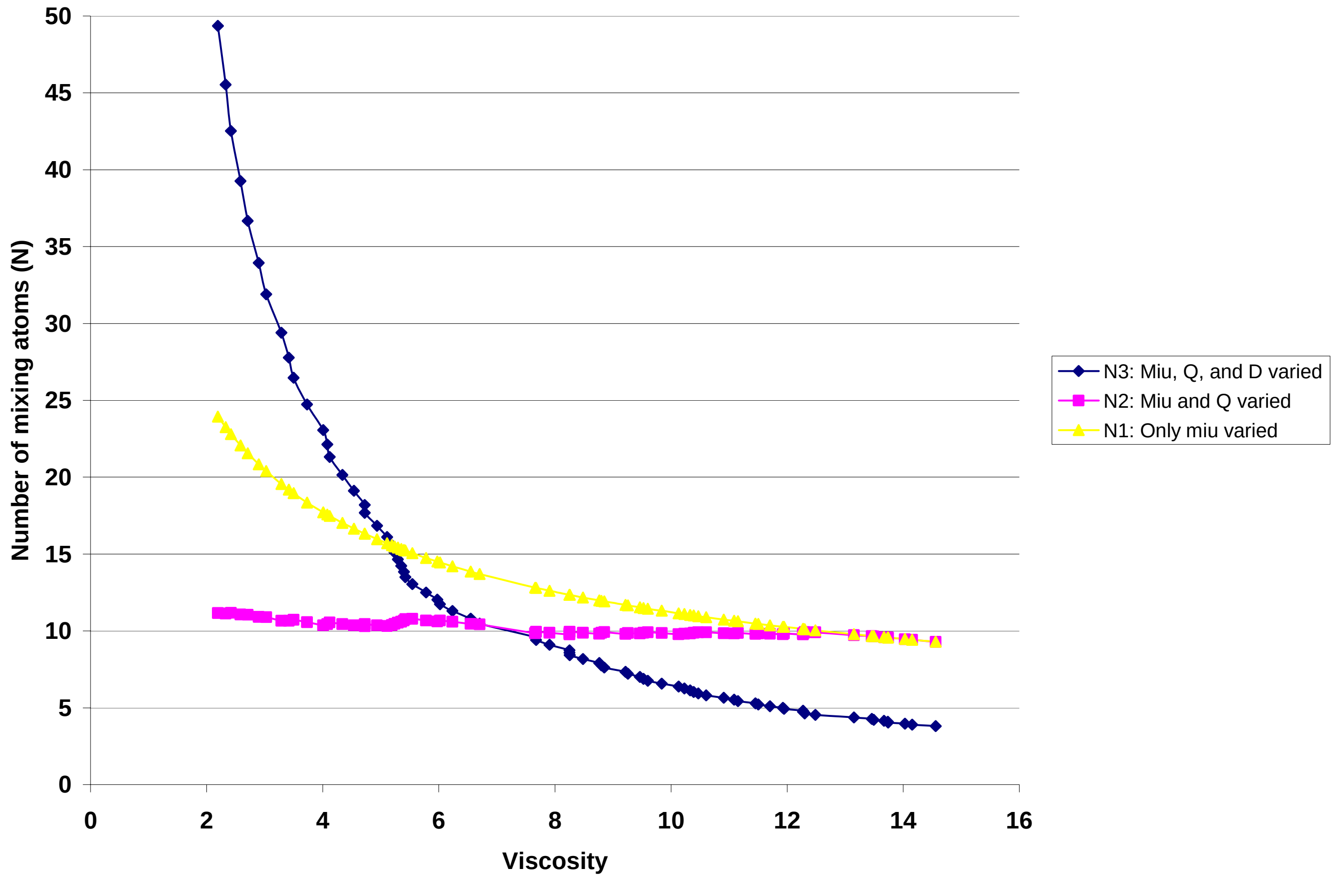

Figure 6. Number of mixing atoms versus viscosity

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