Jurnal LontarPhysics Today
Vol. 1 No. 1 – Februari 2022, p 33 - 37
e-ISSN 2828-0970
Available Online at http://journal.upgris.ac.id/index.php/UPT
DOI: 10.26877/lpt.v1i1.10619

A Mini-Review: Newtonian And Non-Newtonian Approximation To Polymer Melt Viscosity

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Received *04 Januari 2022*
Accepted for publication *12 Januari 2022*
Published *11 Februari 2022*

Abstract

Polymer viscosity is an important thing to study in rheology. Empirical and mathematical approaches must be carried out to determine the mechanism that occurs in the polymer when it enters the melting zone. We know that polymers are non-Newtonian materials when they enter the melting transition region. However, another unique characteristic related to the viscosity of the polymer makes the polymer a superior material according to its application. Therefore, in this paper, we will briefly review Newtonian and non-Newtonian approaches to polymer viscosity. Maybe this paper can help become a reference for further applications in materials that have flowing properties.

Keywords: polymer, viscosity, non-Newtonian, Newtonian

1. Introduction

Viscosity is an inherent property of a material that can flow. In fluids, viscosity is the friction that occurs in the fluid due to the cohesive forces between the liquid molecules [1]. In more detail, viscosity is strongly influenced by temperature, one of which is. In this case, the viscosity is inversely proportional to the temperature. The higher the temperature, the lower the viscosity [2]. According to Liu et al. [3], the higher viscosity of the heavy oil, the higher the burning temperature in the short range of the unburned zone. In this study, gas composition and air injection pressure performed different viscosities. The results exhibited that the oil viscosities of 1180–22500 mPa·s can accomplish stable combustion, and the O_2 content of the gas produced during the stable combustion stage is <0.5%. This result contradicted with other papers from Damayanti et al. [4], the temperature was closely related to viscosity where the higher the temperature, the smaller the viscosity value. In a previous study, it was known the effect of temperature on the viscosity of several syrups which resulted: the viscosity of Kokum syrup, Koronda syrup, Cashew apple syrup, and mango pulp decreases rapidly with increasing temperature [5]. However, the effect of temperature on viscosity is still rarely discussed in studies.

Based on the kinds of literature related to the viscosity of the material [1, 6], it turned out that there was a contradictory pattern between gas samples and liquid samples. Based on Figure 1, the viscosity of the gas sample will increase if it is heated at a high temperature, while the viscosity of the liquid sample will decrease if the temperature is increased. These factors may explain the relatively good correlation between temperature and viscosity. Temperature is required to move the fluid chains from one position to another. Thus, there will be flow in the fluid. So that when explored further, the relationship between force and temperature will be obtained. However, this explanation will be detailed in the next sub-chapter with a non-Newtonian approach.

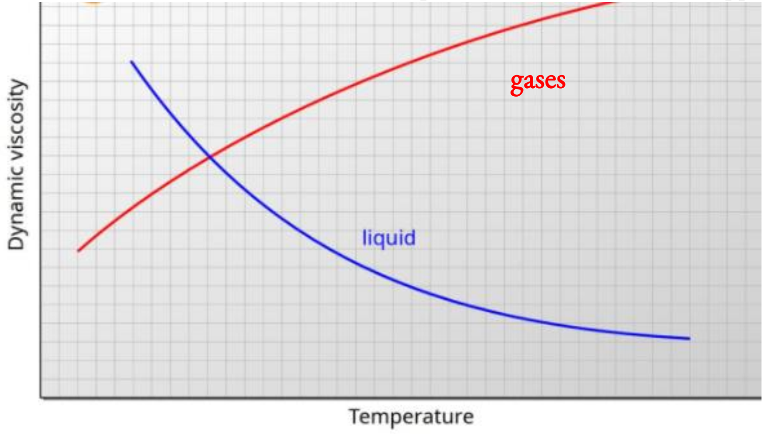

Figure 1. Dynamic viscosity of gases and liquids as a function of temperature [7].

In daily applications, cooking oil is the easiest application we come across from non-Newtonian fluid systems. Cooking oil is a food ingredient with the main composition of triglycerides derived from vegetable ingredients except palm oil, with or without chemical changes, including hydrogenation, cooling and has gone through a refinement/purification process used for frying [8]. The heating process on cooking oil or other polymeric materials can reduce the viscosity of the polymer. The higher the decrease in viscosity of a polymer, the lower its quality.

The discussion of viscosity is very interesting. Especially when associated with the influence of temperature. All this will be discussed further and clearly.

2. Viscosity on polymer

Viscosity generally depends on temperature. when the material flows, there will be a displacement of the position of the particles in the flow at a certain time, so we are more familiar with the "shear rate" ($\dot{\gamma}$). Previously, we needed a certain stress required to displace the fluid whose value is proportional to the shear rate. Thus, the constant of proportionality between these quantities is finally called the (dynamic) viscosity. Mathematically, the proportional relationship between shear rate and shear stress is also known as Newton's law of fluid motion. A fluid that obeys this law is called a Newtonian fluid. The equations are as follows [9]:

$$\tau = \eta\dot{\gamma} \qquad \text{(Newtonian law)} \qquad (1)$$

where τ is stress or (F/A), η is viscosity, while $\dot{\gamma}$ is shear stress. Equation 1 is often called the Newtonian law which is in the flow material. As a result, by looking at the higher viscosity value it can be interpreted that the greater the shear stress required to shift the fluid layer from the initial position to the other position.

A possible explanation for this might be that the increase in atomic distance from the polymer is due to thermal expansion due to heating. If the atomic spacing in the polymer increases with increasing temperature, it is certain that the intermolecular attractive forces decrease. When applied to a flowing material, the fluid layers no longer adhere so tightly to each other as the distance between the molecules increases. If the temperature is continuously increased, the polymer will experience a transition from the solid phase to the liquid phase, in which the flow of the material will be more fluid and free. The presence of a broken polymer chain makes the free volume even greater. So that the behavior of the polymer will deviate from ideal conditions (Newtonian conditions) to be non-Newtonian [10–12].

Due to internal friction within the polymer, shear-thinning will be observed from the melt and polymer solution. This thinning phenomenon is caused by the detachment of polymer chains during flow. If the polymer with a high molecular weight will always be entangled and randomly oriented at rest. However, as the shear rate increases, these bonds will begin to unravel and align causing the viscosity to decrease. Furthermore, at high shear velocities, the main chain of polymer will vibrate and almost move in high speed, even cut off, so that when the polymer melts, the polymer will behave in a non-Newtonian manner. However, the initial conditions will be repeated when the shear speed is high, the polymer will be completely detached and fully aligned. Under these conditions, the viscosity of the molten polymer will be independent of the shear rate, i.e. the polymer will behave like a Newtonian fluid again (see Figure 2).This means the apparent viscosity (η) depends on the applied shear rate and increases rapidly with increasing molecular weight (number of repeat units).

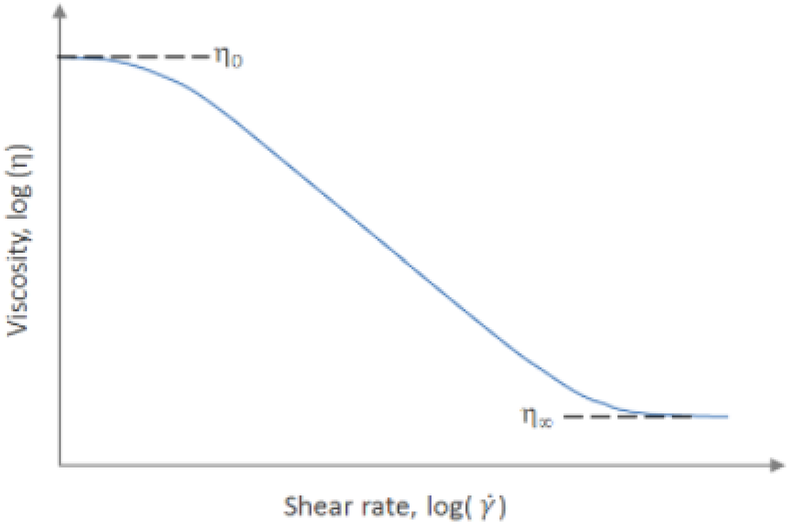

Figure 2. Viscosity behavior of flowing material when in areas with varied shear rates [13].

A strong relationship between stress and shear rate has been reported in literatures [14, 15]. In this melt condition, the shear-thinning regime can be described by the power-law equation of Oswald and de Waele as follows:

$$\tau = K(T)\ \left\lfloor\frac{d\gamma}{dt}\right\rfloor^{n} = K(T)\ \dot{\gamma}^{n} \qquad \text{(non-Newtonian)} \qquad (2)$$

Moreover, some certain flow polymers will require a certain value threshold shear stress as well before starting to flow. A fluid with this flow property is called a plastic fluid and if the flowing fluid has a constant viscosity it is called a Bingham fluid. However, not all polymers have these characteristics. For example, in micro-silica polymers and nanocomposites [16, 17], the solid-like behavior at low shear stresses can be explained by the formation of a silica network structure arising from the attractive particle-particle interactions due to hydrogen bonding between the silanol groups. And after all the polymer chains are broken due to the large shear rate, the material will flow as usual.

The present study was designed to determine the non-Newtonian behavior of the polymer. Equation (3) will express the non-Newtonian approximation when the polymer gets shear-thinning.

$$\tau = \tau_y + K(T)\ \dot{\gamma}^{n} \qquad \text{(non-Newtonian)} \qquad (3)$$

In general, if we return to the behavioral relationship between gases and liquids that differ with respect to temperature, then with the Newtonian fluid approximation, a good approximation is mostly by the exponential function. In liquid fluids, the following approximation is the equation of temperature dependence. Where 0 indicates the fictitious reference viscosity and the constants "a" and "b", and T indicates the temperature [7]. The detail equation was as follows (Equation 4):

$$\eta(T) \approx \eta_0 \ \lfloor e \rfloor^{\frac{a}{T+b}} \tag{4}$$

Based on Figure 1, it can be seen that the behavior of the viscosity of liquids and gases is very contradictory. In gases, the viscosity tends to increase with increasing temperature. Each atom of the gas will experience an increase in the exchange of momentum between the gas layers of each atom. So this condition will greatly affect the viscosity, apart from being caused by other than intermolecular attractive forces. If in a liquid, the exchange of momentum that occurs only applies to the lower region, it is not evenly distributed in all parts of the liquid sample. Thus, the interaction of the momentum of each atom has no decisive influence on the viscosity of the liquid.

In gas samples, this relation can be written in Equation 5. In this equation 0 represents the reference viscosity at reference temperatures T_0 and c which depends on the substance.

$$\eta(T) \approx \eta_0 \ \frac{T0+c}{T+c} \left\lfloor \frac{T}{T0} \right\rfloor^{\frac{3}{2}} \tag{5}$$

With this approach, it is hoped that we will know more about the behavior of the fluid system that we have. By paying attention to the viscosity behavior of the sample, we will be able to know its future applications. Even before we design the development of polymer materials, it is hoped that this basic knowledge will be very helpful as a reference.

3. Conclusion

Based on the main objective of this mini review paper, it is clear that the viscosity of the polymer will be strongly influenced by shear stress and temperature. Under low temperature conditions, the polymer will have Newtonian properties. However, when the temperature is increased and passes through the melting region, the polymer will be non-Newtonian. After all the chains and bonds in the polymer chain are broken, the polymer will return to Newtonian behavior. So in this condition, shear rate or temperature has no effect on viscosity.

Acknowledgements

The author would like to express his gratitude to UPN "Veteran" Jawa Timur which has provided the opportunity and accommodated the author to develop and continue to carry out further research.

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