Rheological Properties of Honey and its Application on Honey Flow Simulation through Vertical Tube

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Abstract. Honey is believed as functional food. Honey is very viscous fluid and make it difficult to flow. Rheological properties of honey is an important parameter to control and process design in food industry where honey used as food ingredients. Rheology is the study of flow and deformation properties of a material when pressure given to it intentionally or naturally. The majority of fluid foods had flow behavior best modelled with power law model which divide fluid into three models; Newtonian and non-Newtonian (Dilatant and Pseudo plastic). The purpose of this study was to examine the rheological characteristics of honey and the effect of temperature on viscosity as well as knowing how accurate the rheological model used (Power Law) to analyze the fluidity properties of honey. The method used is an experimental method with a descriptive analysis. The results showed that the honey used in this study has showed pseudo plastic flow properties with a flow behavior index value of 0.95 ($\tau = 6318.46\gamma^{-0.947}$). Effect of temperature on the viscosity of honey showed that the viscosity of honey decreases with increasing temperature and best modeled with Arrhenius equation ($\mu = 1.05 \times 10^{-10} e^{\frac{76.01}{634.7} T}$). The results of honey flow simulation through the vertical glass tube transport system showed a very high degree of accuracy when compared with the actual results (99.57 %).

1. Introduction

Honey is a natural sweet substance produced by honey bee (Aphis sp.) from floral nectar or other part of plant [1]. According to [2], honey can be classified based on type of honey source, floral and extra floral honey. Extra floral honey refer to source of nectar from other than flower such as leaves and trunk. Honeydew honey is honey whose raw material obtained from Hemipterous insect such as Aphidina, Coccina and Cicadina [3]. Mono floral honey mean its nectar source dominated by only one source of origin while multi floral honey refer to various nectar sources.

Honey has been known as a functional food since a long time ago honey has been used in traditional medicine by many societies in the world. Honey has antioxidant properties and it is believed that the darker the color of honey, the more antioxidant capacity own by the honey [4]. Honey has been also used in treatment to some disease like diabetic ulcers, gastrointestinal disorder, cardiovascular diseases and cancer. Honey is also used as food or food ingredient to give sweet taste. Honey mostly contain sugar fructose and glucose as the main component and the other sugar is also found in very small amount [4]. Protein, vitamin, essential oil and mineral are also found in honey [4].

Rheology is a study the flow and deformation of material under given pressure. Viscosity is the main rheological properties of honey. Honey is usually used in liquid form with high viscosity. Viscosity is simply correlated to the easiness to flow, the higher the viscosity the more difficult the fluid to flow. Honey has viscosity several times (thousand times) of water viscosity and make it difficult to flow. Honey viscosity is mainly affected by water content, temperature and honey composition [5,6]. Composition of honey is affected by the source of nectar and bee types.
Power law model is the simplest and most widely used equation to describe the properties of fluid. The model can be expressed as:

$$\tau = K \left( \frac{\gamma}{\gamma} \right)^n = K \left( \frac{\gamma}{\gamma} \right)^{n-1} \gamma \quad (1)$$

$$\mu_{app} = K \left( \frac{\gamma}{\gamma} \right)^{n-1} \quad (2)$$

In Power law model, rheological properties is time independent and no yield stress. The yield stress is the minimum stress needed to make the fluid flow. The Newtonian fluid (ideal viscous fluid) has n value equal to 1 and K is equal to viscosity which mean viscosity is not affected by its shear rate. Meanwhile for non-Newtonian fluid (n≠1), the viscosity is a function of shear rate and if the viscosity value decrease as the shear rate increase is called as pseudoplastic (shear-thinning) fluid (n<1) and in contract to Dilatant (shear-thickening) fluid (n>1) where viscosity increase as its shear rate increase [7,8]. Thus the two parameters (n and K) is important parameter to describe the flow properties of honey. The natural flow of honey is caused by the force related to gravitational force and shear stress affected by rheological properties of honey with opposite direction to gravitational force. Honey flow through vertical tube is affected by the two forces, gravitational force and shear force due to internal friction within the honey. The thickness of honey attached to the wall surface during flow through vertical tube is affected by the time and honey height from the bottom where honey flowing out the tube [8]. The differential equation which relate the thickness of honey when flowing through vertical tube can be expressed as [8].

$$\frac{\partial (\tau \delta)}{\partial z} = -\frac{\partial \delta}{\partial t} \quad (3)$$

The analytical solution of this differential equation is needed to determine the thickness of honey attached to the tube wall and the solution is

$$\delta = \left\{ \frac{K}{\eta g} \left( \frac{z}{t} \right)^n \right\}^{\frac{1}{n+1}} \quad (4)$$

From the equation above, the thickness of honey attached to the wall is affected by rheological properties of honey. The total volume of honey attached to the wall is determined by integrating the volume over the height range and the total volume of honey left after flowing at certain time will be [8]:

$$q = \int_0^z \pi \left( r^2 - \left( r - \delta \right)^2 \right) \, dz \quad (5)$$

The current study is to determine the rheological properties of honey and its dependency to temperature and to predict the total volume (total mass) of honey left after some flowing times and compare the prediction with the actual value.
2. Material and Methods

2.1 Material

Honey was obtained from Indonesian forest company (PERHUTANI) with water content of 19.79 %. Honey was kept in a closed container and stored at ambient temperature for further analysis. Density of honey was determined by weighing the honey that previously put in 100 ml graduated cylinder.

2.2 Rheological Properties Determination

Rheological properties of honey was determined using rotational viscometer (Raypa RP-1 L Trade, Spain). Spindle L4 with radius of 0.0015 m and cup radius of 0.0235 m were used. The gap distance between the spindle and the cup was 0.022m. Four different rotational rate of spindle were used namely, 20; 30; 50 and 60 RPM. The experiments were replicated twice. Two data were collected, those are rotational spindle rate as independent variable and apparent viscosity as dependent variable. Rheological properties of honey was determined based on Power Law model. The two rheological parameters, n and K, were determined by linearization of equation 2.

\[ \ln \mu_{app} = \ln K + (n-1)\dot{\gamma} \]  \hspace{1cm} (6)

Shear rate (\( \dot{\gamma} \)) was calculated using equation provided by [13]

\[ \dot{\gamma}_w = \frac{2\pi RN}{\delta} \] \hspace{1cm} (7)
The linear regression analysis between $\ln \mu_{app}$ and shear rate $\dot{\gamma}$ was used to determine the value of $n$ and $K$.

2.3 Temperature Effect on Honey Viscosity
Honey was kept at different temperatures (25, 30, 35 and 40 °C) in water bath (Clifton, UK) before being analyzed with rotational viscometer (Raypa type RP-1 L trade, Spain). Spindle L3 with radius 0.006 m and the gap distance of 0.0172 m and 30 RPM was set to measure viscosity of honey. Arrhenius model was used to relate the dependency of viscosity to Temperature.

$$\mu = \mu_0 e^{\frac{E_a}{RT}}$$ (8)

After linearization, equation 8 is becoming

$$\ln \mu = \ln \mu_0 + \frac{E_a}{R} \frac{1}{T}$$ (9)

Two parameter $\mu_0$ and $E_a$ were calculated by linear regression between $\ln \mu$ and $(1/T)$.

2.4 Flow Simulation through Vertical Tube
Honey was poured into vertical tube with diameter of 0.03 m. The height of honey in tube was fixed 0.23 m. The tube was open to let honey flowing out the tube at several flowing times 5, 10, 15 and 20 seconds. At each flowing time, the honey left in the tube was weighed as actual mass of honey. Flow simulation was used to compare the real mass of honey left and the predicted one. The model developed to predict fluid flow was explained detail in [8]. The thickness of fluid flow over the surface ($\delta$) was expressed as:

$$\delta = \left( \frac{\sqrt{2n + 1}}{(\rho g \cos \alpha)^n} \right)^{\frac{n}{n+1}}$$ (10)

The schematic of fluid flow over the surface was presented in Figure 1.
Mass balance of fluid entering the system was set up between the mass of fluid entering the system and leaving the system plus accumulation of fluid mass that might occurred.

\[
\bar{v} \delta W \rho \bigg|_z = \bar{v} \delta W \rho \bigg|_{z+dz} + \frac{\partial \delta \rho W}{\partial z} \, dz
\]

\[
\bar{v} \delta W \rho = \bar{v} \delta W \rho + \frac{\partial (\rho W \bar{v} \delta)}{\partial z} \, dz + \frac{\partial \delta \rho W}{\partial z} \, dz \quad (11)
\]

The density (\( \rho \)) and width (W) are independent to height, z. thus

\[
- \frac{\partial (\rho W \bar{v} \delta)}{\partial z} \, dz = \frac{\partial \delta \rho W}{\partial z} \, dz
\]

\[
- \frac{\partial (\bar{v} \delta)}{\partial z} = \frac{\partial \delta}{\partial z} \quad (12)
\]

From the equation above, the thickness of fluid flow over the surface is the function of height (z) and time (t). The solution of the differential equation above can be seen in appendix A.2.

3. Result and Discussion
3.1 Rheological Properties of Honey
Power law was used to study the rheological properties of honey as reported by [6,5]. In power law model, yield stress was set to zero and viscosity is a function of only shear rate and time independent characteristic [7]. The two parameters in power law model (\( n \) and \( K \)) would describe the rheological properties of honey. The two parameters were determined by linear regression after linear modification of equation which relate apparent viscosity and shear rate (equation 6). The set up condition for the rheological properties of honey was presented in Table 1. All the units were in SI units.
Table 1. Supported Condition for Rheological Measurement

| Specification                                      | Value         |
|---------------------------------------------------|---------------|
| Spindle                                           | L4            |
| Spindle radius (R_D)                              | 0.0015 m      |
| Radius of honey container                         | 0.0235 m      |
| Gap distance between spindle and sample container (δ) | 0.022 m      |
| π                                                 | 3.14          |
| Rotational rate of spindle (RPS*)                 | 1; 0.83; 0.5; 0.33 |
| Water content                                     | 19.79 %       |

*RPS= Rotation per Second

The water content of honey need to be stated due to its main influence on the viscosity of honey apart from other factors such as honey composition [9]. Viscosity of honey is affected by sugar content and sugar content [10]. The calculation and result for determining rheological properties of honey was presented in Table 2. From Table 2, it can be seen that the higher the shear rate (derived from spindle rotational rate), the lower the viscosity of honey which indicate the tested honey had a pseudo plastic behavior. In literature, honey was reported having a pseudo plastic behavior [6,1] and also Newtonian properties [6]. As can be seen in Table 2, the n value of honey was very close to 1 (n = 0.947) which indicating pseudo plastic behavior. The parameter K in Newtonian model fluid is the viscosity itself while in pseudo plastic model fluid, the viscosity was the function of K and shear rate and called as apparent viscosity. The K value obtained was close to the viscosity range of honey, 6540-7010 mPa s.

Table 2. Data and Result in Determining Rheological Properties of Honey

| RPM | RPS | \( \dot{\gamma} \) | \( \mu \) (mPas) | ln \( \dot{\gamma} \) | n-1 | ln K | n | K | R² |
|-----|-----|---------------------|-------------------|---------------------|-----|------|---|----|----|
| 60  | 1   | 0.42                | 6540              | -0.84               |     |      |   |    |    |
| 60  | 1   | 0.42                | 6620              | -0.84               |     |      |   |    |    |
| 50  | 0.83| 0.35                | 6610              | -1.03               |     |      |   |    |    |
| 50  | 0.83| 0.35                | 6750              | -1.03               |     |      |   |    |    |
| 30  | 0.5 | 0.21                | 6890              | -1.54               | -0.05| 8.75| 0.947| 6312.2 | 0.83 |
| 30  | 0.5 | 0.21                | 6980              | -1.54               |     |      |   |    |    |
| 20  | 0.33| 0.14                | 6910              | -1.94               |     |      |   |    |    |
| 20  | 0.33| 0.14                | 7010              | -1.94               |     |      |   |    |    |

3.2 Effect of Temperature on Viscosity

Viscosity of fluid is dependent on temperature and generally increasing temperature of fluid will decrease its viscosity [11, 12]. Figure. 2 showed viscosity of honey at different temperature. It can be seen that the viscosity of honey decreased as temperature increased. [4] reported that at temperature above 40 °C, honey viscosity is not affected by temperature any more.
Arrhenius equation is the simplest and common model to relate the effect of temperature on physical or chemical properties of food system [12]. The temperature dependency of viscosity of honey were also reported following Arrhenius model [13]. The parameter determination of Arrhenius model was presented in Table 3. The activation energy of honey obtained was 77.69 kJ/mole and this value was higher than the activation energy of some liquid food as reported by [12] such as 5.0 kJ/mole for apple sauce and 59.5 kJ/mole for depectinized apple juice. The activation energy was affected by the temperature range where the measurement done [12]. The model to relate the dependency of viscosity was also depend on the range of temperature and [6] reported that the William-Landel-Ferry (WLF) model is better model to relate the dependency of temperature on honey viscosity in the temperature range of Tg (glass temperature) + 100 °C compared to Arrhenius model and Vogel-Tammann-Fulcher (VTF) model.

Table 3. Data and Result in Determining the Effect of Temperature on Honey Viscosity

| T (°C) | T (K) | 1/T | µ (mPa s) | ln µ | ln µ₀ | µ₀ | Ea/R (J/mole.K) | R (kJ/mole) | Ea (kJ/mole) | R² |
|-------|-------|-----|----------|------|------|----|----------------|-------------|-------------|----|
| 25    | 298   | 0.00336 | 4630     | 8.44 | 22.98 | 1.05E-10 | 9344.65 | 8.314 | 77.69 | 0.903 |
| 25    | 298   | 0.00336 | 4710     | 8.46 |       |     |                |             |             |     |        |
| 30    | 303   | 0.00330 | 2290     | 7.74 |       |     |                |             |             |     |        |
| 30    | 303   | 0.00330 | 2430     | 7.80 |       |     |                |             |             |     |        |
| 35    | 308   | 0.00325 | 1450     | 7.28 |       |     |                |             |             |     |        |
| 35    | 308   | 0.00325 | 1690     | 7.43 |       |     |                |             |             |     |        |
| 40    | 313   | 0.00319 | 920      | 6.82 |       |     |                |             |             |     |        |
| 40    | 313   | 0.00319 | 1110     | 7.01 |       |     |                |             |             |     |        |

3.3 Flow Simulation of Honey through Vertical Tube
Rheological properties of honey was used to simulate the flow of honey through vertical tube and compared the prediction with the actual result. The analytic solution of fluid flow through vertical tube was explained in [8]. The vertical tube flow of honey is a resultant between gravitational force and resistant flow related to rheological properties of the fluid. For simplification, friction force due to contact of fluid to surface is negligible. The schematic flow of honey through vertical tube was presented in Figure 3.
Figure 3. The Schematic Flow of honey through vertical tube

From Figure 3, when honey flows through vertical tube, the thickness of honey attached to the tube wall varies with the height. If the height of honey in vertical tube was \( z \), the volume of honey, \( dq \) over an increment of height, \( dz \) was expressed as:

\[
\partial q = \pi \left( r^2 - \left( r - \delta \right)^2 \right) \partial z \quad (13)
\]

Thus to determine the total volume of honey attached to the tube wall (\( q \)) during flowing through vertical tube was

\[
\int \partial q = \int_0^z \pi \left( r^2 - \left( r - \delta \right)^2 \right) \partial z
\]

\[
q = \int_0^z \pi \left( 2r\delta - \delta^2 \right) \partial z \quad (14)
\]

\[
q = \int_0^z \pi 2r \partial z - \int_0^z \pi \delta^2 \partial z
\]

Since

\[
\delta = \left( \frac{K}{\rho g} \right)^{\frac{1}{n+1}} \left( \frac{z}{t} \right)^{\frac{n}{n+1}}
\]

Thus

\[
q = 2\pi r \left( \frac{K}{\rho g} \right)^{\frac{1}{n+1}} \left( \frac{1}{t} \right)^{\frac{n}{n+1}} \int_0^z \frac{z}{n+1} \partial z - \int_0^z \pi \left( \frac{K}{\rho g} \right)^{\frac{1}{n+1}} \left( \frac{z}{n+1} \right)^{\frac{n}{n+1}} \partial z
\]
Thus the total mass of honey left after allowing honey flow through vertical tube at certain time would be:

\[ m_{\text{honey}} = q \times \rho \]  \hspace{1cm} (16)

The data needed to calculate the total mass of honey left in the tube could be seen in Table 4.

**Table 4.** Data Needed in Simulation of Honey Flow through Vertical Tube.

| Specification                  | Value                  |
|--------------------------------|------------------------|
| Mass of Honey                  | 300 g                  |
| Radius of Tube                 | 0.0155 m               |
| Height of honey in tube        | 0.23 m                 |
| Honey Density                  | 1600 kg/m\(^3\)        |
| Gravitational constant         | 9.8 m/s\(^2\)          |
| Flow behavior index (n)        | 0.946                  |
| Consistency Index (k)          | 6.3172 mPa s           |

The flow of honey through vertical tube was tested at some series of flowing times namely, 5; 10; 15 and 20 seconds. The calculated mass of honey left after flowing at certain time was shown for flowing time of 5 second as follow:

\[
q = 2\pi r \left( \frac{K}{\rho g} \right)^n \left( \frac{1}{t} \right)^{n+1} \frac{n+1}{2n+1} z^2 + \pi \left( \frac{K}{\rho g} \right)^2 \left( \frac{1}{t} \right)^{2n+1} \frac{n+1}{3n+1} z^\frac{3n+1}{n+1} \right|_0 \hspace{1cm} (15)
\]

\[
q = 2\pi r \left( \frac{K}{\rho g} \right)^n \left( \frac{1}{t} \right)^{n+1} \frac{n+1}{2n+1} z^2 - \pi \left( \frac{K}{\rho g} \right)^2 \left( \frac{1}{t} \right)^{2n+1} \frac{n+1}{3n+1} z^\frac{3n+1}{n+1} \right|_0
\]

Thus the total mass of honey left after allowing honey flow through vertical tube at certain time would be:

\[
q = 2\pi r \left( \frac{K}{\rho g} \right)^n \left( \frac{1}{t} \right)^{n+1} \frac{n+1}{2n+1} z^2 + \pi \left( \frac{K}{\rho g} \right)^2 \left( \frac{1}{t} \right)^{2n+1} \frac{n+1}{3n+1} z^\frac{3n+1}{n+1} \right|_0
\]

\[
q = 2\times \pi \times 0.0155 \left( \frac{6.3172}{1600 \times 9.8} \right)^{0.947} \left( \frac{1}{5} \right)^{0.947+1} \frac{0.947+1}{2 \times 0.947+1} 0.23 \left( \frac{2 \times 0.947+1}{0.947+1} \right)^{0.947+1} \hspace{1cm} (17)
\]

\[
q = 6.081 \times 10^{-5} - 5.964 \times 10^{-6} m^3 = 5.485 \times 10^{-5} m^3
\]

**total mass of honey left in the tube** = \[ 5.485 \times 10^{-5} m^3 \times 1600 \frac{kg}{m^3} = 0.08775 kg = 87.75 g \]

The comparison of calculated mass of honey left and real mass of honey for all time of flow tested was presented in Table 5.
Table 5. Mass of Honey Left (Actual vs Predicted)

| Time (s) | Mass of Honey Left (g) | Actual | Predicted |
|---------|------------------------|--------|-----------|
| 5       | 90                     | 87.75  |
| 5       | 88                     | 87.75  |
| 10      | 66                     | 64.59  |
| 10      | 64                     | 64.59  |
| 15      | 52                     | 53.74  |
| 15      | 54                     | 53.74  |
| 20      | 46                     | 47.1   |
| 20      | 47                     | 47.1   |

Figure 4 showed the closeness (accuracy) of calculated value and actual value of honey mass attached to the tube at different flowing times. The linear model with the intercept set to zero, thus the slope will describe the accuracy of the predicted values to actual values. The slope 1 mean all (100 %) the actual value equal to the predicted value. As can be seen from Figure 3, the obtained slope was 0.9957 which mean the model developed to predict the mass of honey left comply with the actual value correctly at accuracy level of 99.57 %. The rheological properties of honey is an important input in developing the model and it showed to us that the rheological properties could be used as an important component in developing control and process design in food industry where honey used as one of food ingredients.

Figure 4. Accuracy of Mass of Honey Left (Actual vs Predicted)

4. Conclusion
Honey showed pseudoplastic fluid behavior with n and K value 0.946 and 6318.46 respectively. The effect of temperature on honey viscosity was best modelled with Arrhenius model ($\mu = 1.05 \times 10^{-10}$ $\exp \frac{76.011}{T}$). Simulation flow of honey through vertical tube showed good accuracy between the predicted value and actual value (99.57 %). The rheological properties of honey and equation developed were proven to be accurate in predicting the honey flow through vertical tube.
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