Effect of Temperature on Rheological Behavior of Liquid Milk and Its Impact to Adequacy of Thermal Process

Eko Hari Purnomo¹ ² and Ni Putu Ariva Satyani¹

¹Department of Food Science and Technology, IPB University, Kampus IPB Darmaga, Bogor, Indonesia
²Seafast Center, IPB University, Kampus IPB Darmaga, Bogor, Indonesia

Keywords: Milk Rheology, Temperature, Sterilization.

Abstract: Temperature is one of the factors affecting fluid flow characteristics and the thermal adequacy in milk sterilization in an aseptic system. This research is aimed to study density and rheology of milk at temperature of 20-80 0C and its effect to Reynold number and thermal sterility. Four different kinds of commercial milk were used. The density and rheological properties were measured by using densitometer a Brookfield Viscometer DV II, respectively. The results showed that the milks were Newtonian. Temperature affected the density and viscosity of the liquid milk and consequently affected the Reynolds number. Increased temperatures lead to decreased density and decreased viscosity which could be well described using an Arrhenius model. Combined effect of increased temperature on decreased density and viscosity resulted in increased Reynolds numbers. This indicated that Reynolds number is more affected by the value of viscosity rather than density, as temperature increased. Under a full-scale production set up in one of the milk factories, the four kinds of liquid milk exhibited turbulent fluid flow properties (Reynolds number more than 4000). Therefore, decreased viscosity and density of milk at elevated temperature did not adversely affect adequacy of aseptic thermal process at a constant flow rate.

1 INTRODUCTION

Milk is one of the good sources of protein, vitamin, fat, and minerals with relatively short shelf life (Miller 2007). Pasteurization and sterilization are often used to extend its shelf life. Milk consumption in Indonesia is relatively low as compared to other countries. However, the growth of milk consumption in Indonesia is increasing, which is believed to be associated with the growing of middle-income population (15% within 10 years) (USDA 2016). This market growth drives the milk industry to increase the production of safe and high-quality milk to be able to compete in the market.

Sterilization is more favorable to preserve liquid milk due to its longer shelf life and handling convenience. Liquid milk is commonly sterilized using an aseptic system in which the milk is held at a temperature of around 140° C for few seconds in a holding tube to achieve a minimum sterility level. The Government of Republic of Indonesia requires that thermally sterilized food should have F0 of at least 3.0 minutes to ensure product safety (BPOM, 2016).

Thermal sterilization is determined by two main factors i.e. time and temperature. Minimum residence time of the milk in holding tube is strongly affected by its rheological properties (viscosity (µ), flow behavior index (n), and consistency index (K)) and Reynold number (Re). Depending on its Re, flow of milk in the holding tube can be either laminar (Re<4000) or turbulent (Re>4000). For milk flowing in a specific geometry and a constant volume rate, Re is affected by both milk viscosity and density.

Rheological properties of milk and the effect of temperature on milk’s rheology is well studied. McCarty and Singh (2009) reported that milk with fat content less than 40% (w/w) measured at temperature above 40°C shows Newtonian behavior. Several researchers studied the effect of temperature on milk viscosity (Cheng, Barbano, and Drake, 2019 and Deshpande & Walsh, 2017). Viscosity of milk decreases as temperature increases. However, no study has shown the effect of temperature on milk viscosity and milk density. Therefore, it is important to study the effect of temperature on milk viscosity and density to be able to predict its effect on the Reynold number and finally assess its possible effect to the adequacy of a thermal process in a holding tube during sterilization process.
2 MATERIAL AND METHOD

2.1 Material

Four types of UHT milk i.e. full cream, chocolate milk 1, chocolate milk 2, and strawberry milk were used in this study. The equipment used were density meter Anton Paar DMA 35 and Brookfield Viscometer RVDV-II Pro, water bath, and hotplate.

2.2 Method

2.2.1 Density Measurement

Milk density was measured using portable densitometer Anton Paar model DMA 35. Milk density at different temperatures (20, 30, 40, 50, 60, 70, dan 80°C) were measured.

2.2.2 Characterization of Rheological Properties

Shear stress of the sample was measured using Brookfield viscometer RVDV-II Pro at different spindle speed i.e. 0.5, 1.0, 2.0, 2.5, 4.0, 5.0, 10.0, 20.0, 50.0, dan 100.0 rpm. Shear rate was calculated from the spindle speed using the following formula:

\[ \gamma_w = \frac{2\pi RN}{\delta} \]  

where \( \gamma_w \) is shear rate (s-1), R is radius of the spindle (cm), N is rotational speed of the spindle (RPM), \( \delta \) is gap between spindle and container wall (cm).

2.2.3 Thermal Process Adequacy Analysis

Thermal process adequacy expressed as \( F_o \) value is calculated using the following formula

\[ F_o = \frac{t_{\text{min}}}{10\left(\frac{1}{T_{\text{ho}}} + \frac{1}{T_{\text{ho}}} \right)} \]  

Where

\[ t_{\text{min}} = \frac{L}{V_{\text{max}}} \]  

\( L \) is minimum length of holding tube, \( V_{\text{max}} \) is speed of fastest moving particles, \( T_{\text{ho}} \) is product temperature at the outlet of holding tube, \( z \) value is 100°C, and \( t_{\text{min}} \) is minimum residence time of milk in the holding tube. \( V_{\text{max}} \) is obtained from average velocity and their relation depends on Re. For a Newtonian liquid, Re can be calculated using the following formula:

\[ Re = \frac{\rho DV}{\mu} \]  

Where \( \rho \) is density (kg/m³), D is diameter of the holding tube (m), \( V \) is average speed of milk flowing in holding tube (m/s), and \( \mu \) is viscosity (Pa.s).

3 RESULT AND DISCUSSION

3.1 Milk Density

Density of milk is the intrinsic physical parameter of milk contributing to flow properties. Figure 1 shows that effect of temperature on density of different milk. Milk density decreased as function of time. At a temperature of 20°C, milk density ranges from 1.0319 to 1.0596 g/ml. whereas at a temperature of 80°C, the density ranged between 1.0037 g/ml and 1.0335 g/mL. Similar observation was reported by Minim, Coimbra, and Minim (2002) and Munir et. al. (2016). Kumbar, and Nedomova (2015) stated that density of fresh and UHT milk at different fat contents (0.5, 1.5 dan 3.0%) decreases at higher temperatures. Moreover, density of full cream milk was markedly lower compared to chocolate and strawberry milk. It was believed to be associated with higher fat content of full cream milk (McCarty and Singh (2009), Munir et. al. (2016) and Alcantara et. al. (2012)).
3.2 Milk Rheology

Rheological properties of milk determine flow characteristic of the milk flowing in holding tube during sterilization process. One of the important rheological parameters of milk is its viscosity. Under a specific sterilization system, milk with higher viscosity flows at lower velocity. For a non-Newtonian fluid, viscosity can be strongly influenced by shear rate. The milks used in this study showed Newtonian behavior in which its viscosity was not influenced by shear rate.

Figure 2 shows flow curves of the chocolate milk 1 measured at different temperatures. Shear stress increased as function of shear rate. At a constant shear rate, higher shear stress was observed for milk measured at lower temperature. Relation between shear rate (g) and shear stress (t) of the milk was well explained using Power Law model \( t = K\gamma^n \).

Two rheological parameters extracted from power law model were flow behavior index \( n \) and consistency index \( K \). Table 2 shows that flow behavior index of milks was close to 1. It means that the milks were Newtonian at temperature range of 20-80 °C (Toledo, 2012). Similar observation for milk measured at 25, 35, 45, 55 dan 65 °C (Roozi et al., 2007), milk containing fat content less than 40% (McCarthy and Singh, 2011), milk containing soluble solid less than 20% (Morison, Phelan and Bloore, 2013). Rao (2007) stated that fluid containing low molecular weight substances exhibited Newtonian behavior (linear relation between shear stress and shear rate). In addition, Table 3 shows the effect of temperature on the consistency index \( K \) of milks. Consistency index of full cream milk was lower than chocolate milk 1. Index consistency of milks decreased as function of temperatures.

Since the milks exhibited Newtonian behavior, its viscosity was independent of shear rate. Figure 3 shows viscosity of the milks measured at temperature of 20-80 °C. Viscosity of the milks decreased as temperature increased. Similar trends were also found in other reports (Flauzino et al., 2009, Bozikova and Hlavac, 2013, and Kumbar and Nedomova, 2015). The Arrhenius model used to describe the temperature dependence of viscosity on temperature fitted well to the experimental data. Fitting parameters including the activation energy of the Arrhenius model for temperature dependence of viscosity is presented in Table 4. Activation energy of chocolate milk 2 was the highest indicating that viscosity of chocolate milk 2 was the most sensitive to temperature change (Cuah et al., 2008). Goat milk was reported to have lower activation energy of 6.2736 kJ mol\(^{-1}\) (Gabas et al., 2012). Whereas Velez Ruiz (1998) reported that activation energy of milk concentrated ranged between 2.42 and 11.8 kcal g \(^{-1}\). Activation energy of milk cream, fermented milk, and whey protein were reported to be higher. Activation energy of milk cream, fermented milk, and whey protein were 20.5 kJ mol\(^{-1}\) (Flauzino et al., 2009), 19.57 kJ mol\(^{-1}\) (Goncalves et al., 2017), and 19.92 kJ mol\(^{-1}\) (Tello et al., 2009), respectively.

Table 1: Arrhenius model and activation energy for density of four different milks.

<table>
<thead>
<tr>
<th>Milk</th>
<th>Arrhenius model</th>
<th>Activation energy, kJ mol(^{-1})</th>
<th>R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fullcream</td>
<td>B(_a) = 6.7759 exp (48.116/T)</td>
<td>5.7873 x 10(^5)</td>
<td>0.9958</td>
</tr>
<tr>
<td>Chocolate 1</td>
<td>B(_a) = 6.3166 exp (43.715/T)</td>
<td>5.2579 x 10(^5)</td>
<td>0.9972</td>
</tr>
<tr>
<td>Strawberry</td>
<td>B(_a) = 6.8184 exp (42.290/T)</td>
<td>5.0866 x 10(^5)</td>
<td>0.9925</td>
</tr>
<tr>
<td>Chocolate 2</td>
<td>B(_a) = 6.8052 exp (46.546/T)</td>
<td>5.5985 x 10(^5)</td>
<td>0.9930</td>
</tr>
</tbody>
</table>

Table 2: Flow behavior index (n) of full cream milk and chocolate milk 1 measured at different temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Full cream milk</th>
<th>Chocolate milk 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.0610</td>
<td>1.0176</td>
</tr>
<tr>
<td>30</td>
<td>1.0562</td>
<td>1.0356</td>
</tr>
<tr>
<td>40</td>
<td>1.0360</td>
<td>1.0455</td>
</tr>
<tr>
<td>50</td>
<td>1.0718</td>
<td>1.0501</td>
</tr>
<tr>
<td>60</td>
<td>1.0084</td>
<td>1.0570</td>
</tr>
<tr>
<td>70</td>
<td>0.9605</td>
<td>1.0493</td>
</tr>
<tr>
<td>80</td>
<td>1.0202</td>
<td>1.0693</td>
</tr>
</tbody>
</table>

Table 3: Consistency index (K) of full cream milk and chocolate milk 1 measured at different temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Full cream milk</th>
<th>Chocolate milk 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.6408</td>
<td>0.0743</td>
</tr>
<tr>
<td>30</td>
<td>0.6410</td>
<td>0.0673</td>
</tr>
<tr>
<td>40</td>
<td>0.9411</td>
<td>0.0573</td>
</tr>
<tr>
<td>50</td>
<td>0.0121</td>
<td>0.0486</td>
</tr>
<tr>
<td>60</td>
<td>0.0556</td>
<td>0.0495</td>
</tr>
<tr>
<td>70</td>
<td>0.0197</td>
<td>0.0503</td>
</tr>
<tr>
<td>80</td>
<td>0.0504</td>
<td>0.0528</td>
</tr>
</tbody>
</table>

Figure 2: Flow curve of chocolate milk 1 at different temperatures. The lines represent corresponding power law model of each sample.
3.3 Reynold Number and Thermal Process Adequacy

Milk is often processed using an aseptic system in which thermal sterilization is carried out in a holding tube for few second at temperature of around 140°C (Varzakas & Labropoulos, 2007). Minimum residence time of the milk in the holding tube is controlled by fastest moving particles in the milk. It is almost impossible and impractical to directly measure velocity of fastest moving particles. Velocity of fastest moving particle can be quantitively predicted from its average velocity obtained from flow rate of the milk. However, the relation between maximum velocity and average velocity of milk flowing in a holding tube depends on dimensionless Reynold number defined as \( r DV/m \). Milk flow is under turbulent condition if the Reynold number is higher than 4000. It has been shown that both density \( \rho \) and viscosity \( m \) of milk decreased as temperature increased. Combined effect of density and viscosity of milk, flowing in a commercial holding tube, on Reynold number as temperature increased is shown in Figure 4. Reynold number increased as temperature increased for all the samples.

Increased Reynold number along with increase in temperature indicated that decreased viscosity had a more dominant effect than decreased density. This effect could also be observed from the activation energy of viscosity change (Table 4) which were higher than activation energy for density change (Table 1). The higher the activation energy, the more sensitive the parameter to temperature change.

Figure 4 shows that Reynold number of the milks was higher than 4000 which mean that the flow of the milk was turbulent. For turbulent flow, velocity of fastest moving particle determining minimum residence time is \( 1.23 \times \) average velocity (Steffe, 1996). However, since increased temperature resulted in higher Reynold number, the flow characteristic of the milks in the holding tube remained turbulent. Therefore, the effect of decreased density and viscosity which resulted in increased Reynold number did not adversely affect the safety of sterilized milk.
REFERENCES


