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

Eko Hari Purnomo[1,2] and Ni Putu Arriva Satyani[1]
[1]*Department of Food Science and Technology, IPB University, Kampus IPB Darmaga, Bogor, Indonesia*
[2]*Seafast 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 140ºC 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 F_o 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 40ºC 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.

Purnomo, E. and Satyani, N.
Effect of Temperature on Rheological Behavior of Liquid Milk and Its Impact to Adequacy of Thermal Process.
DOI: 10.5220/0009977900002833
In *Proceedings of the 2nd SEAFAST International Seminar (2nd SIS 2019) - Facing Future Challenges: Sustainable Food Safety, Quality and Nutrition*, pages 38-42
ISBN: 978-989-758-466-4

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^{o}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:

$$\gamma_w = \frac{2\pi RN}{\delta} \tag{1}$$

where γ_w is shear rate (s-1), R is radius of the spindle (cm), N is rotational speed of the spindle (RPM), δ 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

$$F_o = \frac{t_{min}}{10^{\left[\frac{121.1-T_{ho}}{z}\right]}} \tag{2}$$

Where

$$t_{min} = \frac{L}{V_{maks}} \tag{3}$$

L is minimum length of holding tube, V_{max} is speed of fastest moving particles, T_{ho} is product temperature at the outlet of holding tube, z value is 10oC, and t_{min} is minimum residence time of milk in the holding tube. Vmax is obtained from average velocity and their relation depends on Re. For a Newtonian liquid, Re can be calculated using the following formula:

$$\text{Re} = \frac{\rho DV}{\mu} \tag{4}$$

Where r is density (kg/m^3), D is diameter of the holding tube (m), V is average speed of milk flowing in holding tube (m/s), and m 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^{o}C, milk density ranges from 1.0319 to 1.0596 g/ml. whereas at a temperature of 80^{o}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 (McCarthy and Singh (2009), Munir et. al. (2016) and Alcantara et. al. (2012)).

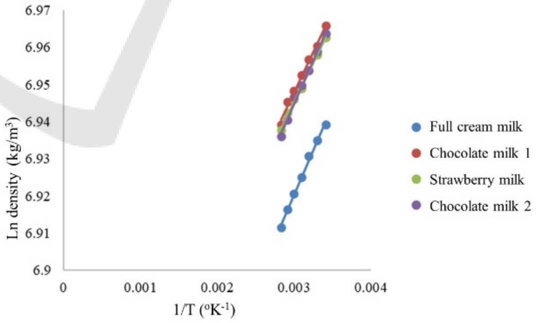

Figure 1: Effect of temperature on milk density. The lines represent corresponding Arrhenius model of each sample.

The dependence of milk density to temperature was well described using Arrhenius model in which natural logarithmic of density is plotted against 1/T (^{o}K). Table 1 shows the Arrhenius model of the four samples including their activation energy. Full cream milk exhibited higher activation energy compared to the three other milks. It indicated that density of full cream milk was more sensitive to temperature change.

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

Milk	Arrhenius model	Activation energy, kJ mol^{-1}	R^2
Fullcream	$B_A = 6.7759 \exp(48.116/T)$	5.7873×10^3	0.9958
Chocolate 1	$B_A = 6.8166 \exp(43.715/T)$	5.2579×10^3	0.9972
Strawberry	$B_A = 6.8184 \exp(42.290/T)$	5.0866×10^3	0.9925
Chocolate 2	$B_A = 6.8052 \exp(46.546/T)$	5.5985×10^3	0.9930

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 ($t=Kg^n$).

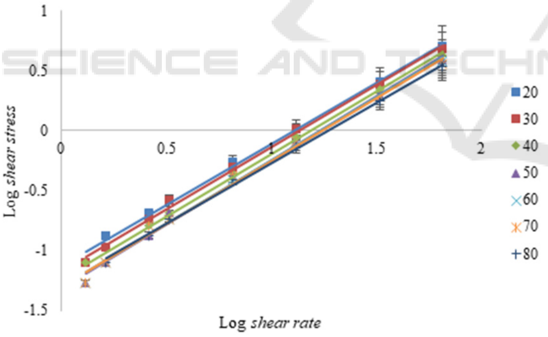

Figure 2: Flow curve of chocolate milk 1 at different temperatures. The lines represent corresponding power law model of each sample.

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.

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

Temperature (°C)	Flow behavior index(n)	
	Fullcream milk	Chocolate milk 1
20	1.0610	1.0176
30	1.0502	1.0356
40	1.0300	1.0455
50	1.0738	1.0691
60	1.0084	1.0570
70	0.9605	1.0493
80	1.0202	1.0093

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

Temperature (°C)	Consistency index (K)	
	Full cream milk	Chocolate milk 1
20	0.0408	0.0743
30	0.0410	0.0673
40	0.0411	0.0573
50	0.0321	0.0486
60	0.0356	0.0495
70	0.0397	0.0503
80	0.0304	0.0528

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 mol^{-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.

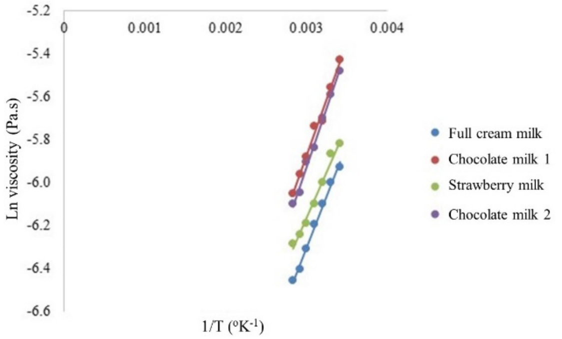

Figure 3: Effect of temperature on viscosity of different milks measured at different temperatures. The lines represent corresponding Arrhenius model of each sample.

Table 4: Arrhenius model and activation energy for viscosity of four different milks.

Sample	Arrhenius model	Ea (kJ mol^{-1})	R^2
Full cream milk	$B_A = 9.197 \exp(964.21/T)$	8.0164	0.9932
Chocolate milk 1	$B_A = 9.033 \exp(1052.30/T)$	8.7488	0.9881
Strawberry milk	$B_A = 8.766 \exp(866.44/T)$	7.2036	0.9836
Chocalate milk 2	$B_A = 9.234 \exp(1102.00/T)$	9.1620	0.9949

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 rDV/m. Milk flow is under turbulent condition if the Reynold number is higher than 4000. It has been shown that both density (r) 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 x 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.

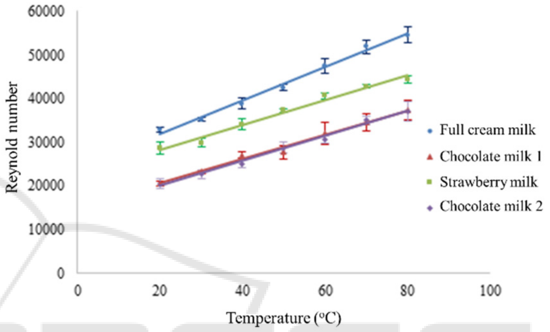

Figure 4: Effect of temperature in Reynold number of different milks.

4 CONCLUSIONS

Density and viscosity of milk are two intrinsic properties of milk which may affect fluid dynamic inside a holding tube. Density of four commercially available milk i.e. full cream milk, chocolate milk 1, strawberry milk, and chocolate milk 2 were lower when measured at different temperature. The four different kind of milk showed Newtonian behavior at different measurement temperatures (20-80°C). Viscosity the milks decreased as function of temperature. Milk density and viscosity dependence on temperature were well described using Arrhenius model. Viscosity is found to be more temperature dependent than density. Effect of density to Reynold number was the opposite of viscosity effect to Reynold number. However, combined effect of increased temperature on density and viscosity resulted in higher Reynold number. Therefore, under a constant flow rate, milk sterilization in a holding tube at higher temperature did not reduce minimum residence time and consequently did not reduce thermal process adequacy.

REFERENCES

Alcantara L.A.P, Fontan, R.C.I., Bonomo, R.C.F., de Souza, E.C., Sampaio, V.S. and Pereira, R.G. 2012. Density and dynamic viscocity of bovine milk affect by temperature and composition. International Journal of Food Engineering. 8(1).

Bozikova M and Hlavac P. 2013. Temperature and storing time influence on selected physical properties of milk band acidophilus milk. Acta Univeritatis Agriculturae et Silviculturae Mendelianae Brunensis. 6:1589-1595.

[BPOM] Badan Pengawas Obat dan Makanan. 2016. Peraturan kepala badan Pengawas Obat dan makanan Republik Indonesia Nomor 24 tahun 2016 tentang Persyaratan Pangan Steril Komersial Jakarta(ID): BPOM.

Cheng, N., Barbano, D.M., and Drake, M. A., 2019. Effect of pasteurization and fat, protein, casein to serum protein ratio, and milk temperature on milk beverage color and viscosity. Journal of Dairy Science 102:2022–2043.

Cuah T.G, Ling H.L, Chin N.L, Choong T.S.Y, and Fakhru'l-Razi A. 2008. Effect temperatures on rheological behaviour of dragon fruit (hylocereus sp). Journal of Food Engineering 4(7): 1-30.

Deshpande, V.K., and Walsh, M.K., 2017. Effect of sonication on the viscosity of reconstituted skim milk powder and milk protein concentrate as influenced by solids concentration, temperature and sonication. Int Dairy J. 78: 122-129.

Flauzino R.D.F, Wilhelms J.A, Tadini C.C., and Romero J.T. 2009. Flow properties and tube friction factor of milk cream: influence of temperature and fat content. Journal of Food Processing. 33: 820-836.

Gabas, A. L., Cabral, R.A.F., Oliveira, C.A.F., Romero J.T. 2012. Density and rheological parameters of goat milk. Cienc. Tecnol. Aliment. 32(2): 381-385.

Goncalves, B.J, Pereira, C.G, Lago, A.M.T, Goncalves, C.S, Giarola T.M.O, Abreu, L.R dan Resende, J.V. 2017. Thermal conductivity as influenced by the temperature and apparent viscocity of dairy products. Journal of Dairy Science 100:1-13.

Kumbar, V and Nedomova S. 2015. Viscocity and Analytical Dofferences between raw milk and UHT milk of Czech cows. Scientia Agricultura Bohemica. 46(2): 78-83.

McCarthy, O.J. and Singh, H. 2009. Advanced Dairy Chemistry: Lactose, Water, Salts and Minor Constituents Volume 3. New Zealand (NZ): Springer.

McCarthy, O.J. and Singh H. 2011. Rheology of liquid and semi solid milk product. New Zealand (NZ): Elsevier.

Miller, G.D., Jarvis, J.K., and McBean, L.D. 2007. Handbook of Dairy Food and Nutrition 3rd edition. Florida (US): CRC Press.

Minim, L.A., Coimbra, J.S.R, and Minim, V.P.R. 2002. Influence of temperature and water and fat contents on the thermophysical properties of milk. Journal of Chemical Engineering Data. 47: 1488-1491.

Morison, K.R, Phelan, J.P., and Bloore, C.G. 2013. Viscocity and non-newtonian behaviour of concentrated milk and cream. International Journal of Food Properties. 16: 882-894.

Munir, M.T., Zhang, Y, Yu, W., Wilson, D.I. and Young, B.R. 2016. Virtual milk for modelling and simulation of dairy processes. Journal of Dairy Science. 99:1-16.

Rao, M.A. 2007. Rheology of Fluid and Semifluid Foods: Principles and Applications 2nd edition. New York (US): Springer.

Roozi, S., Massini, R., Paciello, G., Pagliarini, G,, Rainieri, S. and Trifiro, A. 2007. Heat treatment of fluid foods in a shell and tube heat exchanger: Comparison between smooth and helically corrugated wall tubes. Journal of Food Engineering. 79:249-254.

Steffe, J.F.. 1996. Rheological Methods in Food Engineering 2nd edition. Michigan (US): Freeman Press.

Tello, P.G., Camacho, F., Guadix, E.M., Luzon, G., and Gonzalez, P.A. 2009. Density, viscocity and surface tension of whet protein concentrate solutions. Journal of Food Process Engineering. 32: 235-247

Toledo, R.T. 2012. Fundamentals of Food Process Engineering 2nd edition. New York (US): Chapman & Hall.

[USDA] United States Departement of Agricultural. 2016. Indonesia 2016 dairy and products annual report. Washington(US): USDA.

Varzakas, T.H and Labropoulos, A.E. 2007. The effect of mass flow rate in an indirect ultra-high temperature processing system. Journal of Food Technology. 2(6): 490-501.