Analysis of Milk Fat Deposition Using Avrami Kinetics Model

by

Azharun Saidi Hamzah bin Abu Bakar

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CERTIFICATION OF APPROVAL

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Approved by,

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(DR. LUKMAN ISMAIL)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and the original work contained herein have not been undertaken or done by unspecified sources or persons.

(AZHARUN SAIDI HAMZAH BIN ABU BAKAR)

ABSTRACT

The deposition of milk was conducted to determine the crystallinity content of milk fat which will affect on the mass production and storage of the products where it would be undergone other process for various purposes whether fresh or processed products. Kinetics analyses were conducted to study the deposition of the milk whereas most of the deposits are rich in milk fat. Different heating and cooling temperature, equipments or medium of the milk fat deposition were used and effect of sample size had been selected as the parameter for the experiment. Through the analysis, milks that deposit under fast cooling yielded a higher Avrami constant (k), and a lower Avrami exponent (n) compared with the slow cooling sample. Different heating temperature also gives different time for the milk fat to start to deposit and time required for the milk fat to fully crystallized/deposited. Through experiment, higher heating temperature leads to lower Avrami constant (k), and a higher Avrami exponent (n) while for lower cooling temperature, it resulted in opposite effects. For 80°C to 0°C, k and n value is 2.655 and 0.29 while for 60°C to 0°C, the k and n value is 2.951 and 0.235. Experimental of different equipment shows the higher conductivity equipment (metal cup) produce higher k and lower n value which is 2.655 and 0.29 compared to beaker which is 2.2909 and 0.317. For experiment of different sample size, 25 g shows higher k and lower n value which is 3.5727 and 0.201, compared to 100 g which is 1.799 and 0.429 in the same operating condition.

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Table of Contents

List of Tables:

List of Figures:

Abbreviations and Nomenclatures

SFC – Solid Fat Content

SFO – Sun Flower Oil

LFRA – Leatherhead Food Research Association

XRD – X-Ray Diffractor

NMR – Nuclear Magnetic Resonance

AMF – Anhydrous Milk Fat

n – Avrami exponent

k – Avrami constant/crystal growth

T – Temperature (°C)

t – Time (min)

X – Degree of crystallization

CHAPTER 1

INTRODUCTION

1.1 Dairy Products

Cow and goat milk has been a nutritious food that had been used by many over more than centuries by different type of people to gain the nutrition content inside them. Known as a white liquid produced by mammals, it is the primary source of nutrition for the newborn mammals before being able to digest other foods in their early ages. Early-lactation milk contains colostrums, which carries the mother's antibodies to the baby and can reduce the risk of many diseases in the baby.

Studies indicated that nutrient composition of raw milk vary by species and by a number of other factors, but it contains significant amounts of saturated fat, protein and calcium as well as vitamin C. Cow's milk has a pH ranging from 6.4 to 6.8, making it slightly acidic compared to fresh goat's milk which has a pH ranging from 6.7 to 6.4 (Schultz *et al.*, 1920).

Heat induced desiccation are famous for preservation of milk and milk products. Ghee is obtained by clarification of milk fat at high temperature. It is also known as anhydrous milk fat with melting range of 28°C to 44°C. There are four methods in preparation of ghee which are namely, desi, creamery butter, direct cream and pre-stratification. During the preparation of ghee, high heat was being applied to cream or butter to remove moistures. Both are being clarified at 110°C to 120°C (Ganguli *et al.*, 1971)

Table 1.1: Fresh milk consumption in most large countries (Nelson, 2007).

Country	Milk, Fresh (kg/person)	Country	Milk, Fresh (kg/person)
Malaysia	43.10	Norway	244.50
Japan	75.15	USA	250.68
Spain	152.09	Netherlands	263.92
New Zealand	181.72	Austria	276.67
Portugal	183.38	Germany	287.69
Canada	190.84	Ireland	302.25
Australia	203.1	Switzerland	308.81
Italy	220.16	France	309.30
Denmark	231.93	Sweden	314.31
United Kingdom	233.90	Finland	314.37

Table 1.1 shows that Malaysia is not famous of the dairy products consumption. It has been reported by Nelson (2007) by survey and study on the milk consumption on each country. The data is taken from the Food and Agriculture Organization of the United Nations which shows that the fresh milk consumption is Malaysia is one of the minimum in the list of the majorly know countries around the world (Nelson,2007).

Table 1.2: Milk composition analysis, per 100 grams (Douglas, 2010)

Constituent	**Cow**	**Goat**	**Sheep**	**Buffalo**
Water (g)	87.8	88.9	83.0	81.1
Protein (g)	3.2	3.1	5.4	4.5
Fat (g)	3.9	3.5	6.0	8.0
Carbohydrate (g)	4.8	4.4	5.1	4.9
Energy (kcal)	66	60	95	110
Energy (kJ)	275	253	396	463
Lactose (g)	4.8	4.4	5.1	4.9
Cholesterol (mg)	14	10	11	8
Calcium (IU)	120	100	170	195
Saturated fatty acids (g)	2.4	2.3	3.8	4.2
Monounsaturated fatty acids (g)	1.1	0.8	1.5	1.7
Polyunsaturated fatty acids (g)	0.1	0.1	0.3	0.2

Table 1.2 shows the milk composition analysis per 100 grams by Douglas (2010). It is essential to determine composition of the fat content in the milk which will lead to the deposition in the milk processing.

1.2 Background of Study

Fat- containing products are determined by the characteristics of the crystal network formed by its constituent lipid species (Narine & Marangoni 2002). Early nucleation and growth events lead to the formation of sub-micron primary crystallites from the melt. These crystallites associate into micron-range particles, which further aggregate into larger structures (clusters), until a continuous three-dimensional network is formed (deMan *et al.*, 1999). Van der Waals force stabilized the fat crystal network that formed with existing voids filled with liquid fat. The chemical composition, solid fat content (SFC) and crystal habit influenced the macroscopic properties of this fat crystal network. In the solid state, the polymorphism of the crystal, crystallite size and shape were the habit of the crystal that needs to be observed. During the crystallization process, the SFC and crystal habit are mostly affected by heat, mass and momentum transfer.

As early as 1964, deMan reported the effects of cooling procedures on the solid fat content, consistency, crystal structure of milk fat. In this study, deMan compared the properties of milk fat subjected to fast, stepwise, and tempered cooling regimes. He reported that a slower crystallization process lead to a decrease in solid fat content and hardness, as well as the aggregation of small crystalline particles into larger ones (deMan *et al.*, 1999).

The purpose of this study was to determine the effects deposition in different cooling and heating temperature of the sample, different sample size of the ghee and different type of medium of heating and cooling of the milk fat.

1.3 Problem Statement

The dairy products consumption is increasing by yearly with different of usage of the products as the output in every process. The content of the products also are important in determining the quality and the application for each purpose. For the deposition of milk fat, the crystallization of the fat content is important in studying the kinetics of the milk fat where it is important in determining the Avrami constant and exponent value. From the value, suitable condition can be selected.

1.4 Objectives

The aim of the project is to study the crystallization phenomenon and kinetics analysis of the milk fat using Avrami equation through several tests. The objectives of the projects are:

1. To study deposition of milk fat in different heating and cooling temperature.
2. To determine the effect of using different medium which is metal cup and laboratory pyrex beaker.
3. To determine the difference between different sample sizes of 25 g, 50 g and 100 g of milk fat (ghee).

1.5 Scope of Study

The scope of the study is to determine the characteristic of the milk fat that deposit in the equipment, whether in the storage or in the equipment that related to the milk process.

In order to determine the deposition of the sample, the characteristic of the milk need to be studied first whereby the deposition of the sample is due to the crystal component in the milk. The crystallization behavior of the component can be studied with proper equipment. The milk crystal characteristics such as hardness, solid fat content and chemical composition will be determine in the project with different cooling rate towards the milk fat (ghee).

For the different cooling temperature, sample size of 50 g with heating temperature of 60°C, 70°C and 80°C had been selected as these temperatures are suitable for melting the ghee which acts as the milk fat. Cooling temperature of 0°C, 5°C and 25°C had been selected as ghee will deposited/crystallized at these temperatures.

The sample will be heated at different heating temperatures which are of 60°C, 70°C and 80°C. This is because at these temperatures, the milk fat can be melted and up to 80°C is the most suitable temperature to ensure the crystal memory in the milk fat was being destroyed according to Campos *et al.,* 2002. The sample will be heated for 30 min to ensure the milk fat achieved the temperature and crystal memory was totally destroyed. Cooling temperature of 0°C, 5°C and 25°C had been selected as ghee already deposited/crystallized at these temperatures.

For effects of equipments, metal cup and laboratory beaker has been selected to compare between those equipments to determine the deposition of milk fat. Using same size of equipment and sample size, both depositions was being determined. Metal cup had been chosen to test the deposition on the metal piping/reactor in milk processing while laboratory beaker was used to compare. Sample size of 25 g, 50 g and 100 g was selected to study the kinetics of bigger sample size and the deposition within the same operating condition.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the background literature that is relevant to crystallized milk development, and is divided into two main sections. Section 2.1 introduces background information including experimental of the milk crystallization, the result obtained through experimental and the S-curve of the SFC of the milk that can be related to Avrami equation. Section 2.2 covers the kinetic analysis of the Avrami equation that will be used for determining the crystal growth and Avrami constant.

2.1 Background

Several works on the milk fat deposition/crystallization had been conducted by previous researchers such as deMan, Marangoni *et al.,* (1999) and the work was being improved by Campos *et al.,* (2002). The experimental is related to the food science studies thus most of the researches are being done by the Department of the Food Science in the world wide university. As the study on the deposition and crystal milk properties are important for the mass production of the products, it is important for the chemical engineers to learn on the topic to determine the suitable solution, process and equipment needed to achieved a high production, efficiency and quality.

The test of the crystallization is simple as the milk also acts as the natural polymer whereas the composition of the milk is consists of amorphous and crystal properties. These crystal properties are the main causes of the deposition of the milk due to the heating of the sample to the melt point of the crystal properties in the pasteurization process and the cooling step in the process which causes the crystal to form differently depending on the cooling rate afterwards. Studies by Campos *et al.,* (2002) are using the anhydrous milk fat (AMF) and lard to be compared on the crystallized and SFC properties. The result shows that slow crystallization process leads to softer fat. The penetration test gives a result of greater depth compared to the fast cooling process. For the hardness test, the hardness is changed with the time, however fast crystallization process gives higher values compared to the slow crystallization process.

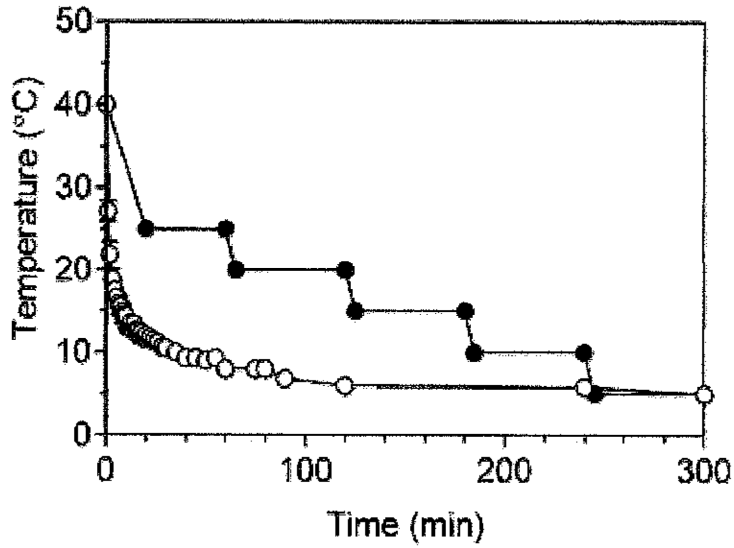

Figure 2.1: Fast Newtonian cooling (5°C/min; open symbols), and slow stepwise cooling (0.1°C /min; closed symbols) used for the crystallization of AMF and lard samples (Campos *et al.,* 2002).

Figure 2.1 shows the observation of the changes in penetration depth as a function of time, during setting, are possibly the result of processes such as dissolution of small crystals and growth of large crystals (Ostwald ripening), polymorphic transformations, nucleation and growth of new crystals, and possible formation of solid bridges between the microstructures (Johansson & Bergenstal,1995).

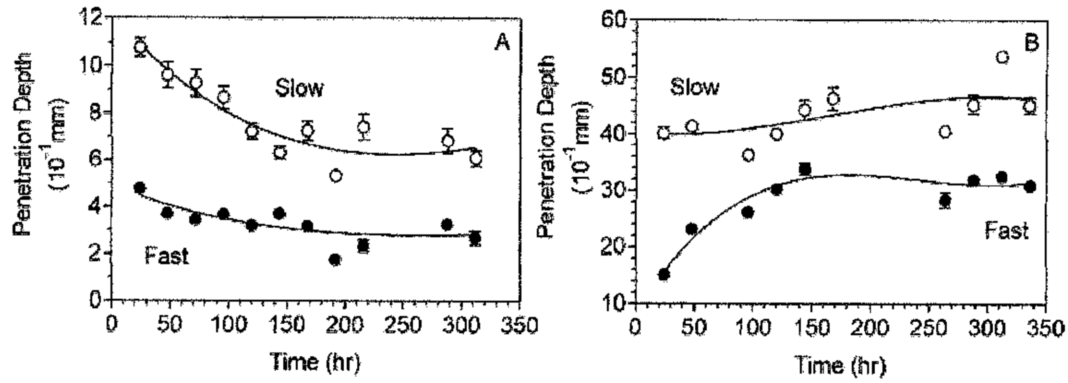

Figure 2.2: Penetration depth obtained by cone penetrometry at 5°C of AMF (A) and lard (B) crystallized under different cooling conditions (Campos *et al.*, 2002).

Figure 2.2 shows the graph of analysis of AMF and lard strength through test of using cone penetrometry. By determing the penetration depth of the substance, the strength can be determined. By plotting the difference in between crystallization for both AMF and lard in different cooling condition, the results are as above.

Herrera & Hartel, (2000), deMan (1964) *et al.*, reported that higher cooling rates and degrees of under cooling usually result in a higher SFC. Boudreau and Saint Amant (1985) reported that when butter is cooled rapidly, more liquid fat is adsorbed to the crystal surfaces, leading to less liquid fat present in the continuous phase, thus resulting in higher SFC readings. Campos *et al.*, (2002) reported that rapid crystallization resulted in higher SFC level.

Figure 2.3 shows the other experimental had been conducted using the effect of sunflower oil towards hydrous milk fat by Martini *et al.*, (2002) for different cooling rate and different percentage of sunflower oil in the sample.

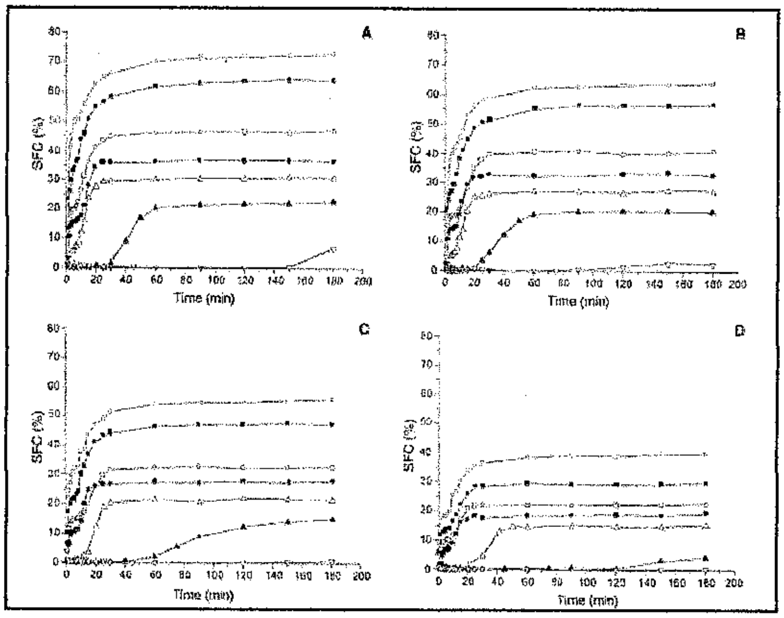

Figure 2.3: SFC with time for the samples crystallized at fast cooling rate (5.5°C/min) (A) HMF, (B) 10–90% SFO/HMF, (C) 20–80% SFO/HMF, and (D) 40–60% SFO/HMF (Martini *et al.*, 2002).

The study of the solid fat content is based on the Avrami model (Avrami, 1939, 1940, 1941). The crystallization curves are constructed by plotting the SFC (%) as a function of time. The equation is:

$$\frac{SFC(t)}{SFC(\infty)} = 1 - e^{kt^n} \qquad (2.1)$$

The curves are based on the hardness vs. SFC (%) which will produce the S curves. The obtained linear data, log hardness vs. log SFC (%) will be constructed based on the Avrami equation, and the Avrami constant (k) and Avrami exponent (n) can be determined other than the Maximum SFC and induction time.

Table 2.1: Chronological summary of the development of milk crystallization

Year	Experiment	Process/Equipment	Typical references	Findings
1920	Acidity of goat-cow-human milk	Colorimetric pH indicator	Schultz and Chandler (1920)	Goat milk is acidic than cow-human.
1961-1999	Physical properties on milk fat	Fast and Step-Wise cooling, polymorphism, crystal properties and SFC determination	deMan (1961)	Fast cooling produced more SFC compared to step-wise cooling.
2000	Effect of low and high melting milk fat, effect of cooling rate agitation rate, chemical composition and thermal behavior.	DSC XRD GC Light microscopy	Herrera and Hartel (2000)	Fast and slow cooling leads to incorporation of different TAG.
2002	Crystallization behavior of blend of milk fat-sunflower oil	Pulse NMR DSC	Martini *et al.*, (2002)	Increase level of SFO leads to decreasing SFC.
	Effect of step-wise and Newtonian cooling on milk fat and lard	Cone penetrometry Pulse NMR DSC XRD PLM	Campos *et al.*, (2002)	Slow cooling leads to soft fat and fast cooling is less stable polymorphism.
	Effect of DAG on milk fat TAG crystallization	NMR	Wright and Marangoni (2002)	DAG undergoes rapid isomerization.
2003	Milk fat fractionation by short path distillation	Pope 2-inch diameter laboratory wiped-film, Short-path molecular still RV3 rotary Vane pump connected in series to a Diffstak Mk2 diffusion pump	Campos *et al.*, (2003)	Milk was being divided to heavy and light fraction on the basis of the milk volatility.
2007	Non isothermal of bovine milk	Pulse NMR	Janssen and MacGibbon (2007)	Destabilized α crystal forms β seeds crystals.

2.2 Kinetic Analysis

The crystallization of milk is largely based on nucleation and crystallization processes where the fat content is entrapped between crystals leading to crystal formation; and can be treated as bulk crystallization (Ismail, 2007). The Avrami phase transition equation is a well-known principle in describing such crystallization kinetics. The original derivations by Avrami (1939) have been simplified by Evans (1945) and included in polymer context by Meares (1965) and Hay (1971). The basic principle can be illustrated by imagining raindrops falling in a puddle. The raindrops produce expanding circles of waves which intersect and cover the whole surface. The drops may fall sporadically or all at once. In either case, they must strike the puddle surface at random points. The expanding circles of waves are the growth front of the spherulites, and the points of impact are the crystallite nuclei (Ismail, 2007). Through probability derivations (Sperling, 1986), the volume fraction of crystalline material, X, known widely as the degree of crystallinity, can be written as:

$$1 - X = e^{-E} \tag{2.2}$$

where E represents the average number of fronts of all such points in the system. For low degrees of crystallinity a useful approximation is $X \approx E$. For the bulk crystallization of polymers, X in the exponent may be considered the volume or volume fraction of crystalline materials, V_t, *i.e.* (Ismail, 2007).

$$1 - X = e^{-Vt} \tag{2.3}$$

For either instantaneous or sporadic nucleation, equation (2.3) can be written as:

$$1 - X = e^{-Kt^n} \tag{2.4}$$

where K represents the growth rate, and n is the Avrami exponent, which depends not only on the structure of the crystal, but also on the nature of nucleation

(Avrami, 1940). The Avrami exponent, n, is the phenomenological index of crystallization, which can be used to distinguish between different mechanisms of crystallization (Campos *et al.*, 2003). For example, when $n = 1$ it corresponds to rod-like growth from instantaneous nuclei; whereas $n = 3$ or 4 refers to spherulitic growth from either sporadic or instantaneous nucleation (Sharples, 1966). For polymer and organics systems, an n value of 2 or 3 indicates two or three dimensional nucleation of the crystal nucleus. However, fractional values of n also exist due to secondary crystallization, *e.g.* lower n values (<1) are caused by linear crystal growth (Pal and Nandi, 2005). The Avrami exponent is strongly affected by crystallization temperature, in crystallization of milk fat, the n values ranged from 0.5 to almost 5. At lower temperature (5°C) the milk fat crystallized in the form of granules, whereas at higher temperature (25°C) they crystallized in the form of spherulites (Campos *et al.*, 2003). Using both n and K as the diagnostic tool of crystallization mechanism, Hay (1971) derived a model for spheres, discs and rods, representing three-, two- and one-dimensional forms of growth, which are summarized in **Table 2.2**.

Table 2.2: The Avrami parameters for crystallisation of polymers (Hay, 1971).

	Crystallization mechanism	***n***	**Growth form**
Spheres	Sporadic	4	3 dimensions
	Instantaneous	3	3 dimensions
Discs[a]	Sporadic	3	2 dimensions
	Instantaneous	2	2 dimensions
Rods[b]	Sporadic	2	2 dimensions
	Instantaneous	1	2 dimensions

[a]Constant thickness; [b]Constant radius

In this study, milk crystallization has been investigated and the degree of crystallinity is measured by the relative deposition, SFC(r), defined as the mass fractions of the depositions on both the wall divided by the initial mass of the milk liquid.

$$SFC(r) = \frac{SFC(t) - SFC(0)}{SFC(\infty) - SFC(0)} \quad (2.5)$$

where SFC(t) is the total deposition at time t (g), SFC(∞) the maximum or asymptotic deposition obtained from the deposition curves when the asymptotic condition or quasi-steady state has been achieved (g); SFC(0) the initial mass of the fat content in milk (g). Relating the achieved equation with the Avrami (1939) will get the equation (2.1). **Figure 2.4** shows the example for the analysis using Avrami equation.

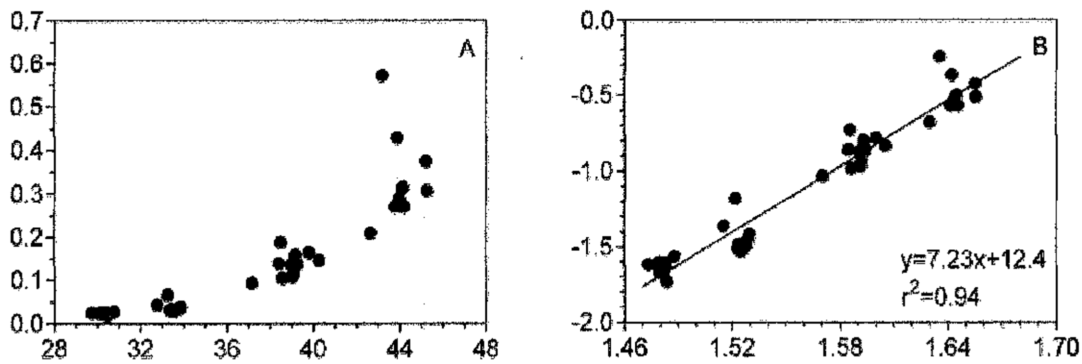

Figure 2.4: Plot of solid fat content (%) vs. time (A), and log (ln(1-SFC (%))) vs. log time (B) of samples crystallized under different cooling conditions (Campos *et al.*, 2002).

$$SFC(\%) = 1 - e^{kt^n} \quad (2.6)$$

$$1 - SFC(\%) = e^{kt^n} \quad (2.7)$$

$$\ln(1 - SFC(\%)) = kt^n \quad (2.8)$$

$$\log(\ln(1 - SFC(\%))) = \log k + n \log t \quad (2.9)$$

CHAPTER 3

METHODOLOGY

This chapter explained the procedure of conducting the experimental of milk fat deposition using ghee. Three types of parameters had been selected which are different cooling and heating temperatures, different medium/equipment used for the milk fat deposition and the experiment of different sample size of the milk fat (ghee).

3.1 Deposition of milk fat using ghee with different cooling and heating temperature

In this experiment, ghee will firstly undergo heating process which will be heated to 60°C, 70°C and 80°C for 30 min. The purpose of heating for 30 min is to ensure the sample achieved the temperature and maximum temperature of 80°C is to destroy the crystal memory in the milk fat.

The milk that had been heated for 30 min will then cooled to different cooling temperatures which are 0°C, 5°C and 25°C. The cooling temperature had been selected due to the milk fat is already started to deposit/crystallize at ambient temperature. Each one of heating milk fat will undergone these three cooling temperatures thus it leaves 9 set of data which is 60°C to 0°C, 60°C to 5°C, 60°C to 25°C, 70°C to 0°C, 70°C to 5°C, 70°C to 25°C, 80°C to 0°C, 80°C to 5°C, and 80°C to 25°C. Each set of data will be analyze by plotting the crystal/deposit percentage versus time and log (ln(crystal%)) versus log time in following the Avrami equation in determining the crystal growth rate and Avrami exponent.

During the cooling of the sample, every 2 min, 5 min or 10 min, the sample will be measured by weighing the total mass of the milk fat and metal cup, mass of the milk fat, the mass of liquid form of milk fat at specific temperatures and the mass of solid form/deposited milk fat.

During the experiment, the sample will be taken out and liquid form of milk fat will be poured out into another beaker and the liquid will be measured. The solid milk fat will be left in the metal cup. Mass of the solid milk fat can be measured by distracting total mass of metal cup and solid milk fat with the mass of empty metal cup. After the milk fat fully crystallized, the total solid mass each time will be divided with total solid fully crystallized to obtain the crystal percentage.

3.2 Deposition of milk fat in different medium/equipment

For the experimental of different type of medium/equipment, stainless steel metal cup has been selected in refers to the stainless steel piping and reactors in the milk fat processing while laboratory pyrex beaker has been selected for laboratory purposes.

In this experiment, temperature of 80°C has been selected for the heating temperature for 30 min as refers to the literature review that this temperature can destroy the crystal memory of milk fat and different cooling temperature of 0°C, 5°C, and 25°C is used to study on the deposition/crystallization behavior.

3.3 Deposition of milk fat in different sample size

In the experiment of different sample size, two sample size of milk fat (ghee) has been selected as 25 g, 50 g and 100 g. This experiment will be using 80°C as the heating temperature with 30 min heating time. For cooling temperature, 0°C, 5°C, and 25°C was selected to study on the deposition/crystallization behavior.

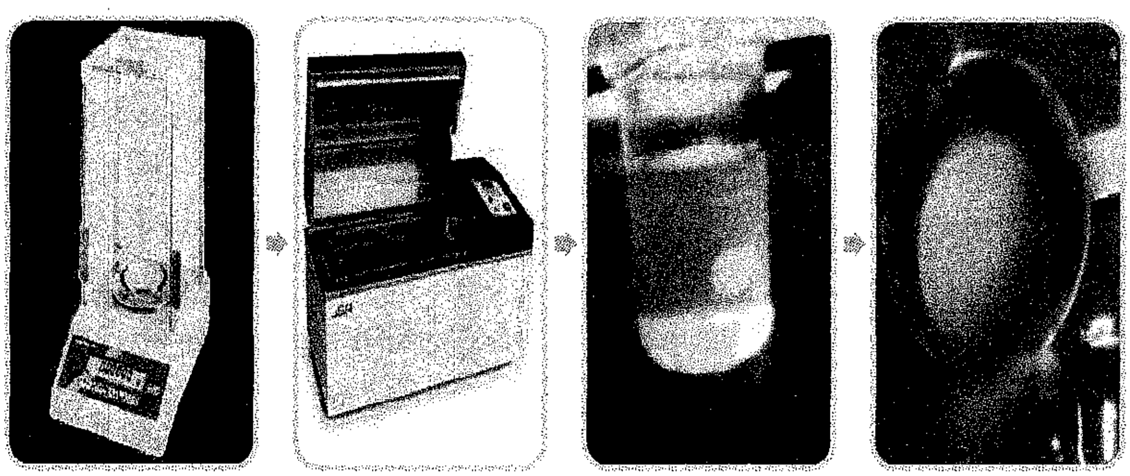

Figure 3.1: Procedure of the experiment, started with measuring the weight, heating the sample, and send for cooling for crystallization analysis

Figure 3.1 shows the equipments that being used in the experimental of the analysis of milk fat deposition using Avrami equation. The equipments being used are weighing scale, water bath, 100ml beaker and metal cup. As the analysis of the deposition is focusing on the mass of the deposit, it is important to ensure all the equipments are working properly.

CHAPTER 4

RESULT AND DISCUSSION

This chapter shows the result that being obtained through experimental on the milk fat. There are three parts of the result based on the objectives which are the deposition of milk fat (ghee) through various heating and cooling temperature, different type of equipment/medium used and the experiment of different sample size.

4.1 Effects of different cooling and heating temperature

The experiment of different cooling and heating temperature was conducted to determine the deposition trend of the milk fat. The experiment was selected by heating the sample at three different heating temperatures which are 60°C, 70°C, and 80°C to three different cooling temperatures which are 0°C, 5°C and 25°C. **Table 4.1** shows the example on how the milk fat was being analyze by determining the time, log t, mass of the milk fat (ghee), solid and liquid mass of the ghee, crystal % which are based on the mass of deposited milk fat at that time in reference to total mass of fully crystallize milk fat and the log (ln(1-X)) value which are important in determining the crystal growth (*k*) and Avrami exponent (*n*) using the Avrami kinetics model.

Table 4.1: Table of milk fat experiment for fix cooling temperature with different heating temperature (60°C, 70°C, 80°C to 0°C)

60 to 0						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	49.7026	0	49.7026	0	#NUM!
2	0.30103	49.7496	15.4258	34.3238	31.47223	0.5377065
4	0.60206	49.3915	32.7516	16.6399	66.82091	0.6234577
6	0.778151	49.0809	41.056	8.0249	83.76382	0.64620773
6.5	0.812913	49.014	49.014	0	100	0.66324568
7	0.845098	49.014	49.014	0	100	0.66324568
8	0.90309	49.014	49.014	0	100	0.66324568
9	0.954243	49.014	49.014	0	100	0.66324568
70 to 0						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	48.9657	0	48.9657	0	#NUM!
2	0.30103	49.008	10.338	38.67	21.30756	0.48558824
4	0.60206	48.888	25.79	23.098	53.15553	0.59914285
6	0.778151	48.828	40.4153	8.4127	83.2996	0.64566232
6.5	0.812913	48.518	48.518	0	100	0.66324568
7	0.845098	48.518	48.518	0	100	0.66324568
8	0.90309	48.518	48.518	0	100	0.66324568
9	0.954243	48.518	48.518	0	100	0.66324568
80 to 0						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.6742	0	50.6742	0	#NUM!
2	0.30103	50.7269	12.7322	37.9947	25.27564	0.50918116
4	0.60206	50.4984	29.3385	21.1599	58.24205	0.60901862
6	0.778151	50.4102	40.9324	9.4778	81.25797	0.64321857
6.5	0.812913	50.3734	50.3734	0	100	0.66324568
7	0.845098	50.3734	50.3734	0	100	0.66324568
8	0.90309	50.3734	50.3734	0	100	0.66324568
9	0.954243	50.3734	50.3734	0	100	0.66324568

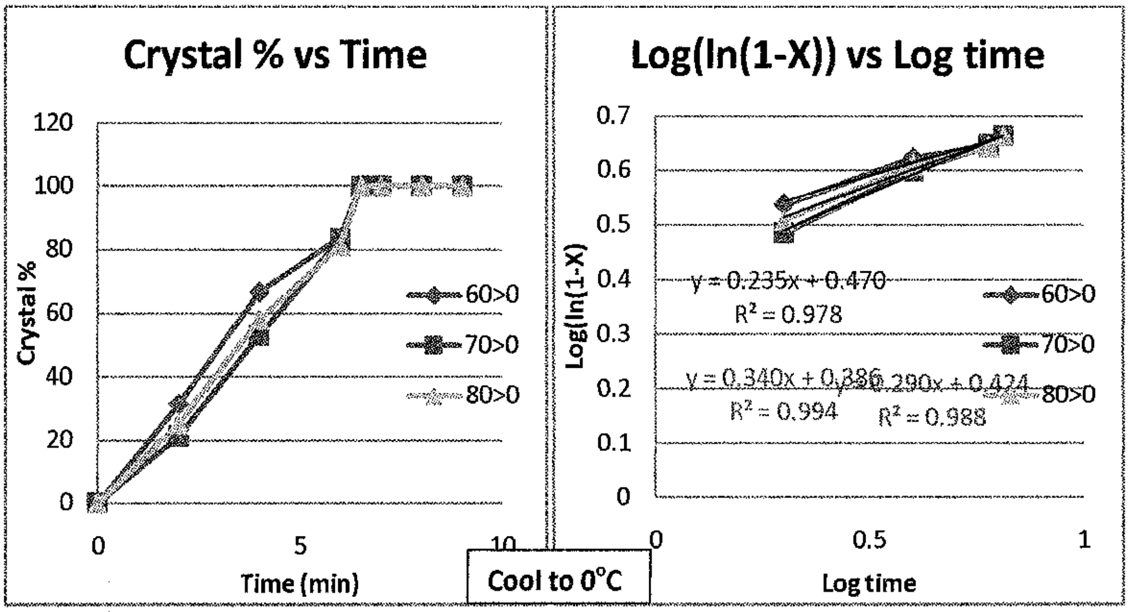

Figure 4.1: Graph of crystal% vs time and log (ln(1-X)) vs log time (60°C, 70°C, 80°C to 0°C)

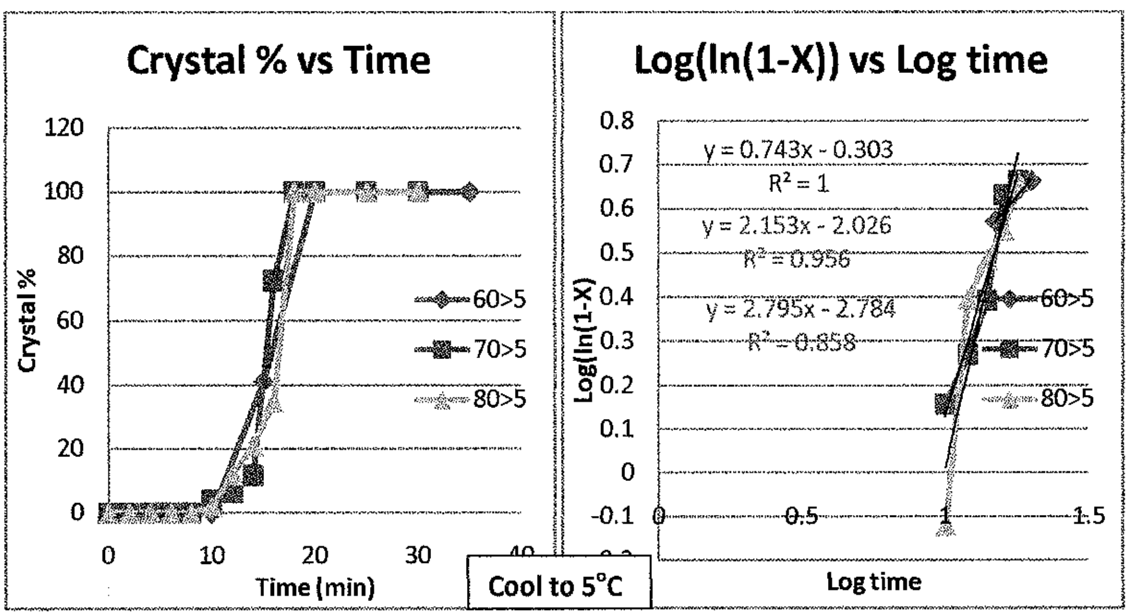

Figure 4.2: Graph of crystal% vs time and log (ln(1-X)) vs log time (60°C, 70°C, 80°C to 5°C)

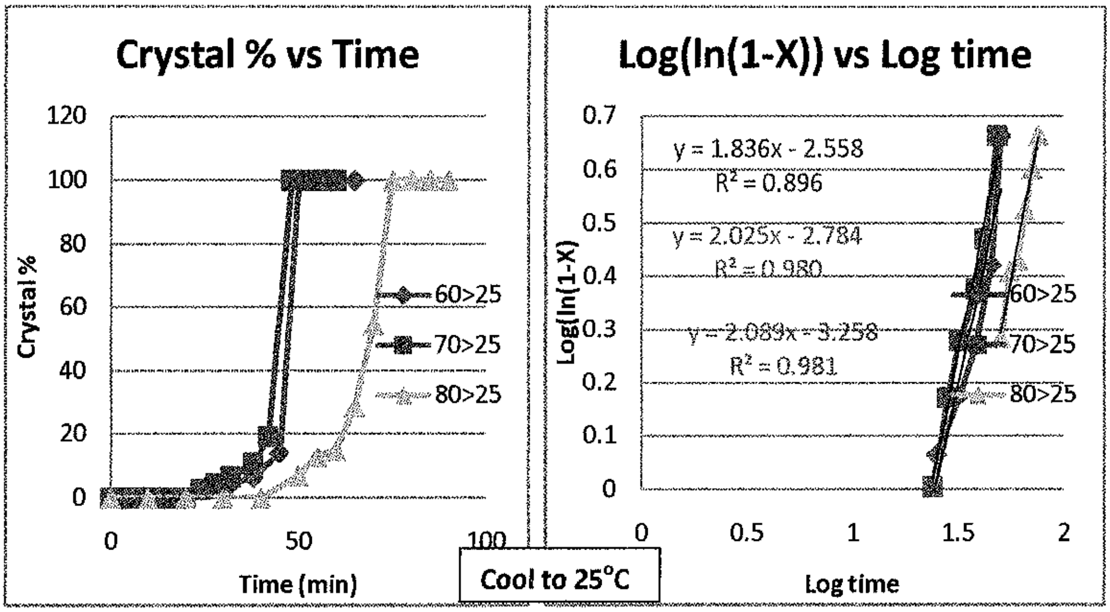

Figure 4.3: Graph of crystal% vs time and log (ln(1-X)) vs log time (60°C, 70°C, 80°C to 25°C)

From the result obtained from 4.1, the studies shows that as the heating temperature increase with constant cooling temperature, the *k* (growth rate) value is decreasing while for *n* (Avrami exponent) is increasing. **Figure 4.1** show that the milk fat deposition process starts with the formation of thin layer of deposit at the wall and at the surface due to the most of heat losses at the surface and the metal cup wall. From the graph, the plot of crystal% versus time of cooling to 0°C shows unlikely S-curve shape however when being plotted between log (ln(1-X)) versus log time, the graph is almost straight line. It shows that at fast cooling of 0°C, the milk fat behave as per Avrami equation and the determination of *k* and *n* value is easier compare to the other cooling temperature.

For the cooling temperature of 5°C (**Figure 4.2)** and 25°C (**Figure 4.3)**, the growth rate is suddenly started to exponentially decrease compare to the cooling of milk fat to 0°C. However, as the growth rate suddenly decrease, the Avrami exponent is increasing exponentially. This is due to the behavior of milk fat that slowly loss its energy and the formation of crystal structure inside the milk fat started to form. It is observed at cooling at higher temperature (25°C) in **Figure 4.3**, it takes time for the milk fat to start forming deposit, however after small amount of deposit started to form, the deposition of milk fat is increasing exponentially leaving the graph of crystal% (mass ratio of solid formation) vs. time to become S-Curve graph and this S-Curve graph will be used to determine the k and n value using the Avrami equation. It can be observed that the crystal nucleation of the milk fat is slow while the crystal propagation/growth rate is higher. The observation of fast cooling (0°C) shows the milk fat deposited quickly at the metal cup wall as the metal is good heat conductor (**Figure 6.1**). This shows the crystal nucleation rate is faster than growth rate as the n value at 0°C is low which is 0.2 to 0.3. For the cooling to 5°C and 25°C, the n value is ~2. **Table 2.2** shows the n=2 it can be deduced that the milk fat is either sporadic rods or instantaneous disc 2-dimension of the crystal growth formation.

4.2 Effects of different equipment (beaker and metal cup)

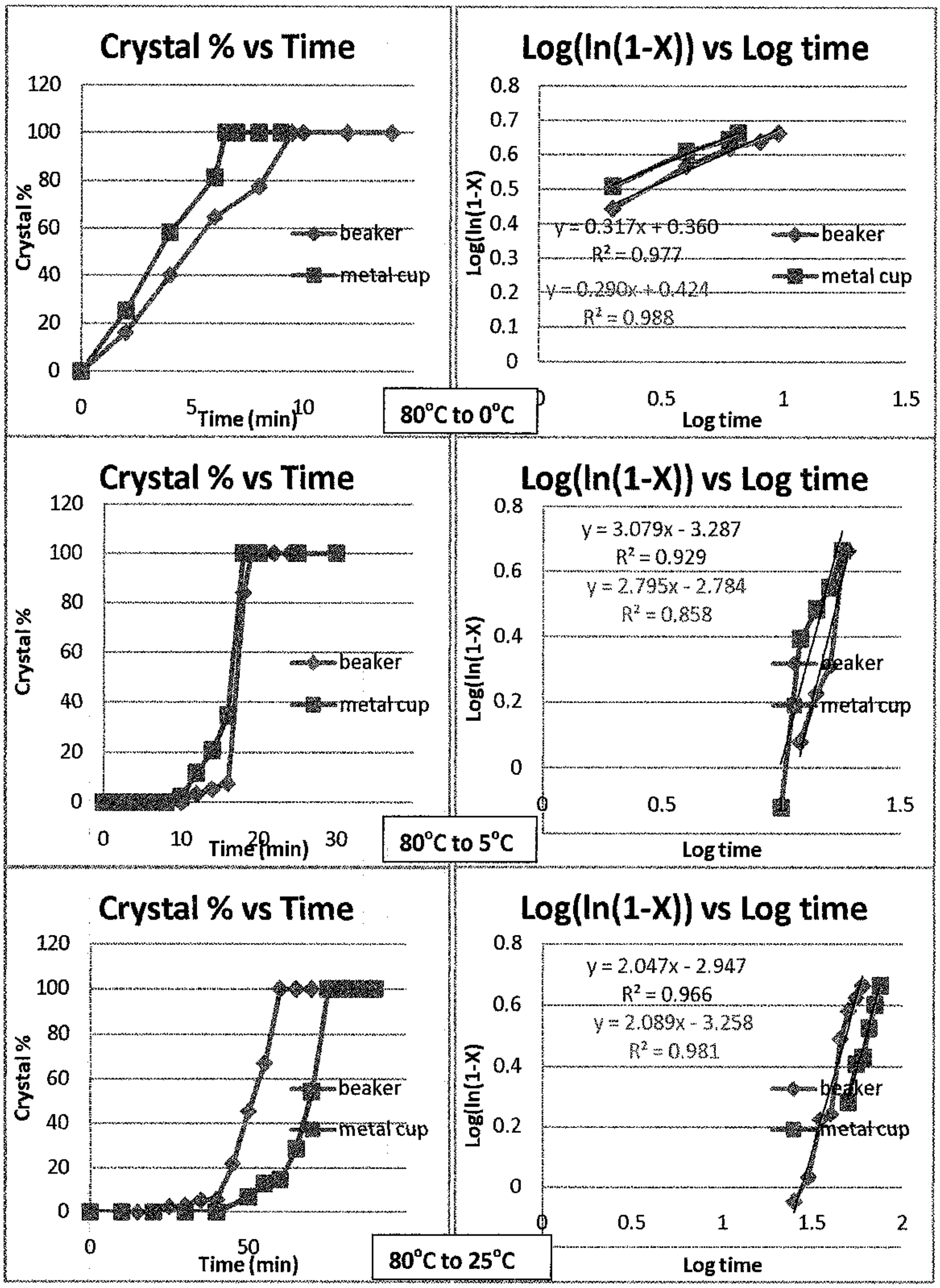

Figure 4.4: Graph of crystal% vs time and log (ln(1-X)) vs log time for different equipment (beaker and metal cup) under cooling of 80°C to 0°C, 80°C to 5°C and 80°C to 25°C

Experiment of different type equipments also gives different result in terms of the k and n value. Laboratory pyrex beaker gives higher k and n value compared to metal cup. This is because the material that being used is different in terms of heat conductivity. As the heat being loss slowly in the beaker due to lower heat conductivity, the formation of deposit is slower compare to the metal cup. However, as the nucleation rate is slower, the growth rate will be higher and this resulted in higher k value for beaker compared to metal cup. The Avrami exponent also higher for beaker compared to metal cup as the sudden increase of solid formation in beaker as refer to **Figure 4.4**.

For the experiment of deposition of milk fat using beaker and metal cup for ambient temperature (25°C), the time required for the milk fat to started and fully crystallize in beaker are faster compared to the metal cup. This experiment shows different result compared to experiment of cooling to 0°C and 5°C whereby the metal cup shows fast deposition compared to beaker. For this part, it is still unknown and further analysis of the milk fat deposition can be conducted for the effect of different heat conductivity equipment.

4.3 Effects of different sample size (25 g, 50 g and 100 g)

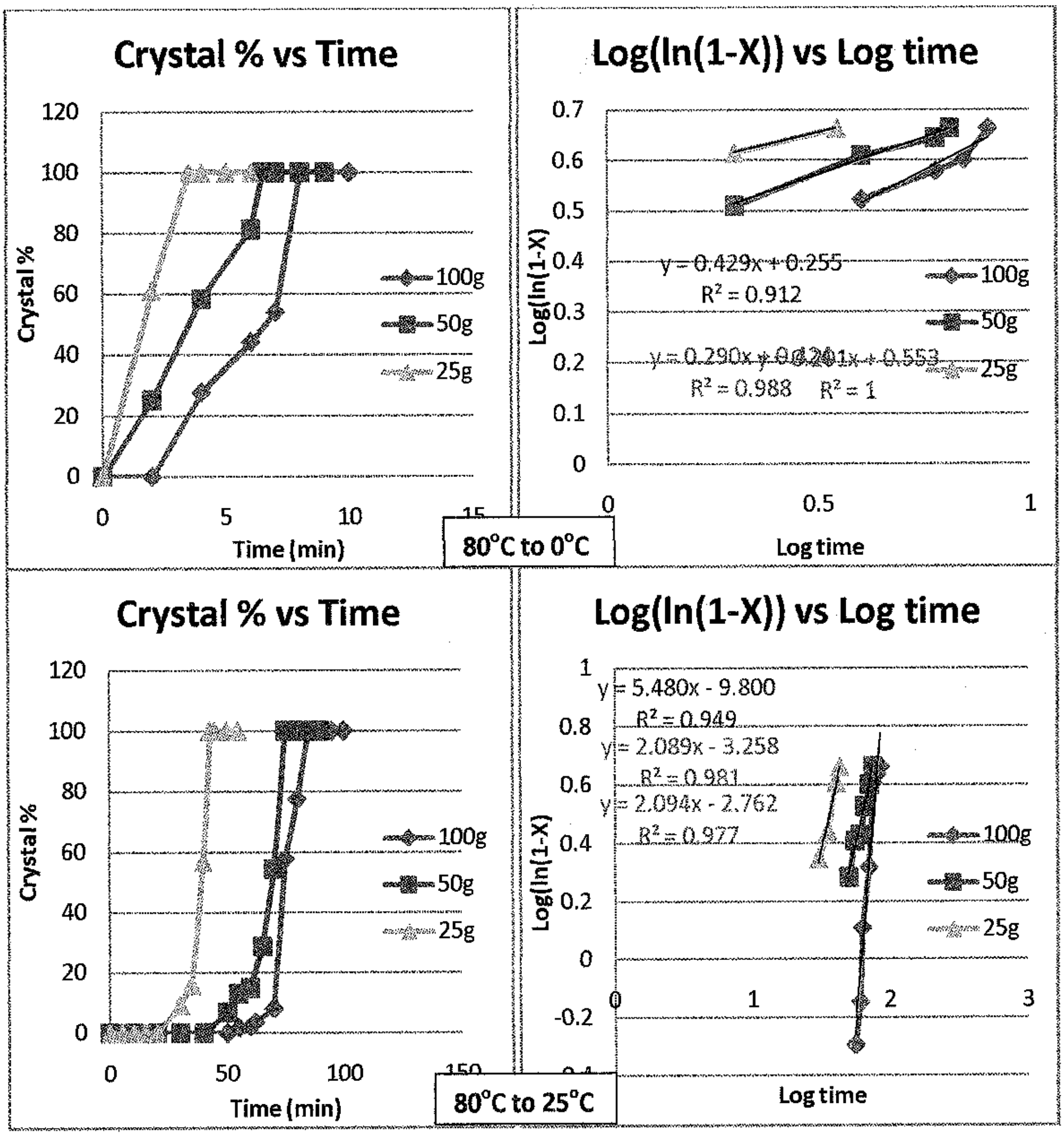

Figure 4.5: Graph of crystal% vs time and log (ln(1-X)) vs log time for different sample size (25 g, 50 g and 100 g) under cooling of 80°C to 0°C and 80°C to 25°C

Determination of deposition of milk fat in different sample size in **Figure 4.5** shows an obvious difference whether in terms of *k* (growth rate) value and *n* (Avrami exponent) value. Sample size plays very important role in controlling the deposition in the process piping or equipment, depending on whether it is batch or continuous process. In this batch experiment, the sample size of 25 g, 50 g and 100 g has been selected. Through graph and calculation, it is obtained that as the bigger sample size that being used, the lower the crystal growth rate is being calculated and more time needed for bigger sample size to fully deposit compared to smaller sample size. This also means that in large scale, the crystal growth formation is lower as more milk fat content can slow the deposition nucleation and formation. However, the *n* (Avrami exponent) value is very high.

From the experiment, if a large scale of milk fat processing was not being supervised or undergone the undesired process, it is dangerous as the sudden increase of the solid formation will occurred. It is very important to control the sample size and operating condition for the large scale production of milk/milk fat processing to reduce and control the formation of the milk fat deposition.

Table 4.2: Summary of log *k*, *k* (growth rate) and *n* (Avrami exponent) value for deposition of milk fat using Avrami equation and graph

		log *k*	*k* (growth rate)	*n* (Avrami exponent)
effect of heating and cooling				
60>0		0.47	2.951	0.235
70>0		0.386	2.432	0.34
80>0		0.424	2.655	0.29
60>5		-0.303	0.497	0.743
70>5		-2.026	0.0094	2.153
80>5		-2.784	0.0016	2.795
60>25		-2.558	0.0028	1.836
70>25		-2.784	0.0016	2.025
80>25		-3.258	0.000552	2.089
effect of equipment				
beaker	80>0	0.36	2.2909	0.317
metal cup		0.424	2.655	0.29
beaker	80>5	-3.287	0.000516	3.079
metal cup		-2.784	0.001644	2.795
beaker	80>25	-2.947	0.00113	2.047
metal cup		-3.258	0.000552	2.089
effect of sample size				
25 g	80>0	0.553	3.5727	0.201
50 g		0.424	2.6546	0.29
100 g		0.255	1.79887	0.429
25 g	80>25	-2.762	0.00173	2.094
50 g		-3.258	0.000552	2.089
100 g		-9.8	1.59E-10	5.48

The summary of experimental that being conducted for the analysis of milk fat (ghee) using the Avrami kinetics model is shown in **Table 4.2**. As the heating temperature increase, *k* value is decreasing and *n* value increase and decreasing of cooling temperature shows a vice versa. Metal cup that have higher heat conductivity gives higher *k* value and low *n* value compared to beaker. Finally, larger sample size lead to lower *k* value and higher *n* value compared to smaller sample size.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The studies of the deposition of milk fat are important in determining the mass production of the product. The deposition of the crystallized structure can lead to many causes such as choking at the pipeline, crystal sediment on the equipment surfaces, and microbial growth of the non-smooth equipment surface. Through various parameters for the study of milk fat deposition, it helps to understand the behavior of the milk fat in the milk processing. Even the content of milk fat in the low in the fresh milk, by times it also can cause several damages or problems in the processing. By studying and determining the characteristics and properties of the milk fat, it helps to improve the process to obtain higher efficiency and products quality.

- Experimental of different heating and cooling of milk fat that leads toward the deposition had been conducted together with different sample size and the type of equipment being used. In this experiment, the cooling to 0°C is fast cooling process and it leads to high k value and low n value while slow cooling which is cool to 25°C is vice versa. As higher heating temperature and higher cooling temperature was being tested, it leads to lower k (growth rate) value and higher n (Avrami exponent) value.

- Different type of equipment being used also shows that low heat conductivity equipment (beaker) leads to slow nucleation/formation of milk fat deposition however the crystal growth will be higher and leads to fast deposition growth. High heat conductivity helps fasten the heat loss from the milk fat towards environment which leads to faster deposition.

- For different sample size, large difference in the n and k value was being observed in this experiment. Large sample size shows slow formation of deposition compared to small sample size with high k value and low n value. This also due to the different sample size and the heat transfer towards the milk fat component which lead to the deposition in a different trending. It is advantageous to perform in the large scale as the crystal nucleation/starting of deposition is slower compared to small scale however, the crystal growth is higher and without proper observation and maintenance of the process, it can cause quick and large deposit which will cause more problems whether in the piping or equipments.

5.2 Recommendation

The experiment had been conducted for a batch process only. To obtain more similar to the process industry, the test should be done in a continuous process together with other equipment such as valves, pumps and others. Each deposit material in the equipment will be tested as the depositions also take place differently in different shape of the equipment. More indicators can be included into the process to determine and check the temperature at the equipments is accurate and the cooling process is stable based on the test requirement. Testing on a large scale can be done if an agreement with related industry or refinery had been conducted to achieve more accurate result compared to the existing test together with specialized person in charge of overall process.

CHAPTER 6: APPENDIX

6.1 GANTT CHART AND KEY MILESTONES

Gantt charts for activities planned along for this final year projects first and second semester are shown in Table 11 and Table 12.

Table 6.1: Gantt chart for final year project first semester (FYP I)

No	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
									Mid-Semester Break							
1	Selection of Project Topic															
2	Preliminary Research Work															
3	Submission of Extended Proposal						●									
4	Oral Proposal Defence										●					
5	Project Work Continues															
6	Submission of Interim Draft Report														●	
7	Submission of Finalized Interim Report															●

Table 6.2: Gantt chart for final year project second semester (FYP II)

No	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues								Mid-Semester Break								
2	Submission of Progress Report									●							
3	Project Work Continues																
4	Pre-EDX												●				
5	Submission of Draft Report													●			
6	Submission of Dissertation (soft bound)														●		
7	Submission of Technical Paper														●		
8	Oral Presentation															●	
9	Submission of Project Dissertation (hard bound)																●

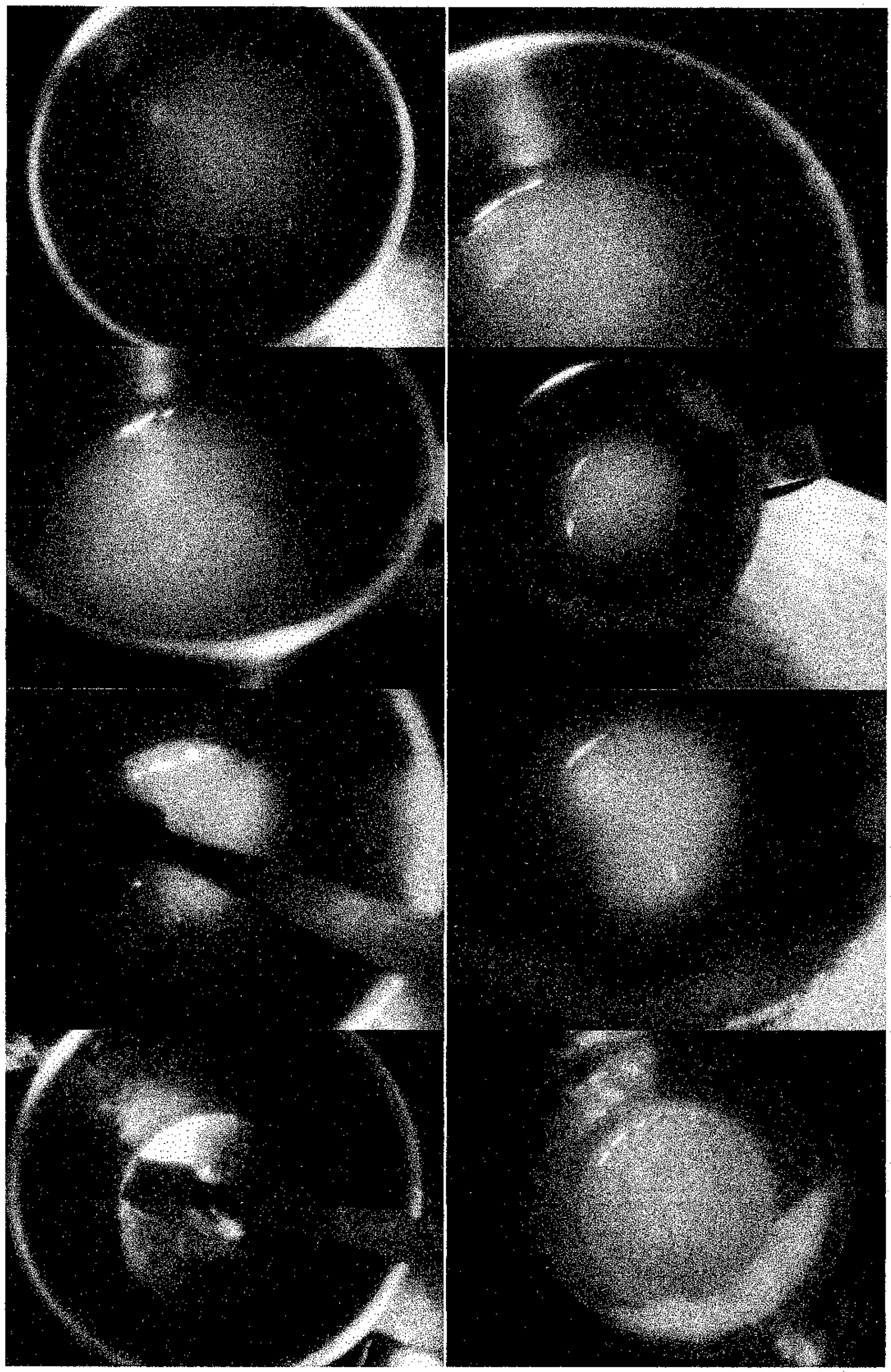

Figure 6.1: Picture of milk fat using ghee for experiment of different heating and cooling temperature and different sample size

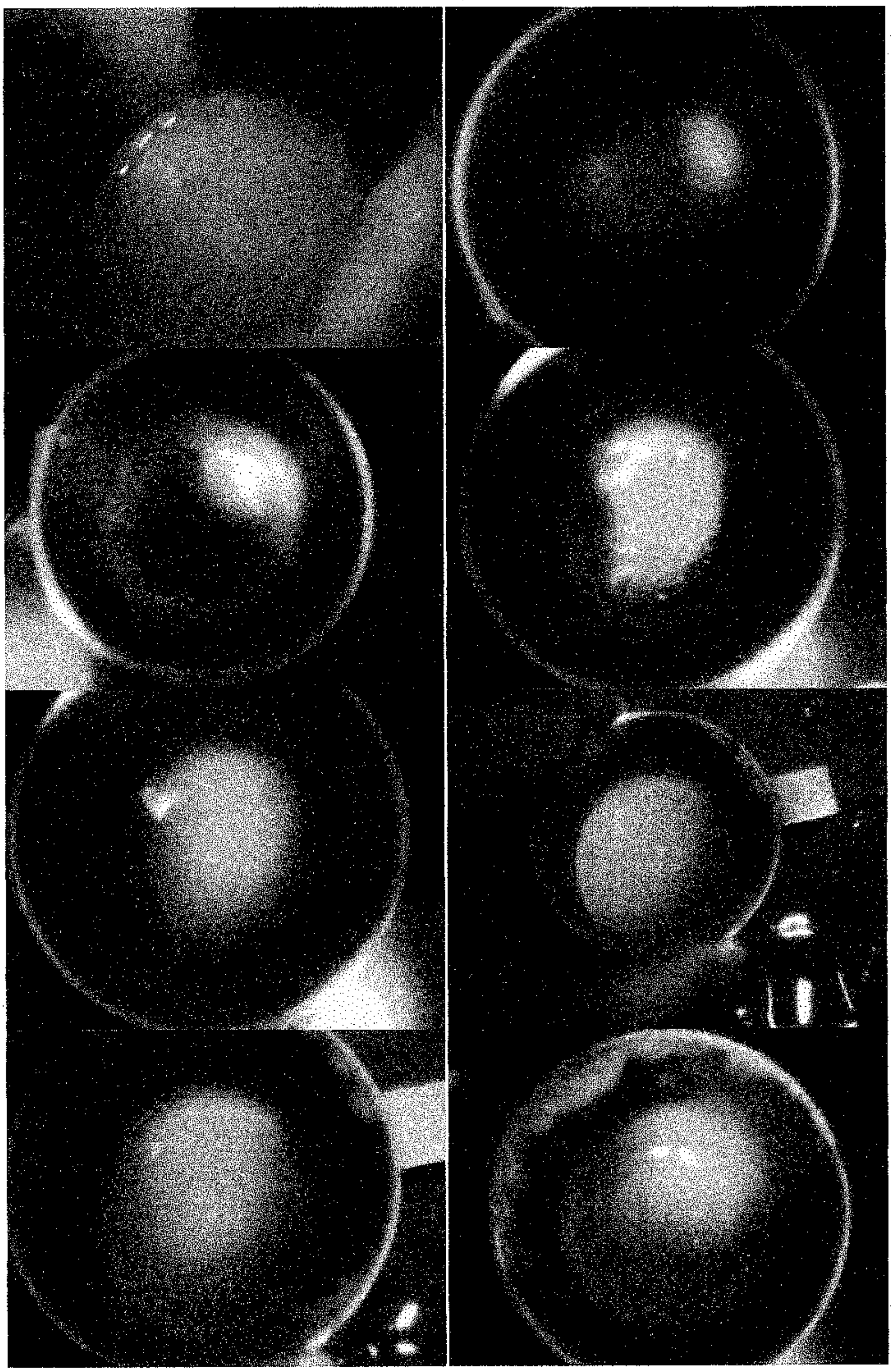

Figure 6.2: Picture of milk fat using ghee for experiment of different heating and cooling temperature and different sample size

Table 6.3: Table of milk fat experiment for fix cooling temperature with different heating temperature (60°C, 70°C, 80°C to 5°C)

60 to 5						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	49.8347	0	49.8347	0	#NUM!
5	0.69897	49.8347	0	49.8347	0	#NUM!
10	1	49.8347	0	49.8347	0	#NUM!
15	1.176091	48.5035	18.1845	30.319	41.21236	0.570395603
20	1.30103	44.1239	44.1239	0	100	0.663245684
25	1.39794	44.1239	44.1239	0	100	0.663245684
30	1.477121	44.1239	44.1239	0	100	0.663245684
35	1.544068	44.1239	44.1239	0	100	0.663245684
70 to 5						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.6065	0	50.6065	0	#NUM!
2	0.30103	50.6078	0	50.6078	0	#NUM!
4	0.60206	50.6085	0	50.6085	0	#NUM!
6	0.778151	50.6111	0	50.6111	0	#NUM!
8	0.90309	50.6115	0	50.6115	0	#NUM!
10	1	50.6125	2.0681	48.5444	4.18443	0.155752041
12	1.079181	50.0108	3.1721	46.8387	6.418176	0.269310681
14	1.146128	49.8756	5.7873	44.0883	11.70956	0.391006774
16	1.20412	49.7712	35.7905	13.9807	72.41566	0.631689524
18	1.255273	49.4237	49.4237	0	100	0.663245684
20	1.30103	49.4237	49.4237	0	100	0.663245684
25	1.39794	49.4237	49.4237	0	100	0.663245684
30	1.477121	49.4237	49.4237	0	100	0.663245684

80 to 5						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50	0	50	0	#NUM!
2	0.30103	49.99	0	49.99	0	#NUM!
4	0.60206	49.99	0	49.99	0	#NUM!
6	0.778151	49.99	0	49.99	0	#NUM!
8	0.90309	49.99	0	49.99	0	#NUM!
10	1	49.99	1	48.99	2.129472	-0.12155059
12	1.079181	49.99	5.6	44.4	11.92504	0.394213561
14	1.146128	49.01	9.84	39.17	20.954	0.48320628
16	1.20412	48.56	16.32	32.24	34.75298	0.550016091
18	1.255273	46.96	46.96	0	100	0.663245684
20	1.30103	46.96	46.96	0	100	0.663245684
25	1.39794	46.96	46.96	0	100	0.663245684
30	1.477121	46.96	46.96	0	100	0.663245684

Table 6.4: Table of milk fat experiment for fix cooling temperature with different heating temperature (60°C, 70°C, 80°C to 25°C)

60 to 25						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	51.046	0	51.046	0	#NUM!
5	0.69897	51.0179	0	51.0179	0	#NUM!
10	1	51.0111	0	51.011	0	#NUM!
15	1.176091	51.0111	0	51.0111	0	#NUM!
20	1.30103	51.0111	0	51.0111	0	#NUM!
25	1.39794	51.0111	1.6041	49.4103	3.191458	0.064636816
32	1.50515	50.8656	2.2623	48.6033	4.500988	0.177333557
38	1.579784	50.6874	3.2557	47.4317	6.477419	0.271451774
45	1.653213	50.1784	7.059	43.1194	14.04432	0.421968695
50	1.69897	50.2623	50.2623	0	100	0.663245684
55	1.740363	50.2623	50.2623	0	100	0.663245684
60	1.778151	50.2623	50.2623	0	100	0.663245684
65	1.812913	50.2623	50.2623	0	100	0.663245684

70 to 25						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	48.93	0	48.93	0	#NUM!
4	0.60206	48.93	0	48.93	0	#NUM!
8	0.90309	48.93	0	48.93	0	#NUM!
12	1.079181	48.93	0	48.93	0	#NUM!
16	1.20412	48.93	0	48.93	0	#NUM!
20	1.30103	48.93	0	48.93	0	#NUM!
24	1.380211	48.93	1.32	47.61	2.745424	0.004293695
28	1.447158	48.72	2.12	46.6	4.409318	0.171351946
32	1.50515	48.42	3.22	45.2	6.697171	0.279138639
38	1.579784	48.29	5.17	43.12	10.75291	0.375695903
42	1.623249	48.08	9.26	38.82	19.25957	0.470999336
48	1.681241	48.08	48.08	0	100	0.663245684
50	1.69897	48.08	48.08	0	100	0.663245684
55	1.740363	48.08	48.08	0	100	0.663245684
60	1.778151	48.08	48.08	0	100	0.663245684

80 to 25						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.0357	0	50.0357	0	#NUM!
10	1	50.04	0	50.04	0	#NUM!
20	1.30103	50.0431	0	50.0431	0	#NUM!
30	1.477121	50.0455	0	50.0455	0	#NUM!
40	1.60206	50.0458	0	50.0458	0	#NUM!
50	1.69897	50.0466	3.3125	46.7341	6.838484	0.283881266
55	1.740363	49.5209	6.2822	43.2387	12.96927	0.408677955
60	1.778151	49.2635	7.1495	42.114	14.75977	0.430059773
65	1.812913	49.0495	13.8854	35.1641	28.66569	0.525783228
70	1.845098	48.797	26.407	22.39	54.51588	0.601896229
75	1.875061	48.4391	48.4391	0	100	0.663245684
80	1.90309	48.4391	48.4391	0	100	0.663245684
85	1.929419	48.4391	48.4391	0	100	0.663245684
90	1.954243	48.4391	48.4391	0	100	0.663245684

Table 6.5: Table of milk fat experiment for different equipment (beaker and metal cup) for 80°C to 0°C, 80°C to 5°C and 80°C to 25°C

80 to 0 (beaker)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	51.0403	0	51.0403	0	#NUM!
2	0.30103	51.0738	8.195	42.8788	16.2102	0.444925061
4	0.60206	50.8532	20.4097	30.4435	40.3716	0.567981766
6	0.778151	51.1113	32.7093	18.402	64.70094	0.620112693
8	0.90309	51.0312	39.2455	11.7857	77.62993	0.6386842
9.5	0.977724	50.5546	50.5546	0	100	0.663245684
10	1	50.5546	50.5546	0	100	0.663245684
12	1.079181	50.5546	50.5546	0	100	0.663245684
14	1.146128	50.5546	50.5546	0	100	0.663245684
80 to 0 (metal cup)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.6742	0	50.6742	0	#NUM!
2	0.30103	50.7269	12.7322	37.9947	25.27564	0.509181163
4	0.60206	50.4984	29.3385	21.1599	58.24205	0.609018622
6	0.778151	50.4102	40.9324	9.4778	81.25797	0.643218573
6.5	0.812913	50.3734	50.3734	0	100	0.663245684
7	0.845098	50.3734	50.3734	0	100	0.663245684
8	0.90309	50.3734	50.3734	0	100	0.663245684
9	0.954243	50.3734	50.3734	0	100	0.663245684
80 to 5 (beaker)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.4754	0	50.4754	0	#NUM!
5	0.69897	50.4599	0	50.4599	0	#NUM!
8	0.90309	50.4602	0	50.4602	0	#NUM!
10	1	50.46	0	50.46	0	#NUM!
12	1.079181	50.46	1.6257	48.8343	3.321239	0.079303523
14	1.146128	50.15	2.6223	47.5277	5.357252	0.224908722
16	1.20412	49.699	3.7781	45.9209	7.718505	0.310400284
18	1.255273	49.0225	41.1476	7.8749	84.06287	0.646557126
19	1.278754	48.9486	48.9486	0	100	0.663245684
20	1.30103	48.9486	48.9486	0	100	0.663245684
22	1.342423	48.9486	48.9486	0	100	0.663245684
24	1.380211	48.9486	48.9486	0	100	0.663245684

80 to 5 (metal cup)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50	0	50	0	#NUM!
2	0.30103	49.99	0	49.99	0	#NUM!
4	0.60206	49.99	0	49.99	0	#NUM!
6	0.778151	49.99	0	49.99	0	#NUM!
8	0.90309	49.99	0	49.99	0	#NUM!
10	1	49.99	1	48.99	2.129472	-0.12155059
12	1.079181	49.99	5.6	44.4	11.92504	0.394213561
14	1.146128	49.01	9.84	39.17	20.954	0.48320628
16	1.20412	48.56	16.32	32.24	34.75298	0.550016091
18	1.255273	46.96	46.96	0	100	0.663245684
20	1.30103	46.96	46.96	0	100	0.663245684
25	1.39794	46.96	46.96	0	100	0.663245684
30	1.477121	46.96	46.96	0	100	0.663245684

80 to 25 (beaker)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.6129	0	50.6129	0	#NUM!
10	1	50.615	0	50.615	0	#NUM!
15	1.176091	50.6162	0	50.6162	0	#NUM!
20	1.30103	50.6176	0	50.6176	0	#NUM!
25	1.39794	50.637	1.2428	49.3942	2.458746	-0.04592579
30	1.477121	50.5675	1.497	49.0705	2.961653	0.035728838
35	1.544068	50.7889	2.7089	48.08	5.359266	0.225005956
40	1.60206	50.0219	2.9221	47.0998	5.781059	0.24417489
45	1.653213	50.5642	11.1939	39.3703	22.14592	0.49103282
50	1.69897	50.5451	23.1402	27.4049	45.78039	0.582501502
55	1.740363	50.4215	33.9728	16.4487	67.21152	0.624059692
60	1.778151	50.5461	50.5461	0	100	0.663245684
65	1.812913	50.5461	50.5461	0	100	0.663245684
70	1.845098	50.5461	50.5461	0	100	0.663245684

80 to 25 (metal cup)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.0357	0	50.0357	0	#NUM!
10	1	50.04	0	50.04	0	#NUM!
20	1.30103	50.0431	0	50.0431	0	#NUM!
30	1.477121	50.0455	0	50.0455	0	#NUM!
40	1.60206	50.0458	0	50.0458	0	#NUM!
50	1.69897	50.0466	3.3125	46.7341	6.838484	0.283881266
55	1.740363	49.5209	6.2822	43.2387	12.96927	0.408677955
60	1.778151	49.2635	7.1495	42.114	14.75977	0.430059773
65	1.812913	49.0495	13.8854	35.1641	28.66569	0.525783228
70	1.845098	48.797	26.407	22.39	54.51588	0.601896229
75	1.875061	48.4391	48.4391	0	100	0.663245684
80	1.90309	48.4391	48.4391	0	100	0.663245684
85	1.929419	48.4391	48.4391	0	100	0.663245684
90	1.954243	48.4391	48.4391	0	100	0.663245684

Table 6.6: Table of milk fat experiment for different sample size (25 g, 50 g and 100 g) at cooling temperature from 80°C to 0°C and 80°C to 25°C

80 to 0 (100 g)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	99.7212	0	99.7212	0	#NUM!
2	0.30103	99.7212	0	99.7212	0	#NUM!
4	0.60206	99.7046	27.2872	72.4174	27.76667	0.52163966
6	0.778151	98.9708	43.3063	55.6645	44.06725	0.57814814
7	0.845098	98.8699	53.0341	45.8358	53.96598	0.600793691
8	0.90309	98.2732	98.2732	0	100	0.663245684
9	0.954243	98.2732	98.2732	0	100	0.663245684
10	1	98.2732	98.2732	0	100	0.663245684

80 to 0 (50 g)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.6742	0	50.6742	0	#NUM!
2	0.30103	50.7269	12.7322	37.9947	25.27564	0.509181163
4	0.60206	50.4984	29.3385	21.1599	58.24205	0.609018622
6	0.778151	50.4102	40.9324	9.4778	81.25797	0.643218573
6.5	0.812913	50.3734	50.3734	0	100	0.663245684
7	0.845098	50.3734	50.3734	0	100	0.663245684
8	0.90309	50.3734	50.3734	0	100	0.663245684
9	0.954243	50.3734	50.3734	0	100	0.663245684
80 to 0 (25 g)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	25.4559	0	25.4559	0	#NUM!
2	0.30103	25.4981	15.7199	9.7782	61.13862	0.614173882
3.5	0.544068	25.7119	25.7119	0	100	0.663245684
4	0.60206	25.7119	25.7119	0	100	0.663245684
5	0.69897	25.7119	25.7119	0	100	0.663245684
6	0.778151	25.7119	25.7119	0	100	0.663245684
80 to 25 (100 g)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	100.6403	0	100.6403	0	#NUM!
5	0.69897	100.6379	0	100.6379	0	#NUM!
10	1	100.6368	0	100.6368	0	#NUM!
20	1.30103	100.6436	0	100.6436	0	#NUM!
30	1.477121	100.6429	0	100.6429	0	#NUM!
40	1.60206	100.6446	0	100.6446	0	#NUM!
50	1.69897	100.646	0	100.646	0	#NUM!
55	1.740363	100.6443	1.6363	99.008	1.662656	-0.29378029
60	1.778151	99.8892	2.0087	97.8805	2.041055	-0.14662627
62	1.792392	99.8012	3.569	96.2322	3.626487	0.110005016
70	1.845098	99.1785	7.9433	91.2352	8.071245	0.319794509
75	1.875061	99.5413	56.9563	42.585	57.87371	0.60834022
80	1.90309	99.1042	76.2049	22.8993	77.43236	0.638429825
85	1.929419	98.4148	98.4148	0	100	0.663245684
90	1.954243	98.4148	98.4148	0	100	0.663245684
95	1.977724	98.4148	98.4148	0	100	0.663245684
100	2	98.4148	98.4148	0	100	0.663245684

80 to 25 (50 g)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	50.0357	0	50.0357	0	#NUM!
10	1	50.04	0	50.04	0	#NUM!
20	1.30103	50.0431	0	50.0431	0	#NUM!
30	1.477121	50.0455	0	50.0455	0	#NUM!
40	1.60206	50.0458	0	50.0458	0	#NUM!
50	1.69897	50.0466	3.3125	46.7341	6.838484	0.283881266
55	1.740363	49.5209	6.2822	43.2387	12.96927	0.408677955
60	1.778151	49.2635	7.1495	42.114	14.75977	0.430059773
65	1.812913	49.0495	13.8854	35.1641	28.66569	0.525783228
70	1.845098	48.797	26.407	22.39	54.51588	0.601896229
75	1.875061	48.4391	48.4391	0	100	0.663245684
80	1.90309	48.4391	48.4391	0	100	0.663245684
85	1.929419	48.4391	48.4391	0	100	0.663245684
90	1.954243	48.4391	48.4391	0	100	0.663245684

80 to 25 (25 g)						
time (min)	log time	ghee (g)	solid (g)	liquid (g)	crystal %	log(ln (1-X)
0	#NUM!	25.8665	0	25.8665	0	#NUM!
5	0.69897	25.855	0	25.855	0	#NUM!
10	1	25.8348	0	25.8348	0	#NUM!
15	1.176091	25.8323	0	25.8323	0	#NUM!
20	1.30103	25.8323	0	25.8323	0	#NUM!
30	1.477121	25.83	2.2602	23.5698	9.273528	0.347752186
35	1.544068	25.2354	3.8489	21.3865	15.79191	0.440830088
40	1.60206	24.4775	13.8601	10.6174	56.86755	0.606459278
43	1.633468	24.3726	24.3726	0	100	0.663245684
45	1.653213	24.3726	24.3726	0	100	0.663245684
50	1.69897	24.3726	24.3726	0	100	0.663245684
55	1.740363	24.3726	24.3726	0	100	0.663245684

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