Microwave Heating of Butter Cream Mixture

Investigation of Process Conditions, Product Quality and Production Efficiency

Master of Science Thesis

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: An illustration of the original almond cake from Almondy AB. The cake consists of two layers of almond cake and both the top layer and middle layer of cake cream consist of butter cream and on top of the cake; a layer of roasted almond flakes is spread.

This master thesis project was carried out at Almondy AB. The experimental parts in pilot scale were performed at SIK – The Swedish Institute for Food and Biotechnology, Göteborg and Binar Elektronik AB, Tidaholm.

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Abstract

The aim of this thesis work was to investigate the possible utilization of microwave heating in the production of butter cream. A literature study has been performed and the effect on texture and temperature distribution of butter cream mixture has been studied during microwave heating in pilot plants. In addition, the current time and energy requirements needed to heat butter cream mixture have been calculated and compared with heating rates and energy efficiencies using the microwave pilot plants.

Fouling and scorched butter cream mixture was the result of the first pilot plant experiment, and due to an uneven temperature distribution, a satisfying texture after heating could not be achieved. In a second microwave heating pilot plant, where a continuous process was mimicked in a microwave tunnel with trays in a row, an almost satisfying texture was achieved. However, some problems were encountered, but these can hopefully be dealt with by further developments and adjustments. A high power level followed by a lower power level during the heating process seems to be a good approach to achieve an even temperature distribution.

The pilot plant process is however not completely optimized. An improved temperature distribution and reconstruction of the second pilot plant to allow for continuous flow of butter cream mixture in an enclosed system through the microwave unit is necessary before introducing into large scale production. Heating rates and energy efficiencies were higher for the microwave pilot plants compared to the current heating equipment. However, these values are preliminary as the comparison is done between a large scale and two pilot plant equipments. A lower heating rate is however correlated with a more even temperature distribution, comparing the results after heating in the two pilot plants.

The time requirement for heating butter cream mixture can most likely be decreased by introducing a microwave heating step, resulting in higher production efficiency and a lower energy consumption. For the utilization of microwave heating to be beneficial, the costs for investments, maintenance and utilized energy source must be competitive compared to the costs for the current heating, both economically and environmentally. Microwave heating of butter cream mixture may also be used in combination with the conventional heating method, that is to use microwave heating up to 70 °C.

To conclude, microwave heating seems to have a high potential to be used during butter cream production, taken into account production efficiency and lower energy consumption. The microwave heating process, however, needs to be further developed to address the problems encountered in the present thesis.

Keywords: microwave, heating, food, continuous, tubular, energy, pilot plant, temperature distribution, productivity, process development

Sammanfattning

Målet med detta examensarbete var att undersöka om mikrovågsuppvärmning kan användas vid produktion av smörkräm. Litteratur har granskats och effekten på konsistens och temperaturfördelning av smörkrämsblandningen har studerats under mikrovågsuppvärmning i pilotanläggningar. Dessutom har den nuvarande tids- och energiåtgången för att värma smörkrämsblandning beräknats och jämförts med uppvärmningshastigheterna och energieffektiviteterna i pilotanläggningarna.

Påbränning och överhettning av smörkrämsblandningen var resultaten av experimentet i den första pilotanläggningen, och på grund av en ojämn temperaturfördelning, kunde en tillfredsställande konsistens efter uppvärmning inte uppnås. Vid experiment i en annan pilotanläggning, där en kontinuerlig process efterliknades i en mikrovågsugnstunnel med tråg i rad, erhölls en nästan tillfredsställande konsistens. Vissa problem uppstod, men dessa kan förhoppningsvis lösas genom ytterligare utveckling och anpassning av processen. En hög effektnivå följd av en lägre effektnivå under uppvärmning med mikrovågor verkar vara en bra metod för att uppnå en jämn temperaturfördelning.

Processen är dock inte helt optimerad. En förbättrad temperaturfördelning och ombyggnad av den andra pilotanläggning för att möjliggöra kontinuerligt flöde av smörkrämsblandningen i ett slutet system genom mikrovågsenheten är nödvändig innan försök och utveckling i storskalig produktion är aktuell. Uppvärmningshastigheter och energieffektiviteter var högre för mikrovågspilotanläggningarna jämfört med under nuvarande uppvärmning. Dessa värden är dock endast preliminära eftersom jämförelsen görs mellan en storskalig anläggning och två pilotanläggningar. En lägre uppvärmningshastighet kan dock korreleras med en jämnare temperaturfördelning, då resultaten efter uppvärmningen i de båda pilotanläggningarna jämförs

Tidsåtgången för uppvärmning av smörkrämsblandningen kan sannolikt minskas genom att införa mikrovågsuppvärmning, vilket då ger högre produktionseffektivitet och en lägre energiförbrukning. För att införandet av mikrovågsuppvärmning ska vara lönsamt, måste kostnaderna för investeringar, underhåll och utnyttjad energikälla vara konkurrenskraftiga jämfört med kostnaderna under nuvarande uppvärmningsmetod, både ekonomiskt och miljömässigt sett. Mikrovågsuppvärmning av smörkrämsblandningen kan också användas i kombination med den nuvarande uppvärmningsmetoden, det vill säga att använda mikrovågsuppvärmning upp till 70 °C.

Sammanfattningsvis verkar mikrovågsuppvärmning ha goda möjligheter att användas under smörkrämsproduktion, med hänsyn till produktionseffektivitet och lägre energiförbrukning. Mikrovågsuppvärmningsprocessen behöver dock utvecklas ytterligare för att ta itu med de problem som beskrivs i denna rapport.

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Abbreviations

BCM: Butter Cream Mixture

HDL: High Density Lipoprotein

HP: Horizontal Processing

LDL: Low Density Lipoprotein

MW: Microwave

SIK: The Swedish Institute for Food and Biotechnology

WHC: Water Holding Capacity

Glossary

Bostwick Device: the equipment that is used to measure the viscosity of the butter cream mixture.

Conventional Heating: the heating phenomena in traditional heating methods, where a product is heated through convection and conduction.

Dielectric Properties: describes how much of the electromagnetic energy that is absorbed, reflected or transmitted. *ε'* – dielectric constant, which describes how well a material can store the energy that is applied from an electric field. *ε''* – loss factor, which describes the ability of a certain material to dissipate energy when an electric field is applied. *tan δ* – the ratio between ε'' and ε', which indicates how good the dissipation characteristics of a material are.

Fouling: protein deposits on surfaces in heating equipments, which can result in a decreased equipment performance and a diminished product quality.

Helical Coil: can be used instead of ordinary, circular tubes during microwave heating processes to increase the heat distribution during flow through a tube. It results in flow in both the axial and radial direction, which evens out the heat distribution and tephlone is a common production material.

Horizontal Processing Tank: the current process equipment in which the butter cream is heated and partly cooled.

Laminar Flow: a flow condition, when the fluid velocity is at its maximum in the center of the tube and approaches a zero value near the tube surfaces. Is the opposite to turbulent flow.

Magnetron: a major component in the microwave heating equipment in which an electromagnetic field is created. The magnetron produces the electrical energy that is further converted into microwaves.

Microwave Cavity: a major component in the microwave heating equipment in which the food product is placed and exposed to microwaves, which will increase the product temperature.

Microwave Heating: polar molecules rotate and dissolved ions migrate under influence of an electromagnetic field. This generates heat within the food product, see *Volumetric Heating* below.

Mode: describes the configuration of each electromagnetic field inside a waveguide or microwave cavity. The size of the waveguide or cavity determines how many modes that can be present.

Planetary Mixer: the equipment in which the butter cream mixture was heated for the viscosity measurements during the project.

Reynolds Number: a dimensionless number, which describes if a tubular flow is laminar or turbulent.

Standing Wave: the result of the superposition of two waves originating from two opposite directions. A large amplitude of a standing wave indicates a large heat generation.

Thermal Pasteurization: inactivation of microorganisms by application of heat.

Tubular Heat Exchanger: an equipment where heat is exchanged between the fluid of interest and a heating or cooling medium, respectively. Water is a common heating or cooling medium.

Volumetric Heating: the heat producing phenomena during microwave heating, where heat is produced directly within the entire food volume, see *Microwave Heating*.

Water Holding Capacity: describes how well a food can hold its own or added water during factors such as heat exposure.

Waveguide: often a hollow metal tube through which the microwaves are transported from the magnetron into the microwave cavity.

Symbols and Variables

B	mass flow rate [kg/min]
c_p	specific heat capacity [kJ/kg°C]
d_p	penetration depth [m]
ε'	dielectric constant
ε''	dielectric loss factor
E	electric field strength [V/m]
f	wave frequency [Hz]
H	magnetic field strength [A/m]
HR	heating rate during current butter cream mixture heating [°C/min]
λ	wavelength [m]
ρ	density [kg/m^3]
P_{abs}	power absorption during the microwave heating [W]
Q	energy requirement during butter cream mixture heating [MJ]
Q	energy requirement during butter cream mixture heating [kWh]
S	volumetric flow rate [m^3/min]
t	heating time during the microwave heating [s]
t	heating time during current butter cream mixture heating [min]
$tan\delta$	loss tangent value
$T1$	first temperature probe in the pilot plant at SIK [°C]
$T2$	second temperature probe in the pilot plant at SIK [°C]
T_{in}	water inlet temperature that heats the butter cream mixture in the HP tank [°C]
T_{out}	water outlet temperature that heats the butter cream mixture in the HP tank [°C]
T_{min}	minimum temperature of the butter cream mixture [°C]
T_{max}	maximum temperature of the butter cream mixture [°C]

$T_{measured}$	butter cream mixture temperature during the viscosity measurements [°C]
TM_{020}	mode used in the center heating microwave cavity
TM_{120}	mode used in the surface heating microwave cavity
v	fluid velocity [m/s]
v_{avg}	average fluid velocity [m/s]
v_{max}	maximum fluid velocity [m/s]
V	cavity volume [m^3]
$x_{average}$	flown distance during the viscosity measurements [cm]
y	mass fraction of chemical components in the butter cream mixture ingredients [g/g]
z	mass fraction of chemical components in butter cream mixture [g/g]

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1. Introduction

Ever since the 1940’s, microwave energy has been used as a heating source, and the food industry is the major consumer. Applications within the food industry are thawing, drying, baking and pasteurization among others (Oliveira & Franca, 2002). Since the 1940’s, the utilization of microwave ovens has increased, leading to the fact that a microwave oven has a central place for thawing and heating of foods in a majority of homes in the Western World (Tang *et al.*, 2002).

Conventional heating is heating through convection and conduction (Pereira & Vicente, 2010). Several advantages with *microwave heating* are suggested in the literature compared to conventional heating. These advantages are: it is not dependent on contact with a hot medium, electrodes or a hot surface; the power can be switched on and off immediately; it has rapid dynamics; it is volumetric, which means that the heating is theoretically more uniform compared to conventional heating. Volumetric heating will be further described later. Considering all these advantages, microwave heating shows potential as a useful method in industrial heating of food materials where conventional heating is less effective, such as for viscous liquids (Coronel *et al.*, 2010).

To kill microorganisms and increase the shelf-life of a food product, *thermal pasteurization* is often used. Together with the increasing demands for a greater variety of food products in combination with a desire of improved quality and higher production rates, novel methods need to be developed. Microwave heating is one of the most promising novel methods to use for thermal pasteurization, both in an environmental and qualitative perspective (Pereira & Vicente, 2010).

1.1. Current Cake and Butter Cream Production at Almondy AB

Almondy AB is a company that produces frozen cakes. The company sells many cakes in Sweden, but approximately 80 % of the cakes is exported to other countries. The company is constantly expanding and today two production lines are used, but hopefully a third production line will be introduced within the following years (Dahlbom, 2011.)

Today, the cake creams used in the cakes are produced in three scraped *horizontal processing tanks*, which from now on will be referred to as *HP tanks*. Each tank has a volume of 2500 l, and the total cake cream production capacity is today approximately 1300-1400 kg/h. To be able to introduce a third production line, a cake cream production of approximately 2500 kg/h is desirable. If microwave heating appears to be a suitable heating method, an increased cake cream production capacity can hopefully be accomplished by replacing the entire or a part of the current heating method during cake cream production with microwave heating (Dahlbom, 2011).

For a cake cream with satisfying properties, it must be pasteurized and have an appropriate texture. Today, water is heated at a pressure higher than 1 atm to a temperature of approximately 105 °C in a hot pan boiler, fuelled by utilization of natural-gas. The hot water is then transported in an enclosed system to the outer shell on the HP tanks, where it increases the temperature of the cake cream mixture to approximately 90 °C, from now on referred to as T_{max} °C. With this final temperature and the current heating time, the pasteurization requirement of 6 minutes above 74 °C is met, and a sufficient texture change of the cake cream mixture can take place to achieve a satisfying final texture (Dahlbom, 2011).

When the desired final temperature of the cake cream mixture inside the HP tank is reached, the hot water in the outer shell, surrounding the HP tank, is replaced with cold water to decrease the temperature of the cake cream mixture to approximately 50 °C. Next, the cake cream mixture is transported to a tubular heat exchanger, where the cake cream mixture temperature is further decreased to 12-15 °C by utilization of ice cold water as the cooling medium. Then, the cake cream mixture is homogenized to obtain a final cake cream with the correct appearance. The final cake cream should be easy-to-spread, completely smooth and well-tasting for a palatable product (Dahlbom, 2011). An overview of the current production system is presented in *Figure 1*.

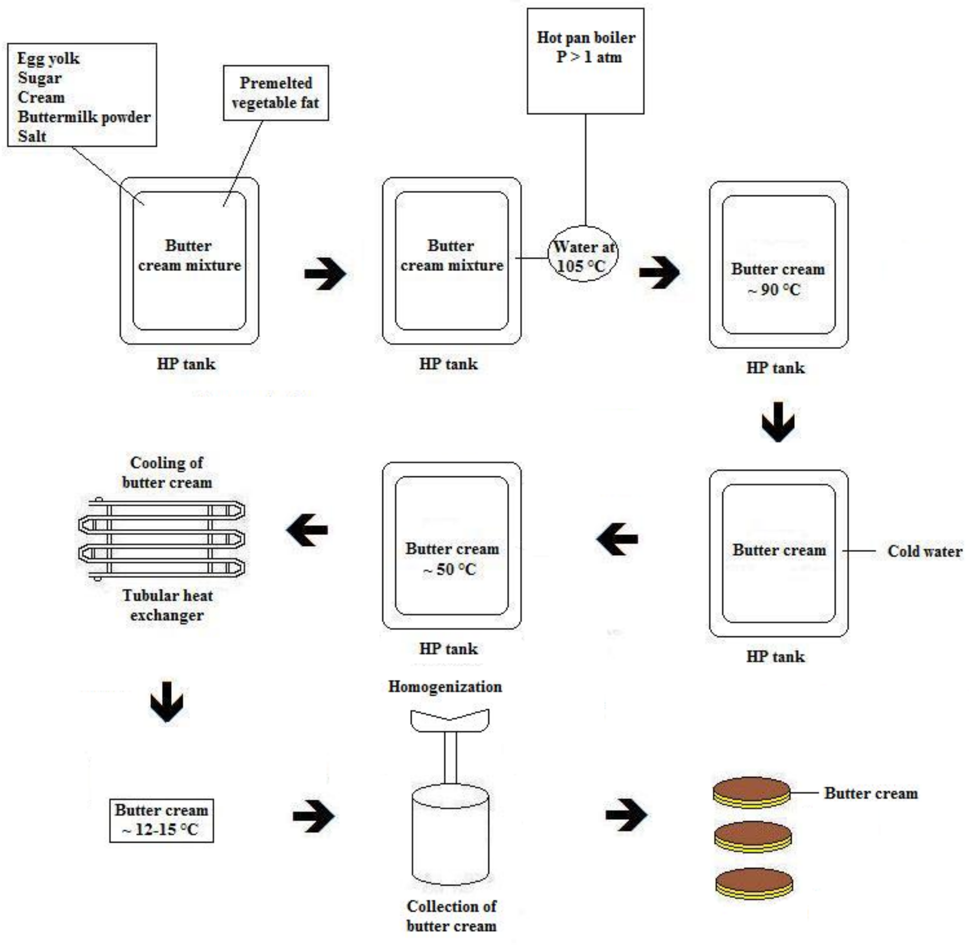

Figure 1: A schematic overview of the current cake cream production system at Almondy AB. Note that the butter cream mixture is kept within the same HP tank during the first five steps, it is only the surrounding environment that changes.

Also, at present, the capacity of the hot water boiler that heats the water for the outer shell on the HP tanks, as well as the capacity of the HP tanks themselves, is at its maximum level. To be able to expand the cake cream production, and indirectly the cake production, without the need of investing in an additional hot pan boiler or additional HP tanks, it is highly desirable to develop a more energy efficient and cost-effective heating process to use during the cake cream production (Dahlbom, 2011).

1.2. Project Aims

The overall aim with this project is:

- To investigate the possible utilization of microwave heating in the production of butter cream

By replacing the currently used heating method during butter cream production with microwave heating, the project also aims to fulfill the following interim targets:

- Shorter processing time
- Decreased energy consumption
- Gentler heat treatment
- Maintained product quality

To accomplish this, it is of great interest to determine if microwave heating is an applicable method for heating of butter cream mixture during butter cream production.

1.3. Objectives of the Project

To be able to fulfill the aims with this project, several tasks have to be performed:

- Read the literature to obtain knowledge about microwave heating and how food products are affected by this heating method
- Perform pilot plant experiments, to determine how the quality of the butter cream mixture changes during microwave heating, in terms of texture and temperature distribution
- Determine the heating rates and energy efficiencies in the pilot plants and during the current heating process
- Calculate time and energy requirements during current heating of butter cream mixture to get knowledge of the current situation

1.4. Limitations of the Project

During this project, only fundamental concepts of microwave, *MW*, heating are considered and only the effect of microwaves on food is considered, mainly continuously processed food. Also, only MW heating in the temperature interval of interest is studied. Focus will be on the heating part of the cake cream production. All the experiments, calculations and assumptions will consider the butter cream mixture, *BCM*. Another limitation in the project is that for the main experiments, only the existing pilot plants at the Swedish Institute for Food and Biotechnology, *SIK*, and Binar Elektronik AB, will be used. Last, but not least, even though thermal pasteurization is a prerequisite during butter cream production, the influence of MW heating on the microbial inactivation of BCM will not be considered in this project.

2. Microwave Heating Theory

In this chapter, some basic concepts and factors that influence the MW heating will be presented.

2.1. Fundamental Knowledge About Microwave Heating

Microwaves are electromagnetic waves and the frequencies used in MW heating range between 300 and 3000 MHz (Oliveira & Franca, 2002). In most food applications, 915 or 2450 MHz are used (Pereira & Vicente, 2010).

James Clerk Maxwell is famous for establishing four fundamental equations within electromagnetic fields, known as the Maxwell's equations. These four equations describe how electromagnetic waves and fields behave and they also give conditions for magnetic and electric fields that they must satisfy. Maxwell explained that where a varying electric field is present, an oscillating magnetic field is induced and vice versa. An electric and magnetic field together form an electromagnetic field which has the possibility of propagating as an electromagnetic wave, which is described below (Radmanesh, 2007).

An electromagnetic wave is composed of an electric field, E, [V/m] and a magnetic field, H, [A/m], which are perpendicular to each other. In *Figure 2*, an electromagnetic wave is visualized. In MW heating, it is the electric field that is the primary source of energy to the object that will be heated. The energy transport occurs in the same direction as the wave travels or propagates, the propagation direction (Bueche & Hecht, 2000). None of the field components are however directed in the wave propagation direction (Meredith, 1998). The wave frequency, f, [Hz] describes how a wave behaves in time and distance. Variations in the amplitude of both the magnetic and electric field can be described as a sinus curve both in the direction of wave propagation and time (Singh & Heldman, 2009). The larger the amplitude of the waves is, the more heat will be generated and where there are no oscillations of the electric field, no heat will be produced (Chieh, 2006). An oscillation can be described as a motion which is regularly repeated in a cycle, for example like a sinus curve, mentioned above (Jones, 2011). Each field configuration inside a waveguide or cavity is called a *mode* (Stein, *et al.*, 1994). The concept of waveguides and cavities will be described later.

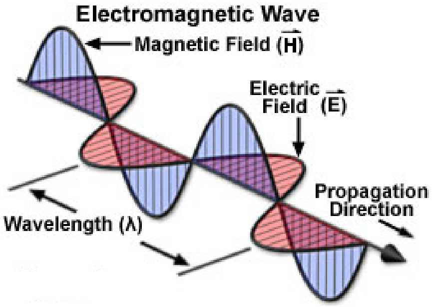

Figure 2: An illustration of the direction of the electric, E, and magnetic, H, fields in an electromagnetic wave, visualized in a 3D coordinate system. Neither the electric nor the magnetic field is directed in the propagation direction. Also the wavelength, λ, [m] is shown in the figure. (Davidson, 2006 - [edited])

A *standing wave* is referred to as the result of the superposition of two waves which are originating from two opposite directions (Ozerov & Vorobyev, 2007). Standing waves are the result of wave reflections when all power, or microwave energy, is not absorbed by the load. Waves are reflected and change propagation direction if the materials they travel through show different resistance against the waves (Tang *et al.*, 2002).

Generation of *volumetric heating* starts when microwaves penetrate a food product during exposure to them. This forces polar molecules within the food, such as water, to rotate and realign by alteration of the magnetic and electric fields around the food product. The electromagnetic field also causes dissolved ions to migrate within the food. The migration of ions in combination with the rotation of the polar molecules produce molecular movement, which is the same as heat (Oliveira & Franca, 2002).

The most important advantage with MW heating is that the heating is volumetric, which is described above. This means, as mentioned earlier, that the heating is theoretically more uniform in contrast to conventional heating (Coronel *et al.*, 2010). Volumetric heating offers faster heating rates and thereby shorter processing times compared to conventional heating (Oliveira & Franca, 2002). This contributes to a decreased energy consumption and a decreased risk of overcooking (Pereira & Vicente, 2010).

Unfortunately, many of the advantages with MW heating are today not yet so well documented in the literature and further studies are required (Pereira & Vicente, 2010). The lack of experimental data, which is important for a successful development of the MW heating equipment, also contributes to the slow progress (Vicente & Castro, 2008).

A property correlated to the power distribution within the food is the penetration depth, d_p, [m]. This property can be defined as the distance the microwave can pass through an infinitely large product, from the surface until the wave intensity, or power, has decayed to 1/e, or approximately 37 % of its initial value (Vadivambal & Jayas, 2010). If the penetration depth is large, this indicates a low energy absorption inside the food, while a small penetration depth is correlated to a high surface heating (Fu, 2004). A frequency of 2450 MHz, generates a smaller penetration depth compared with the penetration depth at 915 MHz (Tang *et al.*, 2002).

Often, MW heating is described as heating “from the inside and out” but this is not generally true. Both the inner and outer parts of the food receive the same amount of energy but due to surface losses, the surface loses heat faster than the inner parts (Ohlsson & Bengtsson, 2002). Considering MW heating from a physical point of view, it is thought to be a combination of four different processes: distribution of power, absorption of power and the resulting heat and mass transfer (Fu, 2004).

Earlier studies on microwave pasteurization of food products considering processing time (Huang & Sites, 2007) and nutritional parameters (Clare *et al.*, 2005) indicate no disadvantages compared to conventional heating. Unfortunately, pasteurization on beef frankfurters showed some negative effects on the size, such as shrinkage and expansion (Huang & Sites, 2007). This study is an example of why MW heating is not yet a commonly used pasteurization method.

2.2. Characteristics of Flow Through a Tube

A fluid that is transported with low velocity through a tube is said to have a *laminar velocity flow profile*. A laminar velocity flow profile is shown in *Figure 3*. A significant increase in flow rate will change the flow profile from laminar to turbulent (Sandeep & Puri, 2009). Laminar flow can however also take place at high flow rates, if the viscosity is very high (Morgan *et al.*, 2010). A parabolic velocity distribution in the tube gives that the maximum velocity, v_{max}, is equal to the double average velocity, v_{avg} (Villamiel *et al.*, 1996). Further, the fluid experiences maximal velocity in the tube center, while close to the tube walls the velocity approaches a zero value (Saleh, 2002). Considering MW heating inside a tube, by utilization of a single-mode applicator, Ohlsson (1994) states that when the diameter of the tube is small, the microwave fields can have a similar appearance as a laminar velocity profile.

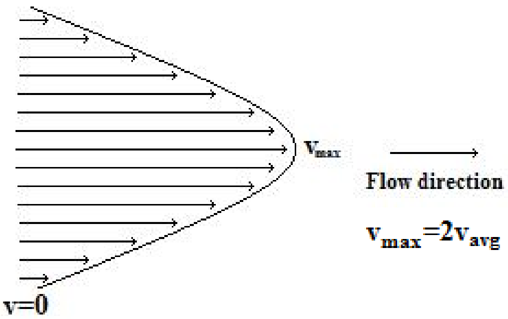

Figure 3: A picture of a laminar velocity profile, where the maximum flow velocity, v_{max}, is in the center of the tube and the velocity close to the tube walls approaches a zero value.

With laminar flow, the heat transfer is often insufficient, but by transporting the fluid through *helical coils*, this can be dealt with, without generating turbulent flow (Sandeep & Puri, 2009). Often, the helical coils used in MW heating processes can be composed of tephlone (Gentry & Roberts, 2005). Flow through helical coils results in flow in both the radial and axial direction. Factors such as flow rate, viscosity and tube to coil diameter ratio affect the helical coil efficiency (Sandeep & Puri, 2009).

During flow of a fluid through a pipe, flow in the axial direction is somewhat hindered due to friction. This results in a higher pressure at the inlet of the tube compared with at the tube outlet and the size of this pressure drop is dependent on the type of pipe, fluid and flow profile (Sandeep & Puri, 2009). If the viscosity is increased upon heating, this can generate a higher pressure drop along the pipe if a constant pressure delivery system is used. This will then lead to a decreased flow rate. The heat up rate of a viscous fluid is thus dependent on the flow rate and the amount of power delivered to the MW heating system. The power level can be adjusted to stabilize variations in flow rate, which means that if the flow rate is reduced due to an increased viscosity, the power level is decreased in an attempt to avoid a too high energy delivery to the viscous fluid, which otherwise can lead to overheating (Hill *et al.*, 1998).

2.3. Major Components in a Microwave Heating Equipment

Most often, a MW equipment is more expensive than a conventional heating equipment is, but design development and reduced heating times decrease the utilization costs of MW heating. This leads to the fact that MW heating is often more economically profitable in the end compared to conventional heating (Tewari, 2008). Factors such as size, frequency, cavity design, power rating and manufacturer affect the cost of the MW heating equipment (Stein *et al.*, 1994). The most important components in a MW heating system are the magnetron, the waveguide and the MW cavity. These will be shortly described below and are schematically presented in *Figure 4*.

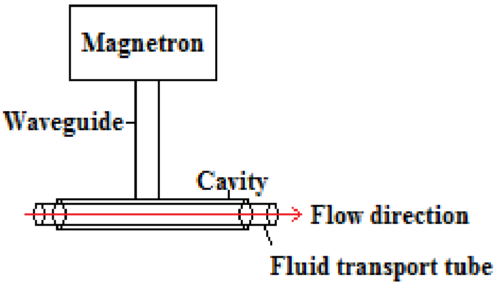

Figure 4: This picture shows a schematic overview of the most important parts in a MW heating system; magnetron, waveguide and MW cavity. In the picture, it is shown in which direction the fluid flows in a tube inside the MW cavity.

2.3.1. Magnetron

The *magnetron* is the main component of a high-voltage system, which is present in MW systems and generates the electrical energy that is converted to microwaves (Vicente & Castro, 2008).

A voltage between 4 000-10 000 V is required for the use of a magnetron, which is a large voltage requirement that can lead to high energy costs (Tewari, 2008). Electrical energy may be generated in several ways. One such was is through combustion of fossil fuel. This electrical energy is then further converted to microwaves. Since the conversion is far away from perfect between the different energy forms, an approximation is that only about 30 % of the energy from fossil fuel is converted into microwaves. In this case, the low total energy efficiency compared to heating directly with fossil fuel, is an aspect to consider regarding utilization of MW heating. Other factors must compensate for the use of microwaves compared to heating directly with fossil fuel (Stein *et al.*, 1994).

Not all power is absorbed by the load during MW heating. Connected to the magnetron, a so called dummy load can be placed, which often consists of water. Instead of power being reflected to the magnetron, the power is redirected to the dummy load, which absorbs the power. By so called MW matching, the degree of absorbed power during the heating can be maximized and the degree of reflected power to the dummy load is then minimized (Thostenson & Chou, 1999).

2.3.2. Waveguide

A *waveguide*, as mentioned above, is a hollow metal tube through which microwaves travel from the MW source to the cavity. Inside the waveguide, the electric field from the MW source is reflected and then further transferred to the cavity (Ohlsson & Bengtsson, 2002). The most simple waveguides are enclosed and have a uniform structure with a cross section that are either rectangular or circular. In practical applications, rectangular waveguides are more often used than circular waveguides (Cheng, 1992).

2.3.3. Microwave Cavity

In short terms, a *microwave cavity* is a device in which a material is heated in a controlled environment by exposure to microwaves (Stein *et al.*, 1994). MW cavities are also often rectangular or circular (Cheng, 1992). The superposition of incident and reflected waves inside these cavities generates standing wave patterns, as mentioned earlier (Bows, 2000). When a food product is placed inside the cavity, the waves will be reflected differently, thus changing the modes and the standing wave patterns (Gunasekaran, 2002). The MW cavities are either single-mode or multimode cavities and they will be shortly described below (Stein *et al.*, 1994).

In single-mode cavities, it is desirable to apply only one specific wave mode that interacts with the material. During design of a single-mode cavity, it is important to have knowledge about for example product material properties and physical dimensions to ensure that the correct mode is applied, or excited. It is also important to avoid introduction of any unwanted modes that can interact with the material (Mehdizadeh, 2009).

Advantages with single-mode cavities are: the fields are well defined and can often be high and matched to the product geometry; these cavities can be used for continuous heating; both standing and travelling wave configurations are possible and the single-mode cavities often provide high efficiency (Stein *et al.*, 1994). It must be remembered that even though the fields can be well defined, the distribution is often non-uniform, which often results in overheated spots (Thostenson & Chou, 1999). Single-mode cavities can thus be very sensitive to changes in position, geometry and other product properties during processing (Stein *et al.*, 1994). Therefore, a common application of single-mode cavities is heating of pumpable fluids, since the load properties are thought to remain stable during this process (Mehdizadeh, 2009).

By combining several single-mode cavities which apply different modes during tubular heating, it is easier to maintain uniform heating. Two different cavities that are used during this project and therefore will be considered below, are the TM_{020} cavity, which heats mainly in the center of the tube, and the TM_{120} cavity, which mostly heats in the periphery of the tube (Isaksson, 2002).[1] For the TM_{020} and the TM_{120} cavities, there is

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[1] These notations for MW cavities will not be further mentioned in this project.

assumed to be no variation in the electric and magnetic field strength along the axis of the cavity (Clarke, 2007).

In a TM_{020} cavity, the heating profile matches the profile of laminar flow if the cavity and pipe is designed so that the zero point of the electric field coincides with the wall of the pipe. This absence of MW heating close to the surface of the pipe prevents the fluid that flows with a lower velocity at that location from being overheated (Mehdizadeh, 2009). Also, buildup of deposits with low thermal conductivity is prevented. Another great advantage with a TM_{020} mode cavity is that the heat treatment is milder, since no temperature gradients are generated as is the case in heat exchangers (Risman & Ohlsson, 1975).

If a tube is used for continuous flow with a single-mode cavity, as in the experiment described in *Section 3.3*, this means theoretically that the flow in the center of the tube receives high energy for shorter times, while flow closer to the wall is receiving lower energy for longer times (Coronel *et al.*, 2010).

For many applications, the temperature can be increased from its initial to its final temperature in one single step. An alternative to this approach is to use several cavity tubes, working at a low power level and thus increase the temperature in several steps (Sabliov *et al.*, 2008).

A multimode applicator discharges the microwaves in a random configuration and the walls of the applicator is used to randomly reflect the waves. Unfortunately, this can lead to several spots in the material with high concentrations of MW energy resulting in overheating (Fu, 2004). This non-uniform heating is improved by several different methods. If the cavity size is increased, it is possible to excite a higher number of modes. The different heating patterns will then start to overlap, which will give a more uniform heating pattern. Another method to even out the heat distribution is to have more than one MW input (Thostenson & Chou, 1999).

The multimode applicators are most often designed based on intuition, experience, trial and error, compared to single-mode applicators (Thostenson & Chou, 1999). To obtain as uniform heating as possible with a multimode applicator, application of as many standing-wave modes as possible is desirable. When designing a multimode applicator, several parameters must be taken into consideration. Examples are uniform heating, size of the applicator, prevention of leakage and required MW power and performance characteristics (Stein *et al.*, 1994).

2.4. Dielectric Properties of Butter Cream Mixture

Below, the concept of dielectric properties is given. First, two definitions of dielectric properties will be described and then, the influence of different factors on the dielectric properties of a food product will be presented.

2.4.1. Definition of Dielectric Properties

Dielectric properties are the most important properties that affect how the electromagnetic energy is distributed during MW heating (Wang *et al.*, 2003). The dielectric properties can also be defined as the proportion of the energy that is absorbed, reflected or transmitted (Vicente & Castro, 2008).

The phenomenon of dielectric heating can be described by two different parts. The first part is the dielectric constant, *ε'*, which describes how well a material can store the energy that is applied from an electric field. The loss factor *ε''* describes the ability of a certain material to dissipate energy when an electric field is applied (Wang *et al*., 2003). This dissipation leads to generation of heat (Vadivambal & Jayas, 2010). The higher dielectric loss factor, the more electromagnetic energy is converted into heat and vice versa (Salvi *et al*., 2009). Worth mentioning is that the loss factor in MW heating in reality is correlated to a gain in heat, since the generated heat is something desirable in this process (Berk, 2009). Most biological materials, such as food, have the same magnetic permeability as free space, and therefore it is stated that no interaction exists between food products and the magnetic field component of electromagnetic waves (Tang *et al*., 2002). The amount of energy that is converted into heat is often described as a function of the electric field intensity, frequency and loss factor (Coronel *et al*., 2010). Both the penetration depth and the wavelength within the food product is influenced by ε' and ε'' (Ayappa *et al*., 1997).

The loss tangent value, *tan δ*, is referred to as the ratio between ε'' and ε'. This value indicates how good the dissipation characteristics of a material are (Içier & Baysal, 2004). As mentioned above, the higher loss tangent, the more MW power is absorbed (Zhu *et al*., 2007). For optimal MW heating, it is desirable with a maximum value of ε'' and tan δ in combination with a satisfactory penetration depth (Stein *et al*., 1994).

2.4.2. Factors Affecting the Dielectric Properties of Food

It is highly significant to have knowledge about the dielectric properties of a food product to be able to develop a successful industrial system. Some of the factors that affect the dielectric properties of a food product include the shape, water content, density, chemical composition and temperature (Pereira & Vicente, 2010).

The chemical composition determines to a large extent the dielectric properties of a food product (Içier & Baysal, 2004). In a food product, the major components are moisture, fat, carbohydrates, proteins and salt. The amount of hydrogen bonds, electrolytes, nonelectrolytes, free or bound water and surface charges has the greatest influence on the dielectric properties (Sahin & Sumnu, 2006). However, ε'<3 and ε''<0.1 for many food components such as proteins and carbohydrates, water not included, which means that these components are transparent to energy. Even if the food components are not affected significantly by MW, their presence influence how the dielectric properties of water and salt are affected, since water and salt can bind to molecules such as proteins, fats and carbohydrates (Sosa-Morales *et al*., 2010). Only if the moisture content is low and the majority of the water is bound, the food components such as proteins and carbohydrates will have a large influence (Tulasidas *et al*., 1995).

Water in liquid form is very polar, resulting in high absorption of MW energy. Therefore, the moisture content highly influences the MW heating of foods (Datta *et al*., 2005). The amount of bound water in the food affects the dielectric properties of the food. Water molecules that are chemically bound do have less influence than free water molecules, since free water molecules can rotate freely when an electric field is applied, which bound water molecules cannot (Içier & Baysal, 2004).

It is important to distinguish between free and bound water in a food product. In the frequency range used in the food industry, both ε' and ε'' for bound water increases when the temperature increases and the opposite for free water (Tang *et al.*, 2002). The reason for the decrease in the dielectric constant for free water has been shown in many high moisture foods, to depend on an interrupted arrangement of water molecules due to an increase in molecular vibrations when the temperature is increased (Zhu *et al.*, 2007).

To what extent salt has an influence on the dielectrical properties, depends on how the salt is bound and how well it can move within the food (Içier & Baysal, 2004). Salt will bind to water molecules in the food, decreasing the amount of free water available for polarization and therefore the dielectric constant will decrease when salt is added. The addition of salt increases the loss factor of water, due to the fact that more ions are added and the migration of charged particles is improved (Sahin & Sumnu, 2006). Further, a moisture content above 35 % often leads to dilution of the salts present in the food (Datta *et al.*, 2005).

Except water and salt, other dipolar molecules such as proteins and carbohydrates affect the MW heating of foods (Tewari, 2008). The stronger binding that exists between bound water and carbohydrates, the lower is the loss factor and the dielectric constant due to the decreased amount of free water (Sahin & Sumnu, 2006). No significant interactions with microwaves can be observed for proteins in general (Datta *et al.*, 2005). Proteins do often have charged surface regions, to which salt or water can bind, leading to different effects (Brewer, 2005).

An increase in temperature leads to denaturation of proteins (Protein, 2011). This then leads to a changed protein structure and thus an increased rearrangement of the charge distribution of the protein, followed by an amplified dipole moment and polarization that will affect the dielectric properties. Further, if water is bound during the denaturation process, the dielectric properties will decrease and vice versa if water is released during denaturation. As mentioned above with carbohydrates, the stronger binding that exists between bound water and proteins, the lower is the loss factor and the dielectric constant due to the decreased amount of free water. When denaturation takes place and water is bound, the mobility of present ions is reduced, decreasing the dielectric properties (Sahin & Sumnu, 2006).

The main parts of the lipids are hydrophobic and do not interact so much with microwaves if water is present (Brewer, 2005). Fats have a low dielectric loss, which means that when an electromagnetic field is applied, not so much heat is generated (Fu, 2004). In egg yolk, the high lipid content aids in decreasing the overall dielectric properties since ε' and ε'' is approximately 4 and 0.2, respectively. The only influence of fat on the dielectric properties is the diluting effect (Bircan & Barringer, 2002). An increase in fat content decreases the amount of free water and this reduces the dielectric properties (Sahin & Sumnu, 2006).

2.5. The Viscosity of Butter Cream Mixture

Denaturation of proteins results in a higher viscosity and the viscosity is thought to be further increased by addition of salt (Anson & Mirsky, 1932). The BCM recipe includes salt in a small amount and also water, and both the egg yolk, buttermilk powder and the cream in the BCM contains proteins. It is of great importance to make sure that the MW heating results in the same viscosity as the heating method used today considering all ingredients that may be of significance.

The total amount of water, fat, protein, carbohydrates and salt in 100 g of BCM is presented in *Table 1* and the calculations are based on chemical composition data from the raw material suppliers, together with the recipe of BCM. Also, the mass fraction, *z* for each chemical component, is presented. Raw material information used to obtain these values are presented in *Appendix B*.

Table 1: The table shows the chemical composition of 100 g of BCM. Almost 100 % of the BCM consists of water, fat, proteins and carbohydrates.

Chemical component	Mass [g/100 g]	Mass fraction, *z* [g/g]
Water	38.4	0.384
Fat	29.3	0.293
Protein	7.7	0.077
Carbohydrates	23.4	0.234
Salt	0.2	0.002

The protein content in egg yolk is approximately 17.5 % (Srilakshmi, 2003). Egg yolk contains both high density lipoproteins, *HDLs*, and low density lipoproteins, *LDLs*. The good emulsifying properties of egg yolk are due to the lipoproteins since they have a high lipid content. It is the LDLs that contribute the most to the emulsion stability and the high viscosity of egg yolk also gives the emulsion high stability. When heat is added, the LDLs are denatured and the emulsifying ability of egg yolk and the emulsion stability is decreased. Addition of salt increases the yolk viscosity and the emulsion stability (Linden & Lorient, 1999).

Upon denaturation, proteins in eggs form a gel and the denaturation and gel formation temperature peak has been estimated to 84 °C (Barringer & Bircan, 2006). Further, the coagulation process of egg yolk starts at 60 °C and at 65 °C, the egg yolk loses its fluidity (Linden & Lorient, 1999). The coagulation is equivalent with irreversible protein denaturation (Froning, 1994).

Whey proteins are one of the protein varieties in milk and about 50 % of these proteins is β-lactoglobulin, where addition of sugar can increase its denaturation temperature with approximately 5 °C (Barringer & Bircan, 2006). As other globular proteins, they are heat sensitive and at 90 °C, they are denatured and a gel is formed. When the temperature is 60 °C, the β-lactoglobulins are partially denatured and a maximum denaturation peak is shown at 80 °C. At 90-95 °C, the denaturation process is completed (Chandan, 2006). This complete denaturation at these temperatures leads to an increase in milk viscosity (Foegeding *et al.*, 2011). The fat content in milk does not affect the heat stability of milk (Chandan, 2006).

The viscosity of foods is related to the level of protein hydration. A commonly used concept is the *water holding capacity*, *WHC*, which describes how well a food can hold its own or added water during factors such as heat exposure. Interactions between proteins and water determine many functional properties of foods, such as water binding, emulsifying properties, swelling, gelation and viscosity (Zayas, 1997). Water considered by the water holding capacity is enclosed in a three-dimensional, gel-like network formed by unfolded proteins (Lagrange, 2005).

The buttermilk powder contains a low amount of fat but the phospholipid content is high and therefore buttermilk powder increases the emulsifying properties of the food product (Tamime & Robinson, 2007). The phospholipids tend to organize themselves and interact with proteins and carbohydrates and in that manner increase the emulsifying properties (Riel, 1985). The buttermilk powder used in the butter cream is produced by so called drum-drying where a heated drying cylinder at 100-130 °C is exposed to a thin layer of the milk for a few seconds. At these temperatures, the whey proteins have denatured, which decreases the solubility of the final product (Belitz *et al.*, 2004). Several advantages are correlated to the use of milk powders. First of all, it increases the viscosity of a food product but it also helps to generate moister products, which improves the texture of a food product. Milk powders also, as mentioned above, aid in creating stable emulsions and enhances the flavour characteristics (Lagrange, 2005).

Thermal properties such as the specific heat capacity and the thermal conductivity determine together with the viscosity how well a viscous fluid can be heated. It is the thermal properties that determine the heating rate of a food product. An increase in the viscosity results in a decreased heat transfer, leading to a more nonuniform heat distribution (Ryynänen, 2002).

2.6. The Fouling Problem during Heating

Fouling can shortly be described as protein deposits that are formed on surfaces in process equipment during heating (de Jong, 1997). It is a very rapid process and it is a large problem since it affects the heat transfer efficiency negatively. A decreased heat transfer results in increased processing costs via an increased energy consumption, utilization of additional equipment and manpower as well as diminished productivity (Bansal & Chen, 2006). Further, fouling leads to enlarged cleaning costs due to an increased utilization of detergents and a higher amount of outflow disposals (Michael & Heppell, 2000). Also, fouling results in an increased pressure drop across the heating system, resulting in a decreased performance of the heating equipment (Puri *et al.*, 2009).

A food product not reaching the required outlet temperature for example during pasteurization, results in unsafe foods with a diminished quality (Bansal & Chen, 2006). The heating rate often influences the location of deposit formation and it is often the bulk product temperature, which changes along the length of the heating tube or surface that is considered during fouling (Michael & Heppell, 2000).

The formation of deposits on the heat transfer surfaces, for example in a tubular heat exchanger, results in tighter or even worse, entirely blocked flow channels. This can lead to a diminished flow rate or an increase in pressure, depending on the pumping equipment (Michael & Heppell, 2000). The kinetics of fouling depends on the protein solubility and often fouling occurs to a larger extent near the tube inlet if the temperature of the product entering the tube is high (Pelegrine & Gasparetto, 2006).

When the temperature is increased, protein molecules denature and react with other or similar protein molecules, which leads to generation of aggregates (Bansal & Chen, 2006). Ling and Lund (1978) have however determined that the rate of protein denaturation does not have a significant effect on the fouling rate, since the activation energy for egg albumin denaturation is several times higher than the activation energy for the fouling process.

Denatured proteins that precipitate and aggregate in the bulk fluid, make it more difficult for the proteins to attach to a heated surface, thereby reducing the amount of fouling. Therefore it is most likely the deposition and attachment of protein molecules to the heat exchanger surfaces that determine the rate of the fouling process (Ling & Lund, 1978). Also, the rate of fouling on the heat transfer surfaces can be different for aggregated and denatured proteins, due to differences in size that affects the transport of the molecules (Bansal & Chen, 2006).

Other variables that are thought to influence the amount of fouling are flow rate and turbulence. Fouling is generally reduced at high Reynolds numbers and high flow rates and amplified at low flow rates and low Reynolds numbers (Michael & Heppell, 2000). The product composition is also thought to have an influence on the fouling process (Puri *et al.*, 2009).

Heating of egg yolk proteins lead to protein denaturation as for other proteins and this leads to an increase in viscosity which can contribute to the fouling of process equipment during processing of egg yolk products (Guilmineau & Kulozik, 2006).

Fat seems to have a small influence on fouling, and therefore the fouling of cream has not been reported as a significant problem. Those fouling deposits that have been produced from cream mainly contain proteins and no fat and it is therefore thought that fouling of cream is influenced by the same factors that influence the fouling of milk (Michael & Heppell, 2000).

Bansal & Chen (2006) also mention that the use of MW heating is thought to reduce fouling. MW heating reduces fouling by avoiding the formation of steep temperature gradients and high surface temperatures that are produced during conventional pasteurization in heat exchangers (de la Fuente *et al.*, 2002).

2.7. Temperature Distribution during Microwave Heating

To ensure uniform heating in a continuous flow MW heating system, it is important to measure the temperature at several locations during the heating process. The more measuring points the better, since a more exact overview of temperature distribution then can be obtained (Salvi *et al.*, 2009). When measuring the temperature during MW heating, it is of great importance to avoid interferences with the existing fields in the heating chamber as much as possible but at the same time have an appropriate contact with the object that is being heated. Interferences with the existing fields are avoided by inserting the measuring probes appropriately, since the electric field distributions most often are known (Stein *et al*., 1994).

As mentioned above, in *Section 2.1*, MW heating is also influenced by heat transfer. Heat transfer by conduction is affected by the porosity of a material, since air transfers heat less effective than other components in a food product (Barbosa-Cánovas *et al*., 2004).

To improve the temperature distribution during continuous MW heating, it is important to use mixers in the flow regimes (Coronel *et al*., 2010). If several cavities are used in series during the heating, it is a good idea to place *static mixers* in between them to improve the temperature uniformity (Morgan *et al*., 2010).

Static mixers are also called motionless mixers. They are used to improve the heat distribution in both laminar and turbulent flows. Also, they can be used to improve mixing in both the tangential and radial direction. Static mixers consist of a pipe with fixed internals. In static mixers, these elements are arranged in a manner which creates swirls in the flow and also layering of fluid elements, both events resulting in an efficient mixing (Kraume *et al*., 2010). An example of a static mixer composed of tephlone is visualized in *Figure 5*.

Figure 5: Static mixers, composed of tephlone, that can be used to reduce temperature differences during flow through a tube, are shown in this picture (ESSKA-teknik - Fackhandel för industri och hemmafixare).

3. Methods and Equipment

The methods and equipment that have been used during this project will be more thoroughly described in this chapter.

3.1. The Changes in Dielectric Properties during Microwave Heating

During this project, no dielectric measurements were performed on the BCM. Therefore, only by assumptions and interpretations of the information available in the literature, the changes in dielectric properties during MW heating of BCM will be discussed, see *Section 4.1*.

3.2. The Changes in Butter Cream Mixture Viscosity during Heating

In this section, a description of the method used to heat BCM for viscosity measurements is presented. Also, the equipment used when determining the viscosity is described.

3.2.1. Butter Cream Mixture Heating in a Planetary Mixer

To gain a better knowledge of how the viscosity is changed during heating, BCM was heated in the *planetary mixer* UMC5 (Stephan Machinery GmbH, Germany), which is visualized in *Figure 6*. The BCM studied in this and the following experiments was produced from the same recipe based on the original recipe of BCM.

In the planetary mixer, 2.5 kg of BCM was heated during each run and first, the vegetable fat was premelted in a kettle on a conventional stove. Further, all the other ingredients were measured in a large container on a scale with one decimal and then poured into the planetary mixer together with the premelted vegetable fat. The planetary mixer is heated through an outside layer with circulating hot water with a predetermined temperature. Conclusively, this heating method therefore has some similarities to the BCM heating in the HP tanks but in a much smaller scale. The planetary mixer has an agitator, a temperature indicator and a manual surface scraper and samples were collected at varying time intervals. At selected time points and observed temperatures on the display seen to the left in *Figure 6* together with thermometer-estimated temperatures, samples were collected and the viscosity was measured in the Bostwick device, described in *Section 3.2.2*. To collect a sample, the lid on the planetary mixer was removed, which interrupted the rotation of the agitator and therefore, the lid was reintroduced as soon as possible after the sample collections to ensure mixing of the BCM as much as possible. The heating was continuous during the entire process, also when no mixing was present during the sample collections and the viscosity measurements. Each sample collection including the viscosity measurement took approximately five minutes but the lid was reintroduced as soon as the sample was collected, prior to the viscosity measurement. The sample collections continued as long as the temperature of the BCM increased within the temperature interval of interest and terminated when the BCM had been overprocessed, with fat separation and a grainy texture.

Figure 6: A photograph of the planetary mixer that was used to heat the BCM for the viscosity measurements.

The results obtained when heating BCM in a planetary mixer are presented and discussed in *Section 4.2*.

3.2.2. Viscosity Measurements with a Bostwick Device

A *Bostwick device* was used to measure the viscosity of BCM. During each viscosity measurement, an enclosed space in the Bostwick device is completely filled with BCM and then one of the walls surrounding the BCM is removed. This allows the BCM to flow, during a predetermined time period, on a lane inside the Bostwick device. Then, with the help of an embedded ruler, it is possible to see how long distance the BCM has flown during this time period, giving a measure of the viscosity. To get a value as appropriate as possible, the longest and shortest distance was measured during each run and an average value was calculated. During each viscosity measurement, it was determined how long distance the BCM flows in the Bostwick device during 30 seconds. The longer distance the BCM has flown, the lower is the viscosity of the BCM. An example of a viscosity measurement with a Bostwick device is shown in *Figure 7*.

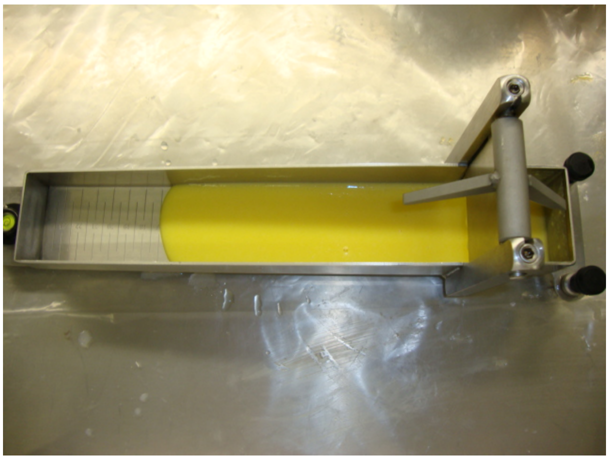

Figure 7: The picture shows one of the many viscosity measurements of BCM performed in the Bostwick device.

3.3. Microwave Heating in a Pilot Plant at SIK

In this chapter, information considering the pilot plant MW heating experiment of BCM at SIK will be given. First, the pilot plant that was used during this experiment will be described together with some preparations prior to the experiment. Further, the different adjustments of the settings that were performed and an explanation of the different measurements during the experimental session will be given. Last but not least, a description of the BCM analysis and calculations after the experiment will be presented.

3.3.1. Description of the Pilot Plant and Preparations prior to the Experiment

For an initial study of how BCM is affected by microwaves, a pilot plant at SIK was used and a schematic picture of this pilot plant is shown in *Figure 8*.

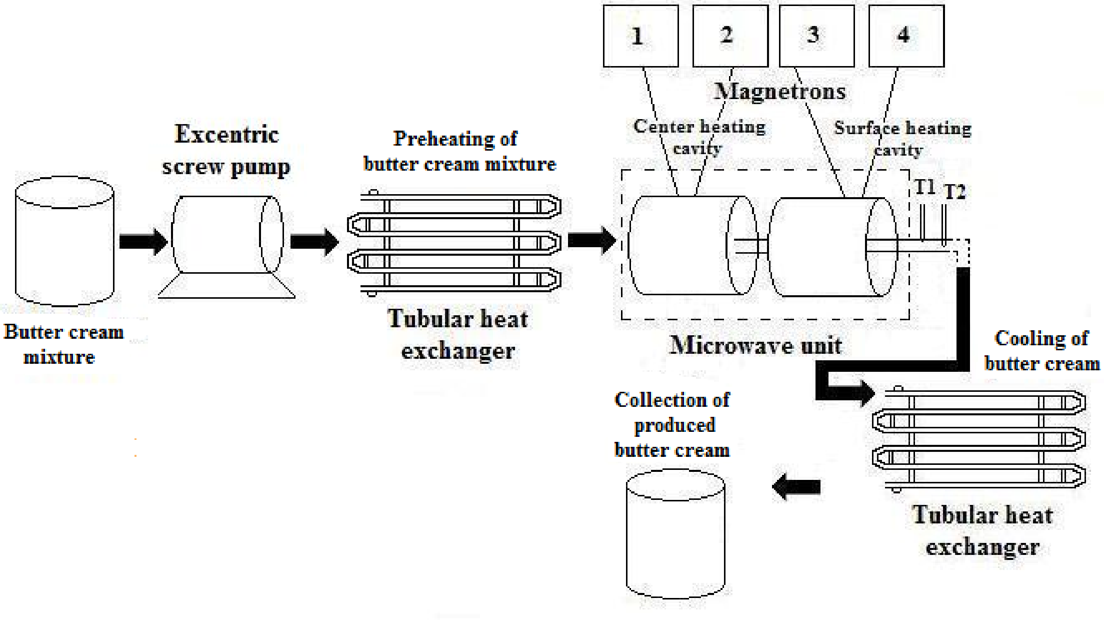

Figure 8: A schematic overview of the MW pilot plant used for the heating experiment at SIK. The tube inside the MW unit was composed of tephlone. Note that the figure is not according to scale.

This pilot plant consists of an excentric screw pump that transports the BCM into a tubular heat exchanger which can preheat the BCM to a desired initial temperature by using hot water as the heating medium. Following the tubular heat exchanger is the MW unit through which the BCM passes and the temperature is increased to the final temperature of interest. The tubes are straight and composed of tephlone with an inner diameter of 20 mm. In the pilot plant, the flow rate can be adjusted to up to several liters per minute by altering the pump frequency. This MW heating system contains two different single-mode cavities; a center heating cavity and a surface heating cavity, to ensure a heating as uniform as possible. The total length of the two cavities is 0.842 m. Each cavity has the maximum power of approximately 4 kW, resulting in a total maximum power of 8 kW. After passage through the MW cavities, the BCM is transported through a heat exchanger again, where the BCM is cooled with cold water as the cooling medium. A tank collects the final butter cream after it has been transported through the second heat exchanger.

The system contains four magnetrons, two for each MW cavity, as can be seen in *Figure 8*. These deliver the power to the system, heating the product that passes through the MW unit. It is desirable to decrease the amount of reflected power as much as possible and as mentioned in *Section 2.3.1*, a water load is present in each magnetron that will take care of the reflected power in an attempt to avoid destruction of the magnetrons. By adjusting the flow rate or the power of the different magnetrons, the amount of energy delivered to the cavities can be altered and the final product temperature of interest can be changed. Temperature measuring probes are located at several places in the whole pilot plant. The most important ones for this process are the two temperature indicators shown in *Figure 8*, labelled as *T1* and *T2*. The first one, *T1*, is located directly after the exit from the MW unit and it measures the temperature near the surface of the tube, while *T2* is measuring the temperature in the center of the tephlone tube only approximately 20 centimeters further down the system, prior to the cooling section. All temperatures are being logged each second by a software program called Easyview. Photographs of the pilot plant used in the experiment at SIK can be seen in *Appendix D*.

Prior to the experimental session at SIK, a basic experimental design was setup at Almondy AB, where the desired final temperature of interest was predetermined at four different levels between 85 °C and T_{max} °C, which as mentioned earlier is 90 °C. Then during the experiment, different parameters such as power output from the four magnetrons, flow rate, heating time, viscosity, fouling and sensory characteristics of the BCM could be observed and noted in the table for analysis after the experiment.

The BCM used in the pilot plant experiment was siphonaged in the production area at Almondy AB only a few hours prior to the experiment and then transported to SIK in a large tank. When measuring the temperature of the BCM in the large tank before initiation of the experiment, it was approximately 35 °C. Every now and then during the experiment, the remaining BCM in the tank was manually agitated with a large plastic stick.

3.3.2. Initial Settings during the Experiment

As mentioned in the experimental design above, the first aim with the experiment was to make appropriate settings to obtain a final butter cream temperature of approximately 85 °C. The power was continuously altered in the beginning to see how the BCM responded to the microwaves and to achieve knowledge about approximately which power levels that were necessary to reach the temperature of interest. The results from the heating of the BCM with these settings are presented and discussed in *Section 4.3.1*.

3.3.3. A First Adjustment during the Experiment

The first adjustment that was made after observing the results from the initial settings was to increase the power from the magnetrons controlling the center heating cavity and decrease the power from the magnetrons controlling the surface heating cavity. At the same time, the cooling step after the MW unit was removed. The results from the heating of the BCM with these settings are presented and discussed in *Section 4.3.2*.

3.3.4. Further Adjustments and Measurements during the Experiment

Next adjustment in an attempt to stabilize the process and to obtain an improved result included reintroduction of the cooling section. Also, the pump frequency, or indirectly the flow rate, was decreased, to expose the BCM to microwaves for a slightly longer time period.

With these settings, the mass flow rate was determined by sample collection during one minute. A container, which was weighed before and after, was used for collection of BCM during this measurement. To measure the density, a glass cylinder with the volume of one liter was filled with BCM exiting from the pilot plant. The filled glass cylinder was then measured and the volumetric flow rate could be determined by calculating the ratio between the mass flow rate and the density. At the time point when these measurements were performed, a larger sample was also collected for subsequent analysis. Further, the power output values from the magnetrons were observed and noted. All the results obtained with these settings are presented and discussed in *Section 4.3.3*.

Last but not least, the flow rate was slightly increased again for further fine-tuning of the system. Also with these final settings, a larger sample was collected. Subsequently to the final sample collection, the experimental session was terminated.

3.3.5. Calculations after the Experiment

As mentioned in *Section 3.3.4*, measurements of the mass flow rate and the density were performed during the same time as the first sample was collected. The length and radius of the MW cavity was known. These values were then used to calculate the heating time, t, during the run with these settings. The heating time is presented and discussed in *Section 4.3.4*.

It is interesting to have knowledge about the energy efficiency of the MW heating system. To calculate an approximate energy efficiency, that is how much of the applied MW energy that is absorbed by the BCM during the MW heating, an equation from Gentry & Roberts (2005) has been used to calculate the power absorption during the MW heating. This value has then been compared with the total forward power value generated by the magnetrons during the heating to obtain an energy efficiency value. The calculated absorbed power value and the energy efficiency are presented and further discussed in *Section 4.3.4*.

Further, the estimations of the heating rates during the MW heating of BCM at SIK and during the current heating method are calculated in the same temperature interval, 45-86 °C. These heating rates are also presented and further discussed in *Section 4.3.4*.

To be able to calculate how much energy that is absorbed during the MW heatings in this project and the energy requirement for heating of BCM, as mentioned later, the specific heat capacity for BCM at different temperatures is required. For an estimation of the specific heat capacity at different temperatures, since no measurements of this variable are performed during the project, theoretical equations by Okos & Choi (2003) have been used and these equations are presented in *Appendix C* together with an example of a specific heat capacity calculation and a table with the calculated specific heat capacities at the temperatures of interest in this project. The density that is used in this power absorption calculation was measured during the settings presented in *Section 3.3.4* and also used in *Appendix H*.

3.4. Microwave Heating in a Pilot Plant at Binar Elektronik AB

Another pilot plant MW equipment was used in a second attempt to heat BCM with microwaves. These experiments were performed at Binar Elektronik AB and the pilot plant as well as the different settings used during the experimental session will be described below.

3.4.1. Description of the Pilot Plant and Preparations prior to the Experiments

The pilot plant used during these experiments can be described as a tunnel oven with a conveyer belt in polypropylene with the width of 0.25 m that transports the product that will be heated through the tunnel. In this equipment, twelve magnetrons are used to supply the system with power. Each magnetron delivers approximately 1 kW to the MW cavity when the magnetron is set on a 100 % power level. The food product is exposed to microwaves during a length of approximately 4.1 m. The cavity is a multimode cavity, which is shortly described in *Section 2.3.3*. Microwaves are applied to the cavity from below, from twelve different locations along the MW unit.

It is desirable to have a tubular continuous process for heating of BCM. Since this tunnel oven equipment is specifically designed for another, container packaged food product, both considering the design and the field distribution, the BCM was however heated in trays located after each other with no space in between them, in order to mimic a continous tubular process as much as possible, except that the BCM will not flow through the MW unit.

The trays were composed of polycarbonate and had an inner size of approximately 54x15x1.5 cm. These trays were covered with a layer of tephlone inside. Neither the polycarbonate or the tephlone is affected by microwaves but they will be heated due to heat transfer from the BCM that is heated by microwaves.

During each run, two trays of water were located before and after three trays filled with BCM. The arrangements of trays used in the different runs are presented in *Figure 9*.

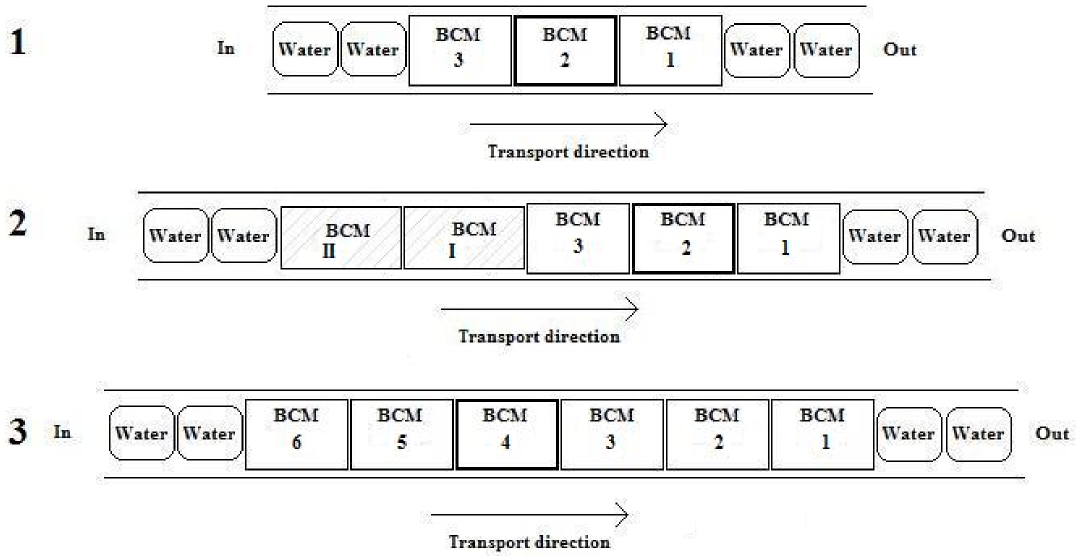

Figure 9: This figure shows schematically in which order the water and BCM trays, respectively, are transported through the tunnel. *Arrangement 1* was used in Run 1-5, *arrangement 2* was used in Run 6 and *arrangement 3* was used in Run 7. The bold BCM trays were the trays on which the temperature measurements mainly were performed. The striped BCM trays, BCM I and BCM II, were only used in Run 5 and did not have the same design as the other trays.

Prior to each run and directly after the MW heating, the temperature of the BCM was determined with a thermocouple wire. The temperature was measured at several locations in the tray but the center temperature in BCM tray 2 or BCM tray 4, respectively, will be considered when using temperature differences during subsequent calculations.

The reason for this choice is that the BCM tray in the middle is supposed to give the results that mostly resembles the results of a continous process, when the settings have had time to stabilize in the preceding water and BCM trays. Water trays are thus located prior to the BCM trays so they can be heated during the start up period of the magnetrons so they function properly when the BCM trays pass.

As can be seen in *Figure 9*, Arrangement 1 with BCM trays 1-3 was used during the first five runs. In Run 6, two other trays with a thinner layer of BCM, I-II, were also heated, see Arrangement 2 in *Figure 9*. Arrangement 3 in *Figure 9*, visualizes that six ordinary BCM trays, 1-6, were heated instead of three during Run 7. BCM tray 2 in Run 1-6 and BCM tray 4 during Run 7 were the trays in which the effect of MW heating was mainly studied, but the effect on the other trays was also observed.

In *Appendix E*, some general pictures from the experiments at Binar Elektronik AB, are presented.

3.4.2. Experimental Settings and Measurements

On the control panel for the MW equipment used at Binar Elektronik AB, it was possible to adjust the power level on the twelve magnetrons as well as the heating time. After each MW heating run, the effect on the BCM considering texture, temperature distribution and scorching, was visually evaluated. The MW heating time and power level from each of the magnetrons were then adjusted prior to the next run, depending on which results that were obtained during the previous run. In *Table 2*, the power levels [%] and heating times [s] during the seven runs with the pilot plant at Binar Elektronik AB are presented.

Table 2: In this table, the power levels [%] and heating time [s] in each of the seven runs performed during this experimental session are presented. * = initial settings, which were changed after a while.

	Power level [%]												**Heating time [s]**
Magnetron	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Run 1	100	100	100	100	100	100	100	100	100	100	100	100	120
Run 2	100	100	100	100	100	100	100	100	100	100	100	100	150
Run 3	100	100	100	100	100	100	100	100	100	100	100	100	180
Run 4	100	100	100	100	100	100	100	100	100	100	100	100	210
Run 5	100	100	100	100	100	100	50	50	50	50	50	50	300
Run 6	100	100	100	100	100	100	50	50	50	50	50	50	420
Run 7*	100	100	100	50	50	50	50	50	50	50	50	50	600

During Run 7, the tunnel lid was opened when the first BCM tray had passed all the twelve magnetrons. The power levels were then further increased to 75 % from some of the magnetrons with a 50 % power level but when the process was resumed, all the magnetrons did not function properly, wherefore some of the power levels were changed again while the process continued. Therefore, no exact power values during the rest of the process during this run can be presented. This will be further discussed in *Section 4.4.7*.

The mass of BCM mixture that was heated in one of the ordinary trays during Run 6 was preweighed to calculate the approximate power absorption during MW heating in this pilot plant. Both prior and after Run 7, the BCM mass in the ordinary BCM tray 4 was weighed to calculate the water losses due to evaporation during the MW heating.

All the results from the runs with the presented power levels and heating times will be further discussed in *Section 4.4*.

3.5. Time and Energy Requirements during the Current Heating Method

To obtain knowledge of the current heating situation, both the time and energy aspects are of interest. For the replacement of the conventional heating method to be successful to some extent, it is important to ensure a decreased time requirement if MW heating is introduced. It is also of interest to be aware of the annual energy requirement at Almondy AB, considering heating of BCM. For these calculations, time-temperature curves from the butter cream production today have been used. Measurements in the graph have made it possible to determine the total time requirement for heating of the BCM to 70 °C and T_{max} °C, respectively, and also the time required to heat the BCM in 10 °C intervals. The total energy requirement during BCM heating has then been determined from T_{min} °C to T_{max} °C.

Four separate butter cream batches produced during year 2011, on the 28th of February, from the three HP tanks have been taken into consideration. For all batches of cake cream that are produced, the temperature is constantly logged versus the time, resulting in specific time-temperature curves for each batch. These time-temperature curves have been used for the calculations. The time-temperature curve from HP tank 552 on 28th of February, 2011, during the heating of BCM between approximately 9.30 a.m. and 11.30 a.m. is visualized in *Figure 10*. The right vertical axis represents the mass in kg, while the left vertical axis shows the temperature in °C. On the horizontal axis, the time in 30 minute intervals is shown. It is the lower curve in the figure that shows the temperature development in the HP tank.

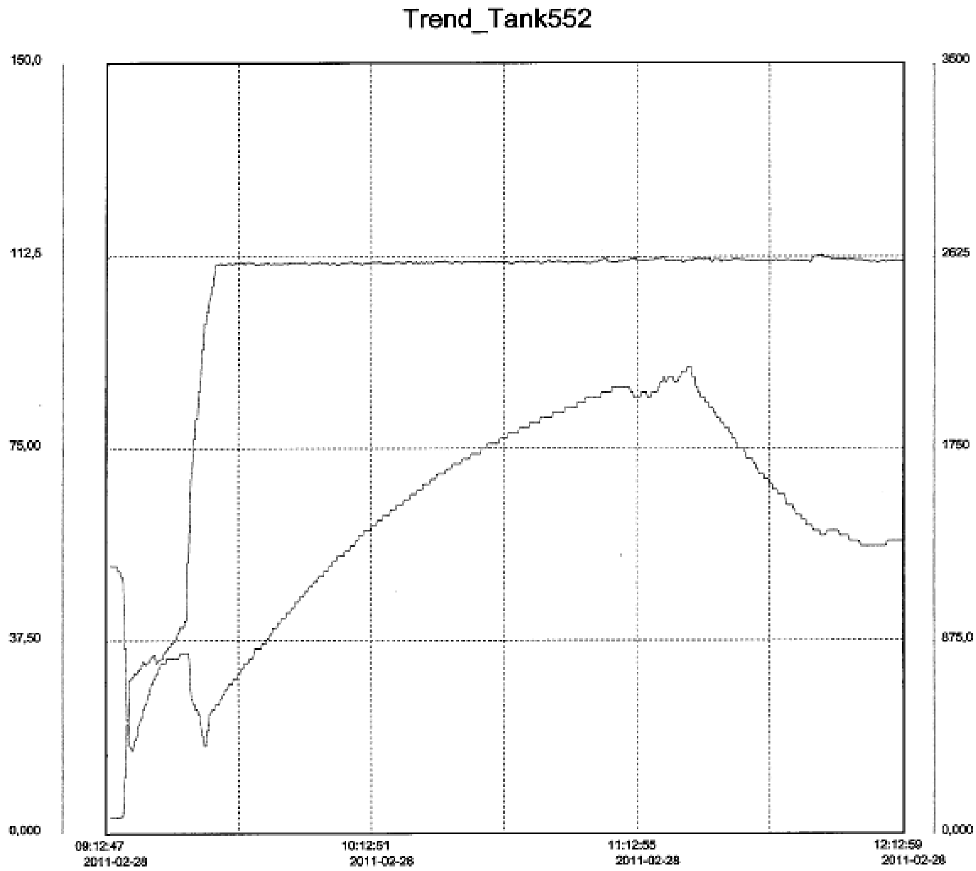

Figure 10: The graph visualizes one of the time-temperature curves that is obtained during heating of BCM in the HP tank. This curve and three others, corresponding to three other BCM heatings, are used for the time and energy calculations.

When the energy requirement during heating of BCM from T_{min} °C up to T_{max} °C has been calculated for heating of one BCM batch, it is possible to calculate the energy requirement per kilogram of BCM and then the annual energy requirement for BCM heating, by utilization of the total consumption of butter cream during one year, based on the amount of sold cakes containing butter cream. All these results are presented and discussed in *Section 4.5*.

3.6. Energy Efficiency during Current Butter Cream Mixture Heating

It is of interest to determine how much energy that is generated from the hot water flowing through the outer shell surrounding the HP tank during heating of BCM in the HP tank. If this energy value then is compared with the energy requirement for heating of BCM, the energy efficiency of the currently used heating system can be calculated. To measure how much energy the hot water generates, an ultrasound flow measuring device named FLUXUS F601 has been used. The water flow through the outer shell on the HP tank has been measured and the flow measuring device was attached on the outside of the tube with hot water exiting from the HP tank. Also, the inlet and outlet temperature of the water was measured by attaching temperature indicators on the outside of the tubes transporting the hot water into and out from the outer shell on the HP tank. The measurements were performed by FR Food AB and the measurements took place during eight BCM heatings in HP tank 553 during three days in March 2011.

The results from these measurements are visualized and discussed in *Section 4.6*.

4. Results and Discussion

In this chapter, the results from the laboratory and pilot plant experiments will be presented and discussed.

4.1. Changes in Dielectric Properties during Microwave Heating

As mentioned in *Section 2.4*, food components such as proteins, carbohydrates and fat may have a significant influence on the heating only if the moisture content is low. Since the water content of BCM is almost 40 %, it cannot be considered as a low moisture food. Therefore, an assumption is that the dielectric properties of water and the influence of salt have the highest significance on the dielectric properties for BCM. However, the other food components such as proteins, carbohydrates and fat might have a contributing effect to the change in dielectric properties of the water in the BCM.

For a successful development of a large scale MW system for heating of BCM, a recommendation after studying the literature and the importance of the dielectric properties mentioned in *Section 2.4*, is to perform measurements on the dielectric properties of BCM if MW heating seems suitable for the heating of BCM. Since BCM is assumed to be a high moisture food and food components such as proteins, carbohydrates and fat then only affect the dielectric properties of the water, it does not seem to be of relevance to know the dielectric properties for the sugar or egg yolk separately but instead the overall dielectric properties of the BCM seem to have larger significance.

Also, it must be remembered that even if the dielectric properties affect how well the food is heated at different temperatures, the BCM composition will not be changed. It is instead important to be aware of how the dielectric properties of a food product, in this case BCM, change during heating to be able to design a MW heating system as optimal as possible.

4.2. The Changes in Butter Cream Mixture Viscosity during Heating

BCM was heated in a planetary mixer by conduction heating and then the viscosity of the BCM was measured in a Bostwick device at different temperatures. The results from the viscosity measurements after eight BCM heatings in the planetary mixer are visualized in *Figure 11*.

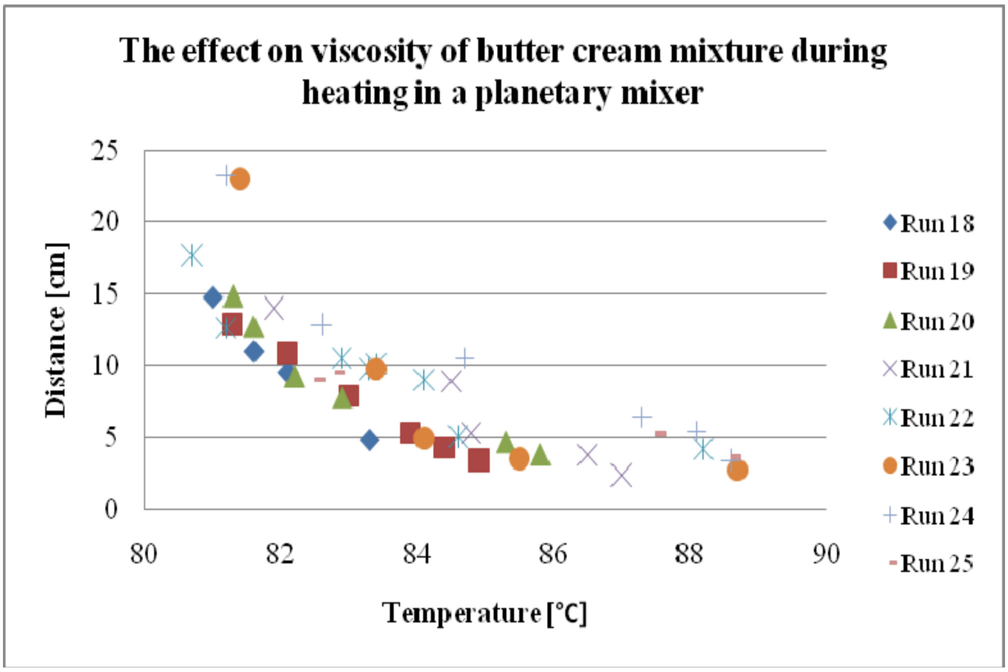

Figure 11: This graph illustrates how the viscosity of BCM is changed during heating in a planetary mixer. A high value on the *y* axis, corresponding to a long distance in the Bostwick device, indicates a low viscosity, whereas a low value at the *y* axis, corresponding to a short distance in the Bostwick device, indicates a higher viscosity. The measurements during eight runs are presented in this graph.

As can be seen in *Figure 11*, the largest increase in viscosity is between 81 °C and 85 °C. Another observation, which is not visualized in the graph, is that the viscosity did increase slightly but not significantly at temperatures between approximately 74 °C and 80 °C. However, it was not possible to measure any distance in the Bostwick device during the time period of 30 seconds but it was observed that the time required for the BCM to flow the whole distance in the Bostwick device was longer at temperatures approaching 80 °C compared to at 74 °C, indicating a higher viscosity.

The reason for the increasing viscosity with an increasing temperature is most likely protein denaturation, mentioned in *Section 2.5*. Further, information mentioned in the literature is that the fat content in milk has no influence on the heat stability of milk. Therefore, the same can be assumed for cream. Moreover, the milk viscosity increases at the highest temperatures due to denaturation of whey proteins and this can be correlated to the viscosity of cream, since the only difference between cream and milk is the fat content. On the other hand, the cream used in the BCM does only contain 2.6 % proteins and probably do not have that large influence on the total viscosity of the BCM at the high temperatures. The egg yolk contains 9 % proteins and most likely they therefore have a larger and the most significant influence on the viscosity increase of BCM during heating. Also, according to the literature, a large part of the egg yolk proteins has denatured at approximately 84 °C and a gel is formed, thus the major viscosity increase has occurred at these temperatures. This is consistent with the results obtained during the experiments, see *Figure 11*.

Another effect, as mentioned in *Section 2.5*, is that the addition of milk powders, such as buttermilk powder, increases the WHC and thus the viscosity. The buttermilk powder already contains a large amount of denatured proteins, which form a gel and has the ability to bind water, even before the BCM is heated.

The results showing that the viscosity slightly starts to increase between 74-80 °C are also consistent with the literature data referred to earlier for both whey and egg yolk proteins, as both whey and egg yolk proteins have started to denature at these temperatures.

There were significant variations between data points from the different runs, see *Figure 11*. Since all the runs are based on the same recipe, the large variations are most likely due to the experimental set up, that made it difficult to measure the temperature and viscosity. The temperature was measured at intervals when the whole stirring process was interrupted in order to emerge a manual thermometer in the planetary mixer, and therefore no continuous measurement of the temperature could be made. Due to a nonuniform temperature distribution in the planetary mixer despite the presence of an agitator and the manual surface scraper which was used at regular intervals, there were large fluctuations in the temperature measurements. Variations in the heat transfer from the planetary mixer to the BCM may also have contributed to the large temperature variations.

Removal of the lid on the planetary mixer prior to each temperature measurement and sample collection resulted in an interruption of the continuous stirring and might also have resulted in water evaporation, decreasing the water content, affecting the properties and characteristics of the BCM. When samples were taken from the planetary mixer for the viscosity measurements, it was difficult to take samples large enough for the Bostwick device, and as a result, the Bostwick device might not have been completely filled during all measurements.

Differences in final temperature of the BCM between different runs, are as discussed above, most likely due to the nonuniform temperature distribution in the planetary mixer. The measured final temperatures of the BCM are lower than the final temperature in the large scale HP tank. To ensure an appropriate texture of the BCM during heating in the HP tank, T_{max} °C, approximately 90 °C is chosen as the final temperature, and this often results in an overcooked BCM, as in these experimental small scale heatings. It is possible that approximately T_{max} °C was reached in these small scale experiments as well, but the temperature measurements were insufficient and the heat distribution was uneven. However, since the BCM is homogenized afterwards in large scale, overcooking is not a problem. Avoiding overcooking of the BCM and thereby avoid homogenization and still achieve a satisfying texture of the final butter cream would of course be beneficial, considering both time and energy requirements.

Althoug variations were obtained in the viscosity measurements, these experiments have given a good estimation and an indication of how the viscosity of BCM changes with an increasing temperature. Utilization of a viscometer is suggested if more exact values of the viscosity is desirable.

4.3. Microwave Heating of Butter Cream Mixture in a Pilot Plant at SIK

During the pilot plant experiment at SIK, the power settings and flow rate were adjusted several times in an attempt to accomplish a satisfying texture of the BCM. Below, the results and a discussion of these different steps of the process are presented. Further, some general observations during the experimental session are presented and discussed. Also, the analysis of the BCM and calculations after this MW heating experiment are presented, followed by some concluding comments and suggestions for possible future improvements.

4.3.1. Initial Settings during the Experiment

As mentioned in *Section 3.3.2*, the first settings during the MW heating experiment in the pilot plant at SIK were adjusted to achieve a final temperature of approximately 85 °C. The settings used to reach this aim resulted in a BCM with very varying texture. Some parts of the BCM had a coagulated texture, while some parts were almost as fluid as before the MW heating. These results are consistent with the information given in *Section 2.5* where it is stated that an increase in viscosity generates a more uneven temperature distribution. Further, the coagulated parts were often partly scorched when exiting the equipment. These coagulated parts had a shape which makes it likely to conclude that these pieces had been transported through the MW unit close to the inner surfaces of the tube.

These observations of the BCM behaviour indicate a too high temperature close to the inner surface of the tube and occurrence of fouling and they further point toward an insufficient heating in the center of the tube, where the fluid part of the BCM most likely has flown. A picture of a coagulated, scorched BCM element, most likely transported close to the inner surfaces of the tube, exiting the MW heating system at these settings can be seen in *Figure 12*.

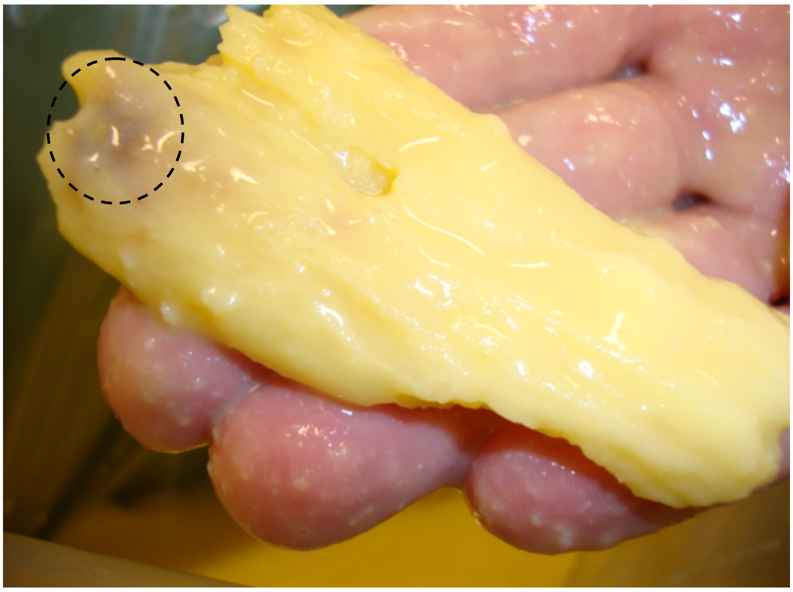

Figure 12: The picture shows the typical appearance of a coagulated BCM element, transported close to the inner surfaces of the tube, exiting from the MW heating system. The dashed circle enclosures a scorched part of the coagulated BCM element, resulting from too high temperatures and possibly fouling.

An explanation may be that an increase in the viscosity of some of the BCM will result in a lower flow rate through the MW unit of these parts. As a result, the fluid parts of the BCM flow even faster and are exposed to the microwaves for an even shorter time, resulting in less heating of these parts. This effect of a decreased flow rate is also described by Sabliov *et al*. (2008). All these events together increase the occurrence of uneven heating of the BCM.

4.3.2. A First Adjustment during the Experiment

During the first adjustment, the power from the magnetrons controlling the center heating cavity was increased, the power from the magnetrons controlling the surface heating was decreased and the cooling step was removed. In the literature, these adjustments are explained with that an increased power level will heat the product even further and vice versa if the power level is decreased (Sabliov *et al*., 2008).

These adjustments resulted in a BCM texture after the MW heating which was more uniform than previously but still with some parts much more coagulated than the others. Less scorching, which was an effect that was possible to visualize, occurred at these settings but now the major problem was that the texture of the major part of the exiting BCM was too liquid. Unfortunately, the flow was now also pulsating and not continuous. In *Figure 13*, the result of the MW heating with the above mentioned adjustments is presented.

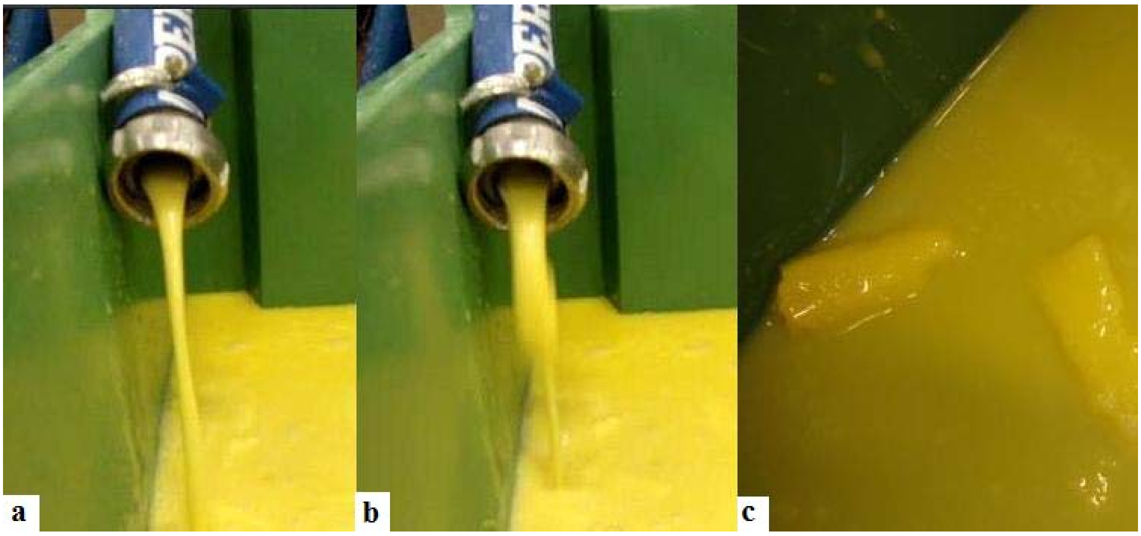

Figure 13: These figures show the typical appearance of the pulsating flow after MW heating of the BCM with an increased center heating and a decreased surface heating. In *a*, the constant flow of uncoagulated, MW heated, BCM is shown, whereas in *b*, the exit of a coagulated BCM element after the MW unit is visualized. The *c* picture shows the combined result of the MW heating of BCM. It can clearly be seen in picture *c* how some parts of the BCM have coagulated, while some are still very fluid, which is an indication of uneven heating. These pictures were taken when no cooling section was used after the MW unit.

These results indicate that the final temperature after the MW heating was too low for all the necessary protein denaturation in the BCM to take place. Also, the reason for the pulsating flow, which occurred only when the cooling section had been removed, can be assumed to be due to the fact that the back pressure became too low to counteract the pressure drop that occurs when the BCM flows through the tube, resulting in an uneven and pulsating flow. The cooling section that was used was located at a slightly higher level than the MW unit, resulting in a back pressure when using it. When deconnecting it from the system, the heated BCM was collected in a tank on the floor, located at a lower level than the MW unit. This, therefore resulted in an insufficient back pressure.

4.3.3. Further Adjustments and Measurements during the Experiment

During next part of the experimental session, the cooling section was reintroduced to avoid the pulsating flow. Also, the pump frequency, or indirectly the flow rate, was decreased to expose the BCM to microwaves for a slightly longer time period and by this approach achieve a higher overall temperature of the BCM and at the same time avoid fouling of the equipment and scorching of the final product.

This decrease in flow rate to achieve a higher final temperature, while keeping the input power constant, resulted in a temperature increase of the BCM and a more acceptable, but still not completely satisfying texture. With these settings though, the scorching problem was present again and the coagulation and scorching of the BCM instead occurred at the center of the tube, indicating a too high center heating with these settings.

Even though the fact that scorching occurred with these settings and that a completely acceptable and uniform texture of the BCM had not been achieved, a sample was collected during the final period of the heating, when the temperatures had remained stable for a while. At the first sample collection, the temperature indicator named *T1* in *Figure 8* showed approximately 86 °C, while the temperature indicator named *T2*, also shown in *Figure 8* showed approximately 94 °C. This sample contained coagulated and scorched clumps and all together it had the appearance of scrambled eggs but with a harder texture. When the first sample was collected, the power output from the four magnetrons was noted. These values and observations will be discussed below, in *Section 4.3.4*.

A second sample was collected a time period later, when the flow rate had been increased again to obtain a slightly lower temperature with the same power delivery from the magnetrons to the MW cavities. Now *T1* showed approximately 84 °C, while *T2* showed approximately 91 °C. This sample had the same appearance as the first sample but it had a slightly more fluid texture, which might have been a result of the slightly lower final temperature.

4.3.4. Calculations after the Experiment

The heating time, t, during the MW heating settings described in *Section 4.3.3*, was determined to be approximately 17 seconds. The equations that have been used and the performed calculations are more thoroughly presented in *Appendix H*. This heating time will be further considered below. The heating time is dependent on the flow rate and with lower flow rates, the required energy amount is less, but at the same time it must be remembered that a low flow rate decreases the production efficiency. Factors such as flow rate, energy efficiency and required productivity should therefore be taken into consideration when designing a continuous MW heating process. This discussion is confirmed by Sabliov *et al.* (2008).

Considering the power output from the magnetrons used during the experiment, *Table 3* presents rough estimates of the forward and reflected power values from the four magnetrons in the system when the first sample was collected and *T1* was equal to 86 °C and *T2* measured 94 °C.

Table 3: The table shows rough estimates of the forward and reflected power values from the four magnetrons in the MW pilot plant used during the experiment at SIK. Magnetron *1* and *2* are controlling the first, center heating cavity, while magnetron *3* and *4* control the second, surface heating cavity. The values are noted when T1 was equal to 86 °C and T2 measured 94 °C.

	Power [W]			
Magnetron	**Forward**		**Reflected**	
1	1150	2410	127	142
2	1260		15	
3	1140	2370	382	534
4	1230		152	
Total	**4780**		**676**	

As can be seen in *Table 3*, the total forward power is equal to 4780 W. Further, magnetron *2* and *4* have slightly larger forward power values than magnetron *1* and *3* but when adding the values from magnetron *1* and *2* and magnetron *3* and *4*, respectively, the total forward power to both the MW cavities are almost identical. Noticeable is that the reflected power is higher from the surface heating cavity, resulting in a higher power delivered to the center heating cavity. This is consistent with the visual results obtained during the first sample collection, when these power values were observed. These power values are however not the true forward and reflected power values. The forward and reflected power values observed on the control panel are only guideline power values that are used to be able to adjust the power output from the magnetrons in the MW heating system to achieve a more satisfying process. Since no measurements are performed on the actual power values, considering the forward, reflected and also lost power values, these values are in this study only used to be able to make further calculations. However, it may be assumed that the sizes of the numbers relative to each other are correct. None of the reflected values are used in the calculations, since all these values are approximations, and therefore it seemed most appropriate to use the forward power values and determine the power losses, such as reflected and lost power, as one number.

The amount of absorbed power, P_{abs}, during the MW heating at SIK is estimated to be approximately 1948 W. The calculations generating this result is presented in *Appendix J*, where the values used in the calculation as well as the absorbed power calculation also are visualized. The energy efficiency of this MW heating system is also calculated in *Appendix J* and it is determined to be approximately 40.8 %. This means that almost 60 % of the power from the magnetrons are reflected, lost in the cavity or lost to the surroundings due to convection.

In these absorption calculations considering the MW heating, it is estimated that the final temperature of the BCM was 86 °C, as shown on *T1*, since this temperature is most similar to the temperature that was manually measured in the BCM that exited from the MW heating unit. It must also be remembered that the BCM was not heated to T_{max} °C during this experiment.

During the 17 seconds when the BCM was exposed to microwaves, the temperature was increased from 45 °C to approximately 86 °C and approximately 0.29 kg of BCM was flowing through the MW unit. This gives a heating rate of approximately 2.42 °C/s and the heating rate in the HP tanks in the same temperature interval has been calculated to be approximately 0.01 °C/s. The heating rate in the HP tank is calculated by using the time-temperature curves, and a more thorough calculation is performed in *Appendix H* where the heating rate in the MW heating system at SIK is calculated as well.

However, the heating rates discussed here are calculated in a large scale HP tank and a small scale MW equipment with very different designs, which may be one of the reasons for the large difference between the heating rates and which makes them unsuitable for comparison. The heated mass of BCM in both equipments is also very different. But, the higher heating rate in the MW equipment indicates the much more rapid heating by using MW heating instead of a conventional heating method within the same temperature interval.

4.3.5. General Observations and Concluding Comments

In this section, some general observations and concluding comments from the MW heating in the pilot plant at SIK will be presented.

During the initial experiment with MW heating of BCM in the pilot plant at SIK, many unforeseen events took place and an explanation may be that this was the first time this product was heated with microwaves. Furthermore, the pilot plant used for this experiment is not specifically designed for MW heating of BCM.

The experimental setup that was designed prior to the experiment was not possible to use. Due to the difficulties with controlling the system, no separate runs for each final temperature of interest could be performed and therefore the specific parameter values for each run could not be determined. As an example, the heating time in the MW unit in the pilot plant was short, compared to the total time requirement for passage through the whole pilot plant but it was not possible to measure during the experiment. It was therefore calculated later, by utilization of parameter values such as the cavity length and flow rate during the settings of interest. This heating time in the MW pilot plant at SIK has been presented and discussed above.

The development of fouling of the equipment at each run was not possible to visualize either since the equipment was not cleaned until after the whole experimental session. Unfortunately, no photographs were taken during the cleaning to visualize the amount of fouling of the equipment, but during the cleaning, many charred parts fell out and these were probably formed continuously during the experiment, affecting the process. Also, the uneven heating of the BCM was most likely exacerbated by the occurrence of fouling deposits within the equipment.

Already at the beginning of the experimental session at SIK, the two temperature indicators in the system did not show consistent results with the temperature of the BCM measured with a manual thermometer at the exit from the MW unit, where the manually measured temperature was more similar to the temperature measured at *T1* than at *T2*. The temperature indicator marked with *T1* in *Figure 8* is as mentioned earlier, located close to the surface of the tube directly after the exit from the MW unit. *T2* on the other hand, measures the temperature in the center of the tube a short distance further down the system. The largest temperature difference between these two probes was more than 30 °C, which is a very large temperature difference between these two locations when the distance between the probes is only approximately 20 centimeters, even though the BCM was transported through an uninsulated tube between the two probes. Most likely this temperature difference between the probes depends on their different positions in the radial direction within the tube, showing the significantly uneven temperature distribution in this direction.

This is consistent with information from the literature, where it is mentioned that an increase in the viscosity results in a decreased heat transfer, leading to a more nonuniform heat distribution (Ryynänen, 2002). Further results from earlier studies have shown that if the viscosity is high and no mixing is applied during the MW heating, this can lead to non-uniform temperature distribution (Salvi *et al*., 2009). An uneven temperature distribution may also rise the question if MW heating generates safe and palatable food products or not, considering inactivation of microorganisms and product quality. This must of course be further investigated and is one of the major drawbacks during pasteurization processes with MW heating (Vadivambal & Jayas, 2010).

When the process had been stabilized as much as possible to achieve a satisfying butter cream texture, and the samples were collected, the temperature difference between *T1* and *T2* had decreased to approximately 7-8 °C but it was still a too high difference to be satisfying and correspond to a completely stable process. A visualization of these temperature fluctuations can be seen in *Appendix Figure 3* in *Appendix F*.

The reason for the temperature fluctuations at higher temperatures might also have been due to the fact that the temperature indicators became covered with protein deposits, resulting in that the temperature of the deposits is logged during a time period. When the protein deposits after a while detach from the indicators, the temperature is different in the flowing BCM, resulting in a measurement of another temperature in the following time period. These fluctuations will of course be repeated each time a new deposit attaches and detaches to one of the temperature indicators.

To conclude, MW heating of BCM was difficult to achieve in the described equipment. The temperature distribution was not even enough to obtain a satisfying texture. Further, a too high amount of fouling occurred for the process to be successful. These factors have to be dealt with if MW heating in this kind of equipment should be used as a heating method during butter cream production in large scale. However, this experiment at SIK was only a pre-trial, where the results may be used as a starting point in additional experiments to achieve more satisfying results. Therefore, no consistent conclusions could be drawn considering heating time, energy efficiency, temperature distribution and power absorption during this experimental set up at SIK.

4.3.6. Possible Future Improvements

To improve the heating process in this kind of MW equipment setup, suggestions are to insert one or several static mixers within or between the MW cavities, to accomplish a more turbulent flow, and in that manner try to avoid fouling. Also, by inserting a static mixer, this will hopefully result in a more even temperature distribution, as mentioned in *Section 2.7*. However, inserting the static mixer within the cavities might possibly lead to further occurrence of fouling. The reason for this is that another surface exposed to the BCM will be present in the cavity, and close to this surface, just as close to the tube inner surfaces, the fluid velocity will be almost zero. No exchange of BCM close to this surface on the static mixer then increases the risk of overheating of the fluid close to the static mixer, generating fouling (Isaksson, *Personal Communication*, 2011). As mentioned in *Section 2.3.3*, the heating profile in a TM_{020} cavity is equal to the laminar flow profile if the zero point coincides with the pipe wall. This then leads to the fact that a much higher field strength is present in the center of the tube, where the static mixer should be placed. Thus, the surfaces on the static mixer will result in an even higher risk of overheating than the pipe walls. Therefore, the best alternative considering static mixers seems to be to place them before, after, or between the cavities. However, then it must be ensured that the turbulent flow that is created by the static mixers is maintained when the fluid enters the subsequent cavity.

Another alternative or complement to achieve the same improvements is to use tephlone helical coils instead of the straight tephlone tubes that are used today. Helical coils, as mentioned in *Section 2.2*, do not generate turbulent flow. Instead, flow through helical coils results in flow in both the radial and axial direction, hopefully contributing to a more even temperature distribution and a lower occurrence of fouling and scorching.

4.4. Microwave Heating in a Pilot Plant at Binar Elektronik AB

In this section, the results from the MW heating at Binar Elektronik AB will be presented and discussed. Also, some future recommendations and suggestions to further process optimizations will be given.

4.4.1. Observations after Run 1

After the heating with the magnetrons set on a 100 % power level and a heating time of 120 s, the BCM temperature had increased from approximately 38 °C to approximately 56 °C in the center of BCM tray 2. This temperature increase was of course not sufficient to coagulate the BCM to a satisfying texture. Only the short sides closest to the water trays had started to coagulate and the temperature was a few degrees higher here compared to in the center of the tray. Otherwise, no special effects were observed. Conclusively, the heating time was too low at this power level.

4.4.2. Observations after Run 2

During Run 2, the heating time was increased with 30 seconds since no negative observations with the prior power levels were seen during Run 1, except the uneven and insufficient heating. Also in this run, the magnetrons were set on a 100 % power level, the heating time was 150 seconds and the initial temperature was approximately 36 °C. After the heating, the BCM in tray 2 had reached approximately 65 °C. The temperature difference between the center and the edges of the tray was a few degrees larger than during the previous run. After the heating, the short sides closest to the water trays as well as a part of one of the long sides on each of these trays had started to coagulate and also some of the BCM close to the sides in BCM tray 2 had started to coagulate. These observations are visualized in *Figure 14*.

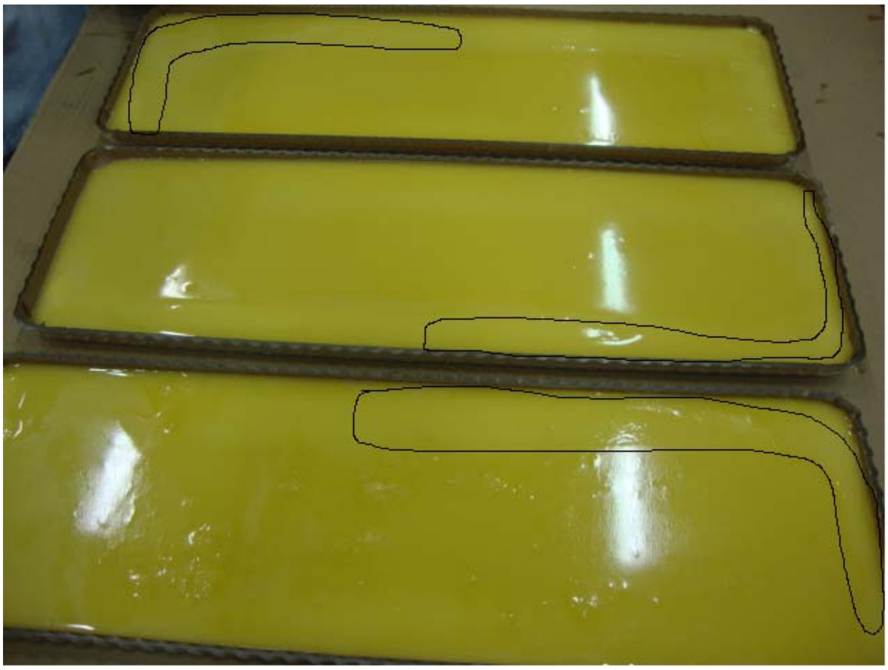

Figure 14: The effects of the MW heating during *Run 2* are visualized in this picture. The enclosed areas are the most interesting ones. The uppermost tray is BCM tray 1, the middle tray is BCM tray 2 while BCM tray 3 is located at the bottom of the picture.

The coagulations of the short sides on the BCM trays closest to the water trays were similar to the observations during Run 1 and the additional coagulations of the long sides might be due to the fact that the position of the trays on the conveyor belt might not have been completely in the center during the two first runs, which might have affected the heating pattern. This placing was more carefully, but still manually, done in the subsequent runs.

4.4.3. Observations after Run 3

Since the heating was insufficient and uneven also during Run 2, probably still due to a too short heating time at the applied power levels, the power level remained at 100 % on all magnetrons and the heating time was increased to 180 s. The heating with these settings resulted in a temperature increase from approximately 31 °C to approximately

63 °C in the center, where the BCM still had not coagulated significantly. The temperature close to the long sides of BCM tray 2 was approximately 70 °C, where the coagulation was initiated but not remarkably high. In the corners of this tray, the temperature was between 70 °C and 83 °C and at these locations, the BCM had almost coagulated completely.

Another interesting effect during Run 3 was observed in BCM tray 1 entering the MW unit. Here, stripes in the same direction as the tray is transported were visible. Every second stripe had experienced some coagulation while the others were still fluid. This is visualized in *Figure 15*.

Figure 15: An illustration of the stripe pattern obtained in BCM tray 1 after the MW heating during *Run 3*. The more pale yellow color in the outer and center stripes indicates a more coagulated BCM, while the darker yellow color in the other stripes indicates a more fluid BCM.

This heating pattern gives an approximate indication of the field distribution. Also, in this tray, the corners seen in the bottom of the picture also showed tendencies of scorching. These observations is consistent with the literature, where it is described how fields tend to reinforce each other at the corners of rectangularly shaped objects, resulting in overheating (Fu, 2004).

4.4.4. Observations after Run 4

In Run 4, the power level was still at 100 % on all magnetrons and the heating time was further increased to 210 s. The BCM temperature in tray 2 increased from 32 °C to 70-83 °C in the center, where some coagulation had taken place. Still, no significant amount of scorching was visible on BCM tray 2 even though the temperature close to the long sides was close to 100°C. The heating of the tray was thus still very uneven, since some parts of the BCM had coagulated while other parts were still fluid. A further observation was that it seemed as if air bubbles had formed inside the coagulated BCM, probably due to boiling, see *Figure 16*.

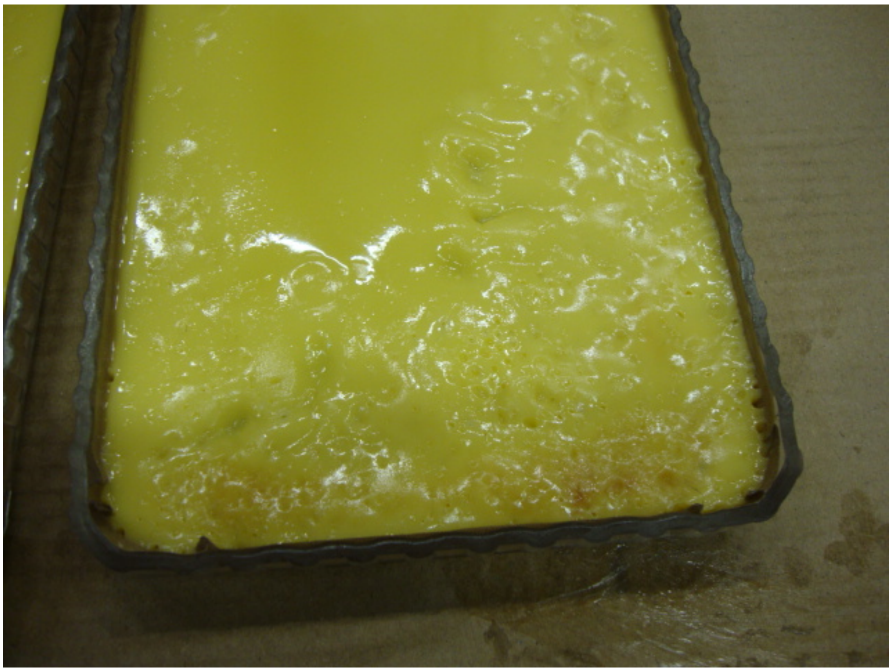

Figure 16: In this picture, the increased porosity due to trapped air bubbles during the BCM heating is visualized.

As mentioned in *Section 2.7*, air is a bad heat conductor, resulting in less heat transfer within the BCM, which decreases the possibility to even out the temperature distribution. Overheating of the BCM is therefore not a desirable outcome during MW heating in this equipment.

4.4.5. Observations after Run 5

Prior to Run 5, it was desirable to obtain a more even temperature distribution and at the same time avoid scorching. To accomplish this, the power level from the six last magnetrons, see *Table 2*, was decreased to 50 %. Also, the heating time was increased to 300 s. By applying a high power level initially, the attempt is to almost increase the temperature to its final temperature and then when the power level is lower, the temperature will increase the last few degrees and the heat transfer within the BCM will have time to take place and give an even heating pattern in the tray. During Run 5, the BCM temperature in BCM tray 2 increased from 26 °C to approximately 66 °C, which is a lower temperature increase than expected. This can be seen in the left BCM tray in *Figure 17*, where the major part of the tray is uncoagulated.

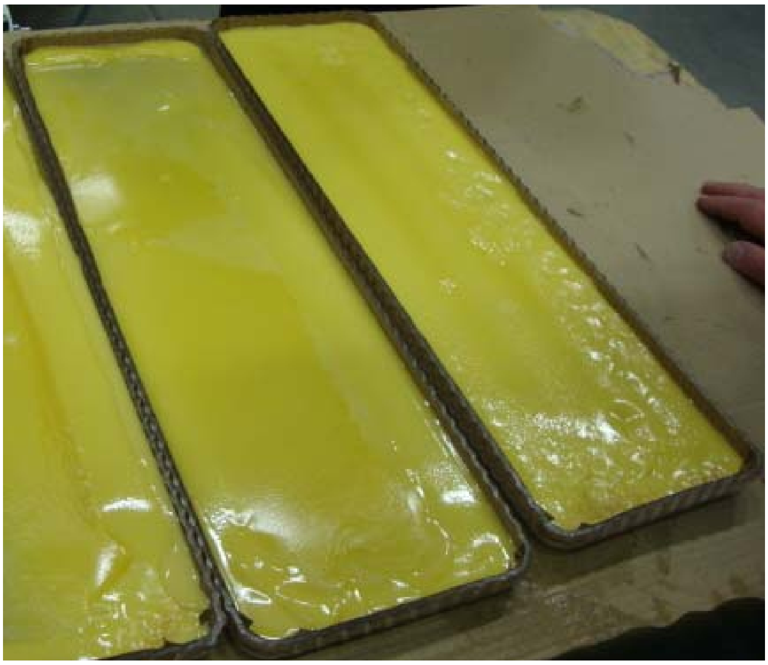

Figure 17: This picture shows BCM tray 1 (right) and BCM tray 2 (left) after the MW heating in *Run 5*. The thinner dark yellow stripes in BCM tray 1 show the uncoagulated parts.

Most likely, something happened with the process in between the heating of the first and second BCM tray, even though they are transported through the MW unit directly after each other.

In BCM tray 1 on the other hand, the BCM had a rather satisfying texture except for two thin stripes in the center of the tray, see the right tray in *Figure 17*. Most likely, the result would have been something similar in BCM tray 2 with these settings, except for the scorching at the short side closest to the water trays, present in BCM tray 1. The coagulation now starts to reach the correct temperature but the small stripes with uncoagulated BCM is still a problem, which must be dealt with.

After the heating in Run 5, a small sample of the coagulated BCM in BCM tray 1 was collected. The sample was placed in a refrigerator for a couple of hours to reach a temperature of 10-12 °C, similar to the temperature of butter cream when it is applied to the cakes during today's cake production. When analyzing the cooled butter cream by feeling at the texture as well as tasting it, it did not taste differently compared to the butter cream that is produced today. It also had a similar smoothness to today's butter cream and it is worth mentioning that this butter cream had not been homogenized, which would further improve its texture and appearance. Of course, if homogenization is not required after the MW heating, as mentioned earlier, this would lead to a decreased energy consumption and time requirement during the overall butter cream production. This must however be further studied and more carefully investigated. It could however be mentioned that the homogenization is performed to overcome the texture generated by overcooking in the HP tanks and since this overcooking had not occurred with the BCM that was cooled after these experiments, this means that MW heating would offer a gentler heat treatment, which also is correlated to the shorter processing times with MW heating. This time aspect of MW heating is discussed in other parts of this report.

4.4.6. Observations after Run 6

To give the BCM more time to even out the temperature distribution within the tray, the power was kept at the same level as in Run 5, with a 100 % power level on the first six magnetrons and a 50 % power level on the six last ones. Further, the heating time was increased to 420 s. During this run, two larger trays containing a thinner layer of BCM, were also exposed to microwaves, see the middle part in *Figure 9*.

The two trays containing a thinner layer of BCM, BCM tray I and BCM tray II, had a final center temperature that was approximately 91°C and the initial BCM temperature was approximately 29 °C. Close to the long and short sides, scorching and overheating had occurred and the BCM had most likely started to boil during the heating. Also, the tray material became soft and changed the shape of the tray. This lead to the fact that more BCM was located in the center of the tray, and where the layer of BCM was too thin, the scorching and overheating occurred, see *Figure 18*. This kind of trays did therefore not seem appropriate to use for MW heating of BCM to these temperatures.

Figure 18: The picture shows the MW heating of BCM in the BCM tray I during *Run 6*. These trays were not suitable to use during MW heating to the final temperature of interest, which resulted in an uneven layer of BCM in the tray that became scorched and overheated.

In BCM tray 2, the temperature increased from 29 °C to approximately 85 °C and most of the BCM had coagulated to what appeared as a satisfying texture except for a small stripe in the center of the tray. Unfortunately, it was now noticed that a layer of water was present under the layer of coagulated BCM in this tray, probably due to the fact that the BCM mixture behaves like a mixture of water and oil, where the water separates from the rest of the mixture when no mixing is applied. This is not a desirable situation, wherefore this problem must be solved during the process optimization. Now, it was also considered that this equipment is not an enclosed system, wherefore water evaporation might occur during the heating. To be able to determine eventual water losses during the MW heating, BCM tray 2 was weighed before and after the heating in Run 7.

In BCM tray 1 and 3, the corners were scorched again and a small stripe in the center appeared uncoagulated. The corner scorching will most likely disappear when the process becomes continuous since no corners then will be present, but considering the small uncoagulated center stripe, this is a problem and it is desirable to move the energy focus from the corners to the center of the tray.

The mass of BCM heated in one of the ordinary BCM trays was determined prior to heating to be able to calculate the approximate power absorption during MW heating of BCM to a rather satisfying texture, when a maximum amount of BCM was heated. The total mass heated was therefore calculated to be 6.6 kg. In total, 7.32 trays with BCM could be heated during this heating time, see *Appendix J*. Assuming that the temperature increase was similar in all trays, 29-85 °C, this gives an approximate power absorption of 2424 W. Dividing this value with the total forward power delivery to the cavity, which is estimated to be approximately 9000 W, a power absorption of 26.9 % is obtained. This is a lower absorption than in the MW equipment at SIK and this value indicates that more than 70 % of the delivered power is lost in the cavity or to the surroundings or reflected back to the magnetrons. It is possible that this power absorption could have been larger, since a large amount of energy probably was required for the evaporation of water during the heating, which is discussed below. However, this equipment is specifically designed for another kind of food product which also might affect the result. Moreover, since the design of the two pilot plants used during the experiments are very different, it is difficult to compare these with each other. Instead it could just be concluded that the energy efficiencies of both these two MW equipments are higher than the energy efficiency during the current heating method. As also mentioned in *Section 4.3.4*, the power values from the magnetrons are not exact here either but an estimation is that approximately 1000 W is delivered to the cavity from the magnetrons at 100 % power level. The calculations during these reasonings are presented in *Appendix J.*

It is also of interest to determine the heating rate during the MW heating at Binar Elektronik AB and during heating in the HP tanks in the same temperature interval. These heating rates are calculated in *Appendix H.* The heating rate in this MW equipment is calculated to approximately 0.13 °C/s, compared to the heating rate of approximately 0.012 °C/s in the HP tank. As in the earlier heating rate comparison between MW heating and conventional heating, the heating rate in the MW equipment is many times higher than the heating rate in the HP tank in the considered temperature interval. Also, the heated masses are very different, as well as the size and design of the equipments and therefore any comparison should ba handled with caution.

Instead of the load volume and density, the maximum mass that could be heated in the tunnel during this time period if a maximum number of trays would be used, is calculated for this heating rate calculation. Further, the specific heat capacity is estimated with the same equations as earlier.

Furthermore, the heating rate comparison is done between a large scale HP tank and a small scale MW equipment, which again could lead to inconsistent results. It is still possible to get an indication of the fact that heating with microwaves is a much more rapid heating method than the currently used heating method.

A heating rate of 2.42 °C/s in the pilot plant at SIK is relatively high compared to the heating rate of 0.13 °C/s in the pilot plant at Binar Elektronik AB. Datta *et al*. (2001) describe that a high heating rate generates a more nonuniform heating than if the heating rates are lower. This was thus also seen during the two different pilot plant experimental session, where the heating was more nonuniform during the heating at SIK with the higher heating rate. However, a comparison of the two pilot plants are difficult to make due to their many differences in design and performance and also to that different masses of BCM was heated during the different experiments.

4.4.7. Observations after Run 7

Since the heating had been improved in the previous run, compared with the heating during the first runs, but still with an excessive heating at a few locations, and an insufficient heating at some points, the major issue seemed to be an insufficient time for temperature levelling, which indicates that a longer heating time with a decreased power level on a few more magnetrons would be a reasonable improvement. Therefore, prior to Run 7, the heating time was increased to 600 s and only the three first magnetrons were kept on a 100 % power level and the rest on a 50 % power level. During this run, six BCM trays instead of three, were heated continously, wherfore BCM tray 4 was the one that was mainly considered.

When the BCM tray 1 had passed all twelve magnetrons, the tunnel lid was removed to visualize the heating effects on that BCM tray. Except for some scorching at the first short side and one of the long sides, which is similar to the results in the previous runs, the coagulation did not seem complete, see *Figure 19*.

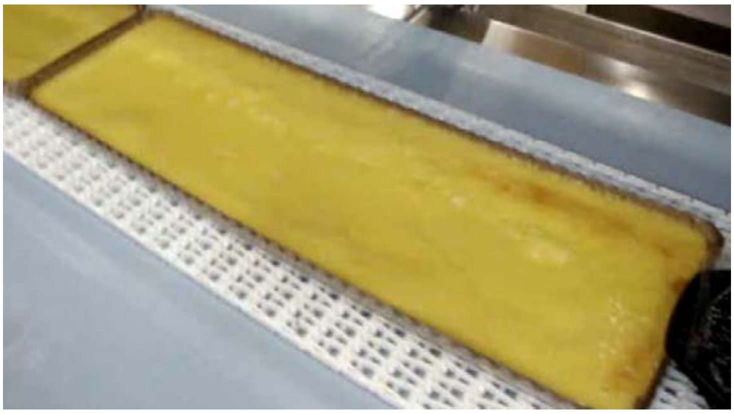

Figure 19: This figure shows the BCM tray 1 after the MW heating in *Run 7*. This rather nonuniform heating pattern resulted in an adjustment of the applied power levels in an attempt to achieve a more uniform heating in the subsequent BCM trays.

Therefore it was decided to increase the power level on a few of the 50 % power level magnetrons to 75 % instead in an attempt to achieve a more satisfying coagulation at BCM tray 4, see the lower part of *Figure 9*. Unfortunately, an error occurred in the process when it was resumed again and it is therefore not possible to ensure that all the six BCM trays were exposed to the same power levels. However, considering the obtained results anyway, the temperature in BCM tray 4 increased from approximately 28 °C to 91 °C.

As mentioned above, a filled BCM tray was weighed before and after the MW heating in Run 7 to determine the water losses due to water evaporation. The weight loss was determined to be 26 g or 1.7 % of the total mass. These calculations are presented in *Appendix K*. A large scale butter cream production with these water losses would result in great economical losses as well as a negative effect on the butter cream characteristics, as mentioned in *Section 4.2* during the viscosity measurements. Further, a decreased water content in the butter cream would result in that the applied amount of butter cream on each cake had to be increased to maintain the same mass of butter cream on each cake. This would then lead to increased production costs.

4.4.8. Concluding Comments and Future Developments

When heating BCM with microwaves in the pilot plant at Binar Elektronik AB, the most important conclusions seem to be that a lower power delivery from some of the magnetrons in combination with a longer heating time gives the best result. These settings allow for a rather rapid initial temperature increase of the BCM and during the last time period, the BCM temperature can increase more slowly to its final temperature and then it is possible for temperature levelling to take place in the tray. This would hopefully result in an even coagulation of the BCM and a minimal occurrence of scorching.

Further, additional adjustments of the field distribution is desirable, to maintain a more even heating pattern without uncoagulated stripes. For example, additional dislocation of the magnetrons can be a suggestion to accomplish this field levelling.

However, even though this process was successful to some extent, it is far from fully adapted to be used in large scale. First of all, this system was not enclosed, which was clearly seen when the BCM mass decreased with 1.7 % after heating due to water evaporation. Also, a layer of water was formed in the bottom of each tray under the coagulated BCM, as a result of insufficient mixing. An enclosed system would most likely solve the water evaporation problem and a continuous flow with mixing characteristics would probably not generate the water layer. Further, an open system is not recommended to use in a microbiological aspect since it would then not be possible to completely control the pasteurization requirements.

During these experiments, the attempt was to heat the BCM to its final temperature. The heating appeared much more even, compared to the results obtained at SIK. However, it is desirable to replace the batch production of butter cream in the HP tanks with a continuous tubular process, which this equipment could not offer. By heating several BCM trays located as close to each other as possible in the MW unit to resemble a continuous process only gave an indication of how the heating would appear in a continuous process. For future investigations, this is one major issue to take care of. As mentioned after the experiments at SIK, the temperature distribution and the occurrence of scorching and fouling must then be carefully investigated in the more specifically designed pilot plant too.

4.5. Time and Energy Requirements during the Current Heating Method

Calculations have been performed to calculate the time requirement for heating BCM in the HP tank to 70 °C and T_{max} °C, respectively, and the energy requirement for heating of BCM to T_{max} °C. Determination of the time requirement for heating up to 70 °C can be of interest, since heating up to this temperature probably only result in a low occurrence of protein denaturation and therefore the texture is only slightly changed. Thus, MW heating in this temperature interval can therefore be easier since the texture will be more uniform, resulting in a more even heating and occurrence of less fouling. As mentioned, the specific heat capacities have been calculated by using *Appendix Equation 1-5* in *Appendix C* and all the calculated values are also presented in *Appendix C*.

In *Figure 20*, a comparison of the time requirement when heating the BCM in the HP tanks from T_{min} °C to 70 °C and T_{max} °C, respectively, is presented. The heating times are approximately 47 and 97 minutes for heating up to 70 °C and T_{max} °C, respectively.

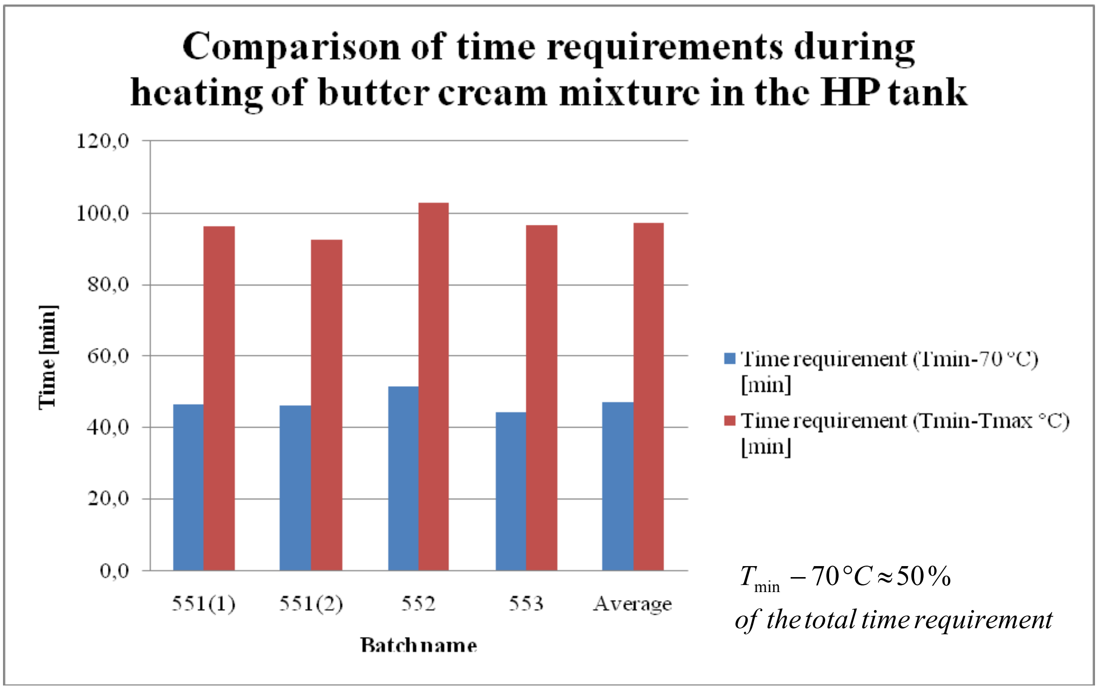

Figure 20: A comparison between the time requirements for heating the BCM in the HP tank from T_{min} °C, to 70 °C and T_{max} °C, respectively.

As the figure shows, a large part of the time required to heat the BCM in the HP tanks to its final temperature, T_{max} °C, is ascribed to the first 70 °C, as represented by the left staple of each batch. Calculating the ratio between the heating times for the two temperature intervals, it can be seen that approximately 50 % of the heating time for complete BCM heating in the HP tank is attributed to the temperature increase from T_{min} °C to 70 °C. Heating the BCM with microwaves up to 70 °C or T_{max} °C instead of using the current heating method will therefore most likely decrease the heating time of this amount of BCM and increase the production efficiency considering this aspect, independent in which temperature interval MW heating is used.

Considering the time required to increase the temperature in 10 °C intervals, it increases as the temperature increases. This is an expected result, since the temperature difference between the surrounding hot water and the BCM is at its maximum in the beginning of the heating and thus will the heat transfer be more rapid in the beginning. When the temperature of the BCM starts to approach the temperature of the hot water, the heat transfer is more inefficient, resulting in a longer time requirement to increase the temperature 10 °C. This behavior during the heating is visualized in *Appendix Figure 4* in *Appendix G*.

The increased time requirement for increasing the temperature in 10 °C intervals is consistent with a decreasing heating rate with an increasing temperature. The decreasing heating rate with an increase in the butter cream temperature can be observed in *Appendix Figure 5* in *Appendix G*. Also, the calculations on which this graph is based on, are presented in *Appendix G*. A decreasing heating rate with an increasing temperature is due to the reason mentioned above; the larger the temperature difference is between the surrounding hot water and the BCM, the higher is the heating rate. The differences in heating rates between batches within the same temperature interval is most likely due to different masses in each batch.

The energy requirement, 0.1955 MJ/kg of BCM, is an average value of four batches during heating of BCM up to T_{max} °C in a HP tank. Calculations on the different batches to obtain this value is presented in *Appendix G*. Considering an average annual energy requirement for BCM heating up to T_{max} °C, it can be calculated to be approximately 1275 GJ. This energy amount corresponds to approximately 27 ppm of the total energy produced from fossil fuels and biofuels in Sweden during 2006 (Lindholm, 2010). These data and calculations are visualized in *Appendix I*. For this calculation, the average energy requirement for heating the BCM in the HP tank up to T_{max} °C is used.

Several errors may have contributed to inconsistencies during the time and energy requirement calculations. Firstly, reading errors on the time-temperature curves prior to the calculations generate small inaccuracies in the results and the fact that no BCM heating is similar to another also gives rise to variations between the batches. The equations for specific heat capacities used in these calculations are also based on the chemical composition of the product and is not specifically correlated to the BCM or measured on this food product.

Further thoughts considering the energy requirements for BCM heating is that the calculated energy requirement per kilogram presented above will be the same, independent on which heating method that is used. Worth to consider in the future is however to try to obtain a heating system as energy efficient as possible, this means that the losses are as small as possible.

The MW heating calculations presented earlier in this report and the time and energy calculations in this section, can to some extent most likely be applied to the other cake cream mixtures that are heated in the HP tanks today. Therefore, the time and energy benefits might be even larger. However, this discussion and these calculations are outside the boundaries of this project.

4.6. Energy Efficiency during Current Butter Cream Mixture Heating

When the hot water flow as well as the inlet and outlet temperature of the hot water passing through the outer shell of the HP tanks were measured, the results presented in *Figure 21* were obtained.

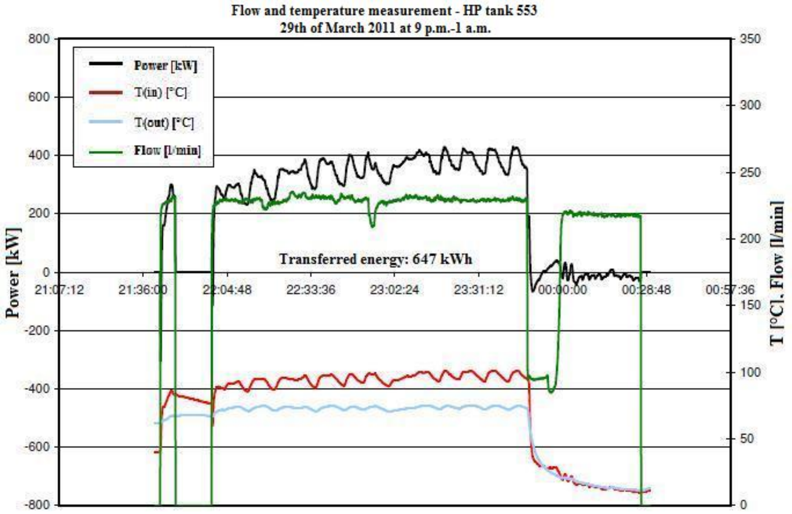

Figure 21: This graph presents one of the flow and temperature measurements of the water in the HP tanks. This measurement is performed on HP tank 553 at the 29th of March 2011 between 9 p.m. and 1 a.m. The graph is generated by FR Food AB.

As can be seen in *Figure 21*, the inlet temperature of the hot water during the stable part of the process was slightly above 100 °C, as mentioned in *Section 1.1*, whereas the outlet temperature of the water is approximately 75 °C. The water flow through the HP tank is approximately 225 l/min. Further, the amount of transferred energy from the hot water has been calculated to be 647 kWh, which is presented in *Figure 21*.

The calculated energy efficiency can be described as the ratio between the energy requirement for heating the BCM and the transferred energy from the hot water that is used to heat the BCM. The calculated average energy requirement for heating the BCM to its final temperature is approximately 145 kWh and this average value together with the calculations and results for each batch is presented in *Appendix I*. However, it is not only the BCM that requires energy. Also the heat transfer surfaces as well as the water in the outer shell requires energy for heating during the process. The ratio between 145 kWh and 647 kWh generates a percentage of approximately 22.4 %. This means that only 22.4 % of the energy generated from the hot water is used for heating of the BCM while the rest is lost to the surroundings or used to heat the HP tank itself. When it is desirable to have a process as energy efficient as possible, 22.4 % is not an uplifting value. The low energy efficiency shows again the importance of replacing the current heating method with a more energy efficient heating method. The energy efficiency calculation above is presented in *Appendix L*.

An important observation during these measurements, not visualized in a graph, is that the temperature of the inlet water was different at the beginning of some of the eight measurements. One theory for this behavior is that the hot water boiler is used above its maximum capacity and cannot function properly the entire time, which results in varying inlet temperature. As mentioned in *Section 1.1*, this is one of the reasons for performing this project since the current equipment cannot withstand a higher utilization which would be required if the production capacity should be increased.

4.7. Energy Efficiency Comparison

Comparing the energy efficiency of the MW heating system at SIK and the HP tank, the MW heating system generates a higher energy efficiency, 40.8 % versus 22.4 %. The energy efficiency of the MW equipment at Binar Elektronik AB, 26.9 %, is also higher than the energy efficiency of the large scale HP tank, 22.4 %.

However, in a broader perspective, several aspects must be taken into consideration. First, a small scale MW heating system is compared with a large scale HP tank, making them inappropriate to compare. Furthermore, the total energy consumption of the current production system and the two MW equipments, respectively, must be considered. As mentioned above, it is not only the BCM that requires energy for heating. Also the heat transfer surfaces as well as the water in the outer shell on the HP tank require energy for heating during the current process. These energy demands should be further considered during energy calculations for the current heating method. Moreover, associated equipment such as pumps, preheaters, coolers as well as homogenizers in both equipment types require energy during utilization. Another factor to consider is that losses also take place during the conversion of electrical energy to microwaves. This is not included in these MW energy efficiency calculations but must be considered in future energy calculations. As can be seen, several factors must therefore be accounted for to achieve a complete energy efficiency during butter cream production.

Even if the energy efficiency is higher for the MW heating system at SIK compared to the MW heating system at Binar Elektronik AB, the process at Binar Elektronik seems to be more appropriate to use, considering the obtained results. Also, even though MW heating generates a higher energy efficiency, compared to the currently used heating method, the economical investment aspect must be considered too. Investing in a large scale MW heating system would probably be expensive and therefore it is important to ensure that it is profitable, in a longterm perspective, to invest in a MW heating system, compared to investing in an additional hot pan boiler as well as additional HP tanks.

As mentioned in *Section 1.1*, the hot water boiler is fuelled by utilization of natural-gas and if replacing the HP tank with MW heating, it is important to investigate if the utilization of another energy source is more or equal environmental and economic profitable.

5. Conclusions and Future Aspects

To get an overview of the most significant results during this project, some conclusions will be presented below. Also, some possible topics for future studies will be suggested.

5.1. Conclusions

The overall aim with this project was to investigate the possible utilization of MW heating in the production of butter cream at Almondy AB by replacing the current heating method during butter cream production with MW heating. At the moment, this aim is not completely fulfilled, since further investigations are required. However, the objectives of this project have made it possible to approach the aim. First of all, laboratory experiments showed that the viscosity of BCM increased with an increasing temperature due to protein denaturation. These experiments also indicated that a noticeable viscosity increase could not be seen at temperatures below 70 °C.

During the initial MW heating experiment in the pilot plant at SIK, it was clear that heating the BCM satisfactory with microwaves in this equipment up to approximately T_{max} °C was difficult to accomplish. The temperature distribution was very uneven, which resulted in a BCM with varying texture depending on where in the tube it had flown. Further, fouling occurred, resulting in protein deposits inside the MW heating unit as well as scorched BCM parts exiting from the MW unit. This contributed to a decreased equipment performance as well as a diminished quality and insufficient heating of the BCM.

In the MW pilot plant at SIK, the heating time during the best settings was calculated to approximately 17 seconds, when the BCM was heated from 45 °C to 86 °C. Comparing the heating rate in the MW pilot plant, 2.42 °C/s, with the heating rate in an HP tank during the current heating method in the same temperature interval, 0.01 °C/s, it can clearly be determined that heating with microwaves is a much more rapid heating method than the conventional heating method that is used today. However, it must be remembered that a pilot plant MW equipment is compared to a large scale HP tank.

When using the pilot plant MW equipment at Binar Elektronik AB, more promising results during heating of BCM were obtained. A combination of a maximum power level, *100 %*, from six of the magnetrons, with a lower power level, *50 %*, from the other six magnetrons in the system, in combination with a heating time of 420 s gave the best results. These settings resulted in a relatively uniform heat distribution and the texture was rather satisfying. However, great water losses of 1.7 % in this open system was a negative result, which must be dealt with. Further improvements of, and successful experiments in this pilot plant are necessary, before development of, and trials in, a large scale production should be initiated.

The heating rate in the pilot plant at Binar Elektronik AB was determined to be 0.13 °C/s, compared to 0.012 °C/s in the HP tank during heating from 29 °C to 85 °C. Again, the heating rate is higher in the MW equipment than in the HP tank, showing the promising effects of replacing heating of BCM in the HP tanks with MW heating.

A higher heating rate in the pilot plant at SIK is however consistent with a more uneven heating compared to the heating pattern and heating rate in the pilot plant at Binar Elektronik AB.

The time requirement during BCM heating in the HP tanks showed that approximately 97 minutes are required for heating up to T_{max} °C and that approximately 50 % of the total heating time, 47 minutes, is required for heating the BCM up to 70 °C. Below 70 °C, almost no protein denaturation has taken place, which is a process that can obstruct the MW heating at higher temperatures, and therefore the time requirement in this temperature interval can be of interest too, if heating of BCM at higher temperatures does not seem suitable. Using MW heating will most likely increase the production efficiency of BCM, independent in which of these temperature intervals MW heating is applied.

During the project, it was determined that 0.1955 MJ/kg is required for heating BCM up to T_{max} °C, approximately 90 °C. Considering the annual butter cream production at Almondy AB, approximately 1275 GJ is required for complete heating of the BCM. This is the energy consumption if no energy was lost to the surroundings or used to heat the equipment itself. Introducing MW heating will hopefully decrease these energy losses and thus decrease the total energy consumption.

It is determined that only 22.4 % of the energy generated from the hot water was required to heat the BCM. This low energy efficiency underscores the importance of finding a more energy efficient heating method. This value can be compared to the calculated energy efficiency value of the pilot plant MW equipments, which were estimated to be 40.8 % and 26.9 % at SIK and Binar Elektronik AB, respectively. These are thus higher values and demonstrate that MW heating is a more energy efficient method. However, these numbers are based on approximations and must be further investigated to be verified. These values are also determined on pilot plant equipments where smaller BCM masses are heated and it would be of greater interest to determine the energy efficiency of a MW equipment with the desired capacity.

To conclude, the results obtained during this thesis project show the potential of replacing the conventional heating method during butter cream production with MW heating and by this replacement increase the cake production. However, further investigations, process development and upscaling are necessary for a successful progress.

5.2. Future Aspects

For future studies, since more work is required before the current heating method during production of butter cream can be replaced, several issues can be considered:

The design of the pilot plant must be further developed. A suggestion is to let the BCM be continuously pumped through through a MW unit in an enclosed tephlone coated tube or channel, but otherwise with settings similar to those in the equipment used at Binar Elektronik AB. How this channel would look like and which dimensions that are required for a large scale production is also important to determine and investigate. It is of importance to ensure that the production area allows for an equipment with the required size and capacity.

Considering the power level, a high power level is suggested to be combined with a lower power level, with a satisfying heating time. This will then, as mentioned before, allow for a rapid temperature increase, followed by temperature levelling. The exact power values that are required must be further investigated. More, in a continuous process, it is important to ensure that no fouling or product scorching occurs. To improve the temperature distribution even further, perhaps static mixers can be used prior to the MW cavity for this purpose.

When the dimensions for a large scale equipment are determined, it is also of interest to calculate the heating rate and energy efficiency of this equipment, to make a more thorough comparison with the current heating method.

If MW heating is thought to be appropriate for heating of BCM, it is important to consider a measurement of the dielectric properties of BCM, since it is, according to the literature mentioned in *Section 2.4*, very valuable to have knowledge of the dielectric properties when developing a large scale MW heating system.

Furthermore, it must be investigated how the microbiological status of the BCM is affected during MW heating. If the microbal inactivation in BCM is not maintained or improved during MW heating, compared to during the current heating method, MW heating would not be suitable to use for heating of BCM. Utilization of a holding tube could be used to ensure that pasteurization requirements are met.

Last but not least, the economical aspect must be more thoroughly studied by making an economical budget for the investment, maintenance and energy costs of a large scale MW heating system.

If the investigation of the mentioned topics shows promising results, there are strong indications for the possibility to replace the current heating method during butter cream production with MW heating.

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Appendices

In these appendices, the major part of the calculations during this project will be presented. Further, values that have been visualized in a graph in the report are also presented.

Appendix A: Butter Cream Mixture Viscosity Measurements

The graph visualized in *Figure 11* in the report shows how the viscosity of BCM changes with temperature. In *Appendix Table 1*, the values used to plot this graph are presented. In this table, the temperature, $T_{measured}$, is given in °C and the flown distance in the Bostwick device, $x_{average}$, is given in centimeters. The $x_{average}$ values are average values of the shortest and longest flown distance in the Bostwick device during each viscosity measurement.

Appendix Table 1: In this table, the results obtained during *Run 18-Run 25* during the viscosity measurements of BCM heated in a planetary mixer, are presented.

Run	**$T_{measured}$ [°C]**	**$x_{average}$ [cm]**
18(1)	81	14.75
18(2)	81.6	11
18(3)	82.1	9.5
18(4)	83.3	4.75
19(1)	81.3	12.875
19(2)	82.1	10.875
19(3)	83	7.875
19(4)	83.9	5.25
19(5)	84.4	4.25
19(6)	84.9	3.375
20(1)	81.3	14.875
20(2)	81.6	12.75
20(3)	82.2	9.25
20(4)	82.9	7.75
20(5)	85.3	4.625
20(6)	85.8	3.75
21(1)	81.9	14
21(2)	84.5	8.875
21(3)	84.8	5.25
21(4)	86.5	3.75
21(5)	87	2.375
22(1)	80.7	17.625
22(2)	81.2	12.625
22(3)	82.9	10.5
22(4)	83.3	9.75
22(5)	83.4	10.125
22(6)	84.1	9
22(7)	84.6	5
22(8)	88.2	4.125
23(1)	81.4	23
23(2)	83.4	9.75
23(3)	84.1	4.875
23(4)	85.5	3.5
23(5)	88.7	2.75
24(1)	81.2	23.25
24(2)	82.6	12.875
24(3)	84.7	10.5
24(4)	87.3	6.375
24(5)	88.1	5.375
24(6)	88.6	3.375
25(1)	82.5	9
25(2)	82.8	9.5
25(3)	87.5	5.25
25(4)	88.6	3.625

Appendix B: Butter Cream Mixture Composition

BCM consists of four major chemical components: water, fat, proteins and carbohydrates. The major ingredients in BCM are cream, egg yolk, sugar, vegetable fat, buttermilk powder, water and salt. Mass fractions, x, in g/g for each ingredient have been calculated by dividing each ingredient mass with the total mass, which is considered as 100 g of BCM.

In the recipe, salt is mentioned as one of the major components since it is taken into consideration when discussing the dielectric properties but in the subsequent calculations of the specific heat capacity of BCM, only water, fat, proteins and carbohydrates are considered.

Further, to calculate the fractions of different chemical components based on the chemical composition in the different ingredients, the information from the raw material suppliers have been used and this information for the egg yolk and sugar mixture is presented in *Appendix Table 2*.

Appendix Table 2: This table visualizes the chemical composition of the mixture of egg yolk and sugar. The mass fractions, y, of the different components are given in g/g BCM. The egg yolk and sugar are already mixed prior to utilization in the BCM.

Egg yolk + sugar	
Component	**Mass fraction, y [g/g]**
Water	0.29
Fat	0.16
Protein	0.09
Carbohydrates	0.45

Appendix Table 3 presents the chemical composition of cream.

Appendix Table 3: In this table, the chemical composition of cream is presented. The mass fractions, y, of the different components are given in g/g BCM.

Cream	
Component	**Mass fraction, y [g/g]**
Water	0.69
Fat	0.25
Protein	0.026
Carbohydrates	0.038

For the cream, the total fraction of components is more than 1, which is not possible. This is most likely due to roundings of the different values, resulting in a total fraction above 1. The different fractions are used separately in the calculations, so this small deviation from 1 will not have a significant effect.

In *Appendix Table 4*, the chemical composition of vegetable fat is presented.

Appendix Table 4: This table visualizes the chemical composition of vegetable fat. The mass fractions, *y*, of the different components are given in g/g BCM.

Vegetable fat	
Component	**Mass fraction, *y* [g/g]**
Water	0
Fat	1
Protein	0
Carbohydrates	0

In *Appendix Table 5*, the chemical composition of the buttermilk powder is presented.

Appendix Table 5: In this table, the chemical composition of the buttermilk powder is presented. The mass fractions, *y*, of the different components are given in g/g BCM.

Buttermilk powder	
Component	**Mass fraction, *y* [g/g]**
Water	0.0325
Fat	0.0575
Protein	0.3325
Carbohydrates	0.5

The mass fraction of each chemical component in the BCM, *z*, in g/g, originating from the different ingredients can then be calculated, since the mass fraction of each ingredient in BCM as well as the mass fraction of each chemical component in each ingredient are known. These results are presented in *Table 1* in the report and in *Appendix Table 6* below.

Appendix Table 6: This table presents the mass fractions, z, of water, fat, protein and carbohydrates in 100 g of BCM. Explanations to the abbreviations in the table: BMP = buttermilk powder, prot. = protein, carb. = carbohydrates.

Chemical component	**Mass [g/100 g]**	**Mass fraction, *z* [g/g]**
Water	38.43	**0.3843**
Fat	29.31	**0.2931**
Protein	7.67	**0.0767**
Carbohydrates	23.39	**0.2339**

The values showed in bold in *Appendix Table 6* is used during calculations of the specific heat capacity of BCM, see *Appendix C*.

Appendix C: Specific Heat Capacity of Butter Cream Mixture

The total amount of water, fat, protein and carbohydrates in the butter cream are used to calculate the specific heat capacity at different temperatures. To calculate the specific heat capacity, *Appendix Equation 1-5* are used based on the chemical composition of a food product. (Okos & Choi, 2003) The chemical composition is, as mentioned above, presented in *Appendix Table 6*. The specific heat capacities are calculated in kJ/kg°C and the temperatures are given in °C.

$$c_{p,water}^{BCM}(T) = 4.1762 - 9.0864\times10^{-5}T + 5.4731\times10^{-6}T^{2} \tag{1}$$

$$c_{p,fat}^{BCM}(T) = 1.9842 + 1.4733\times10^{-3}T - 4.8008\times10^{-6}T^{2} \tag{2}$$

$$c_{p,protein}^{BCM}(T) = 2.0082 + 1.2089\times10^{-3}T - 1.3129\times10^{-6}T^{2} \tag{3}$$

$$c_{p,carboh}^{BCM}(T) = 1.5488 + 1.9625\times10^{-3}T - 5.9399\times10^{-6}T^{2} \tag{4}$$

$$\begin{aligned} c_{p,total}^{BCM}(T) &= z_{water}^{BCM}\times c_{p,water}^{BCM}(T) + z_{fat}^{BCM}\times c_{p,fat}^{BCM}(T) + \\ &+ z_{protein}^{BCM}\times c_{p,protein}^{BCM}(T) + z_{carboh}^{BCM}\times c_{p,carboh}^{BCM}(T) \end{aligned} \tag{5}$$

The specific heat capacity for each component in the food product is calculated and then the overall specific heat capacity for BCM is calculated by multiplying each component specific heat capacity with the corresponding mass fraction, *z*, in *Appendix Table 6* and then summarizing all these values. Calculations below are exemplified at 65.5 °C.

$$\begin{aligned} c_{p,water}^{BCM}(65.5\,°C) &= 4.1762 - 9.0864\times10^{-5}\cdot 65.5 + 5.4731\times10^{-6}\cdot 65.5^{2} = \\ &= 4.193729375\,kJ/kg°C \end{aligned} \tag{1}$$

$$\begin{aligned} c_{p,fat}^{BCM}(65.5\,°C) &= 1.9842 + 1.4733\times10^{-3}\cdot 65.5 - 4.8008\times10^{-6}\cdot 65.5^{2} = \\ &= 2.060104518\,kJ/kg°C \end{aligned} \tag{2}$$

$$\begin{aligned} c_{p,protein}^{BCM}(65.5\,°C) &= 2.0082 + 1.2089\times10^{-3}\cdot 65.5 - 1.3129\times10^{-6}\cdot 65.5^{2} = \\ &= 2.081750281\,kJ/kg°C \end{aligned} \tag{3}$$

$$\begin{aligned} c_{p,carboh}^{BCM}(65.5\,°C) &= 1.5488 + 1.9625\times10^{-3}\cdot 65.5 - 5.9399\times10^{-6}\cdot 65.5^{2} = \\ &= 1.651860094\,kJ/kg°C \end{aligned} \tag{4}$$

$$\begin{aligned} c_{p,total}^{BCM}(65.5\,°C) &= 0.3843\times4.193729375 + 0.2931\times2.060104518 + \\ &+ 0.0767\times2.081750281 + 0.2339\times1.651860094 \approx 2.761592869\,kJ/kg°C \end{aligned} \tag{5}$$

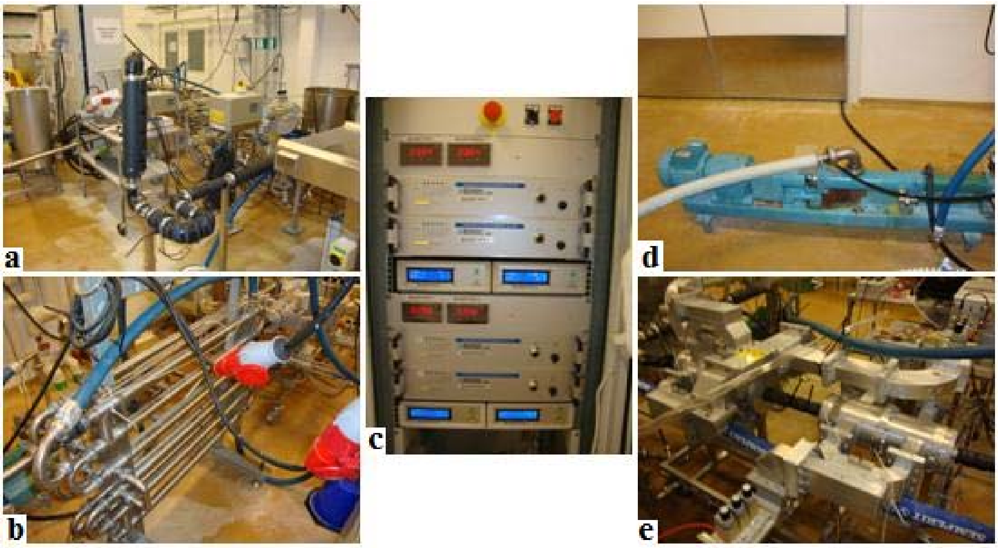
During the energy requirement calculations during heating of BCM with both the conventional method and microwaves, respectively, the specific heat capacity at different temperatures have been used. They are calculated with the same equations as shown above and all the used specific heat capacity values are shown in *Appendix Table 7*. For all energy calculations in a 10 °C interval, a median temperature within the temperature interval of interest has been calculated, for which the specific heat capacity has been determined. For the larger temperature intervals, the sum of the energy requirements of interest has been determined.

Appendix Table 7: This table shows all the specific heat capacities that have been used during the energy requirement calculations.

Temperature [°C]	**c_p^{BCM} [kJ/kg°C]**
18.2	2.719863417
22.15	2.723484143
22.85	2.724123207
25	2.726081183
25.25	2.726308378
25.4	2.726444648
26.8	2.727714774
27.15	2.72803182
32.5	2.73285388
34.9	2.735002284
35	2.735091602
37.4	2.73723048
37.5	2.737319401
45	2.743943266
55	2.752636175
57	2.754355706
65	2.761170329
75	2.769545727
84.65	2.777477469
85.6	2.778250321
85.7	2.77833159

Appendix D: Microwave Heating Equipment Used at SIK

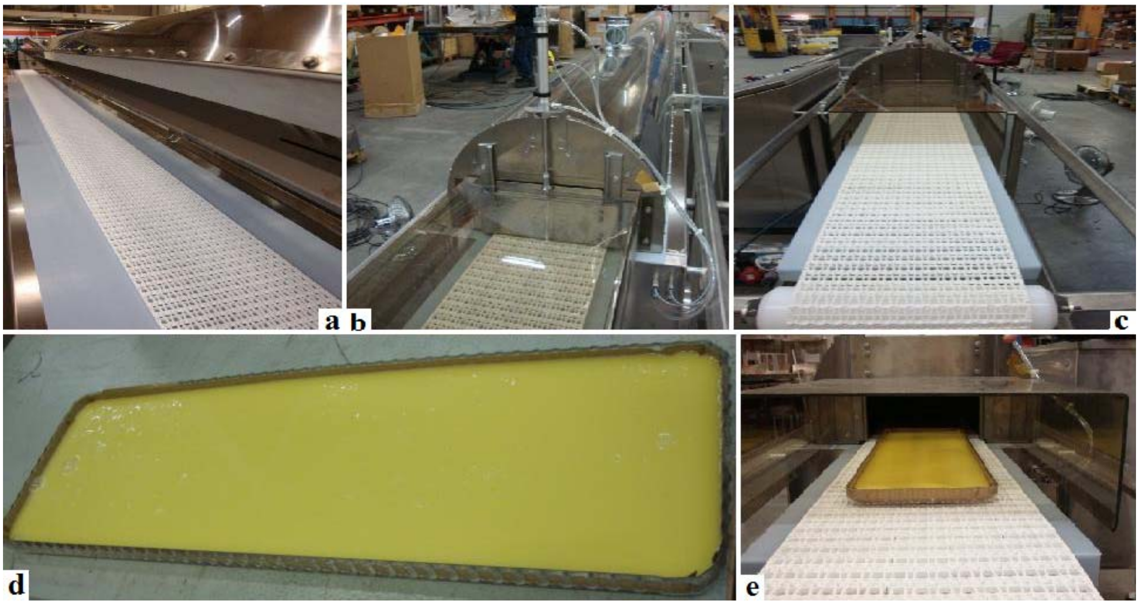
In *Appendix Figure 1*, the major parts of the pilot plant equipment used in the MW heating experiment at SIK are shown.



Appendix Figure 1: The pictures show the major parts of the pilot plant equipment used in the MW heating experiment at SIK. Picture *a* shows an overview of the whole plant, with part of a holding tube in the foreground, *b* presents the type of heat exchanger used for preheating of the BCM and cooling of the heat treated butter cream, *c* shows the display and control panel where the power level of the four magnetrons could be adjusted, *d* shows the pump that was used to pump the BCM into the heat exchanger for preheating and *e* shows part of the two MW cavities through which the BCM passed during heating.

Appendix E: Microwave Heating Equipment Used at Binar Elektronik AB

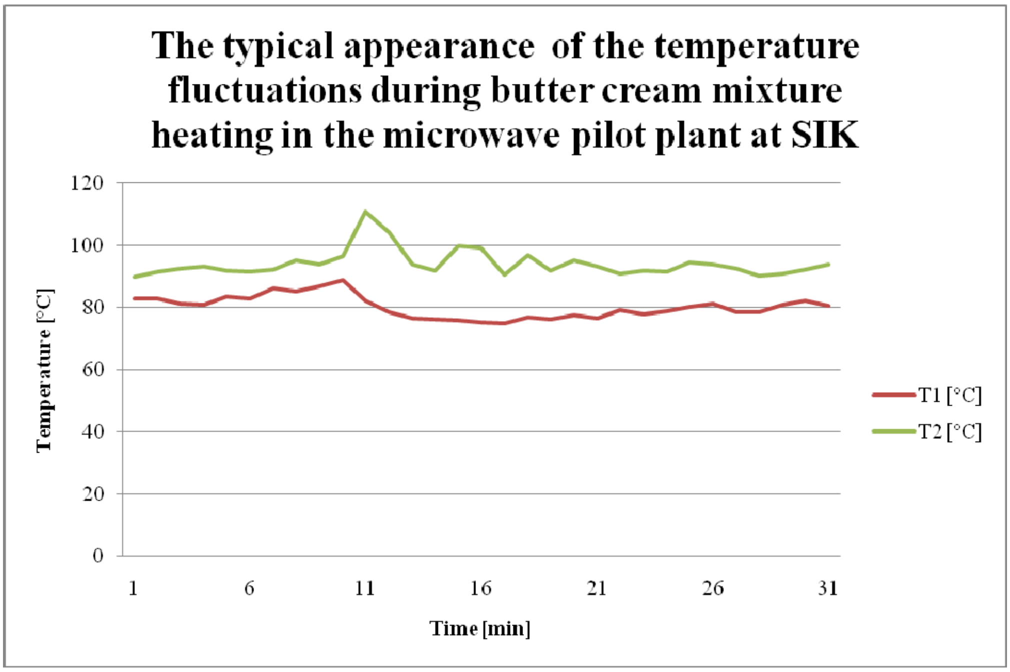
In *Appendix Figure 2*, general pictures from the pilot plant experiments at Binar Elektronik AB are shown.



Appendix Figure 2: In this collage, illustrations from the pilot plant experiments at Binar Elektronik AB are shown. The *a* picture shows the conveyor belt when the tunnel lid is open, *b* shows the exit from the tunnel, *c* shows the tunnel entrance, *d* shows a tray filled with BCM and *e* shows a MW heated BCM tray exiting from the tunnel.

Appendix F: Temperature Fluctuations during the experiment at SIK

During the microwave heating experiment at SIK, large temperature fluctuations occurred. In *Appendix Figure 3*, an example of the temperature fluctuations during the experiment in the MW pilot plant is visualized.



Appendix Figure 3: This graph clearly shows the temperature fluctuations of the BCM at higher temperatures during heating of BCM in the MW pilot plant.

Appendix G: Heating Times, Heating Rates and Energy Requirement

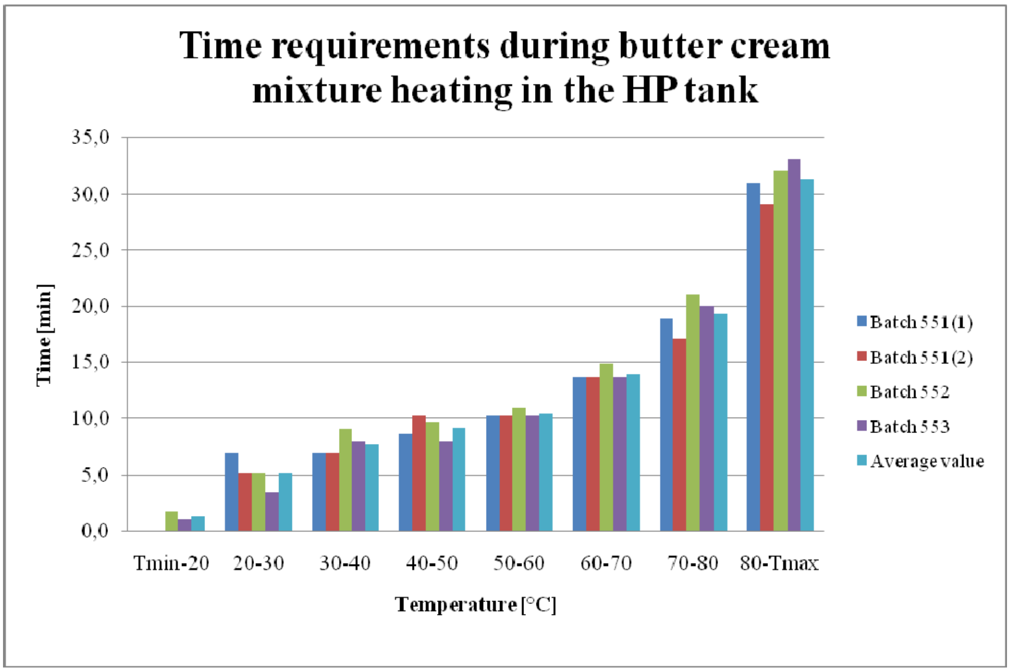
The heating times during BCM heating in an HP tank are determined by measuring with a ruler in the time-temperature curve obtained for each batch and these heating times are presented in *Appendix Table 8*. For each temperature interval, an average value of the four batches is also calculated.

Appendix Table 8: In this table, the heating times for the 10 °C intervals during heating of BCM in a HP tank is presented. These values are used to plot *Appendix Figure 4*.

Batch	**551(1)**	**551(2)**	**552**	**553**	**Avg. value**
Mass [kg]	2648.0	2772.0	2633.0	2637.0	**2672.5**
T_{min} (°C)	19.5	24.3	16.4	16.4	**19.2**
T_{max} (°C)	89.3	89.3	91.2	91.4	**90.3**
Heating time, $t_{Tmin-20\ ^\circ C}$ [min]	0.0	0.0	1.7	1.0	**1.4**
Heating time, $t_{20-30\ ^\circ C}$ [min]	6.9	5.1	5.1	3.4	**5.1**
Heating time, $t_{30-40\ ^\circ C}$ [min]	6.9	6.9	9.1	8.0	**7.7**
Heating time, $t_{40-50\ ^\circ C}$ [min]	8.6	10.3	9.7	8.0	**9.2**
Heating time, $t_{50-60\ ^\circ C}$ [min]	10.3	10.3	10.9	10.3	**10.5**
Heating time, $t_{60-70\ ^\circ C}$ [min]	13.7	13.7	14.9	13.7	**14.0**
Heating time, $t_{70-80\ ^\circ C}$ [min]	18.9	17.1	21.1	20.0	**19.3**
Heating time, $t_{80-Tmax\ ^\circ C}$ [min]	30.9	29.1	32.0	33.1	**31.3**
Heating time, $t_{Tmin-Tmax\ ^\circ C}$ [min]	96.2	92.5	102.8	96.5	**97.0**

Additionally, the heating time for heating from T_{min} °C, approximately 20 °C to T_{max} °C, approximately 90 °C, was calculated by summarizing the heating times of interest for this interval. This heating time is also presented in *Appendix Table 8*.

In *Appendix Figure 4*, the time requirement for heating in 10 °C intervals during BCM heating is visualized.



Appendix Figure 4: This graph shows the time requirements for increasing the temperature in 10 °C intervals during the BCM heating in the HP tank. Four different BCM heatings and an average value of these four batch productions at each temperature interval are presented. This graph is plotted based on values in *Appendix Table 8*. Note that for the two first batches, no calculation was possible to perform at the first temperature interval, since T_{min} °C was either approximated to 20 °C or above 20 °C.

Further, to calculate the heating rates during heating of BCM, *Appendix Equation 6* was used. As an example, the heating rate for the temperature interval 30-40 °C for Batch 551(1) is calculated below:

$$Heating\ rate_{30-40^{\circ}C}^{Batch551(1)}[^{\circ}C/\min] = \frac{\Delta T[^{\circ}C]}{t[\min]} = \frac{(40-30)[^{\circ}C]}{6.9[\min]]} = \tag{6}$$

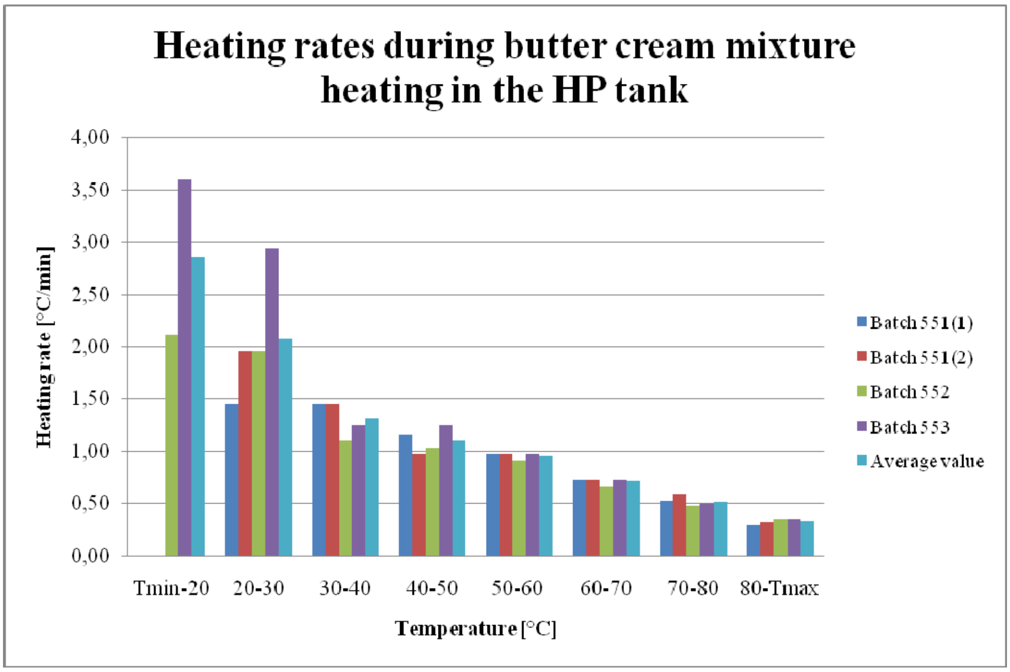
$$= 1.449 \approx 1.45\,^{\circ}C/\min$$

Similar calculations were performed for each temperature interval for the four batches and the results are presented in *Appendix Table 9*.

Appendix Table 9: This table shows the heating rates, HR, for the 10 °C intervals during heating of BCM in the HP tank. These values are used to plot *Appendix Figure 5*. The heating rates are presented in [°C/min].

Batch	**551(1)**	**551(2)**	**552**	**553**	**Average**
Total mass [kg]	2648.0	2772.0	2633.0	2637.0	2672.5
Tmin [°C]	19.5	24.3	16.4	16.4	19.2
Tmax [°C]	89.3	89.3	91.2	91.4	90.3
$HR_{Tmin\text{-}20\ °C}$ [°C/min]	0.00	0.00	2.12	3.60	2.86
$HR_{20\text{-}30\ °C}$ [°C/min]	1.45	1.96	1.96	2.94	2.08
$HR_{30\text{-}40\ °C}$ [°C/min]	1.45	1.45	1.10	1.25	1.31
$HR_{40\text{-}50\ °C}$ [°C/min]	1.16	0.97	1.03	1.25	1.10
$HR_{50\text{-}60\ °C}$ [°C/min]	0.97	0.97	0.92	0.97	0.96
$HR_{60\text{-}70\ °C}$ [°C/min]	0.73	0.73	0.67	0.73	0.72
$HR_{70\text{-}80\ °C}$ [°C/min]	0.53	0.58	0.47	0.50	0.52
$HR_{80\text{-}Tmax\ °C}$ [°C/min]	0.30	0.32	0.35	0.34	0.33
$HR_{Tmin\text{-}Tmax\ °C}$ [°C/min]	0.73	0.70	0.73	0.78	0.73

The graph visualizing the heating rates in 10 °C intervals during heating of BCM in the HP tank is presented in *Appendix Figure 5*.



Appendix Figure 5: The graph shows the heating rates in 10 °C intervals [°C/min]during heating of BCM in the HP tank. Heating rates for four different batches in the different temperature intervals are visualized in the graph together with an average value of each heating rate.

To calculate the energy requirement, *Q*, in MJ/kg during heating of BCM in 10 °C intervals, *Appendix Equation 7* is used.

Here the specific heat capacity, c_p, is given in kJ/kg°C and the temperature, T, is given in °C. To give an example of an energy requirement calculation, the energy requirement for the temperature interval 40-50 °C in Batch 551(1) will be shown.

$$Q[MJ/kg]_{40-50°C}^{Batch551(1)} = c_p[kJ/kg°C] \cdot \Delta T[°C] =$$
$$= (2{,}743943266\,\mathrm{kJ/kg\,°C} \cdot (50-40)\,°C) \cdot \frac{1}{1000\,MJ/kJ} = \quad (7)$$
$$= 0.0274\,MJ/kg$$

The results from all the calculations are presented in *Appendix Table 10*.

Appendix Table 10: In this table, the energy requirement, Q, in MJ during heating of BCM in 10 °C intervals is presented. Further, the energy requirement for heating from T_{min} °C to T_{max} °C is also presented. These energy requirements are presented in [MJ/kg].

Batch	**551(1)**	**551(2)**	**552**	**553**	**Average**
Total mass [kg]	2648.0	2772.0	2633.0	2637.0	**2672.5**
T_{min} (°C)	19.5	24.3	16.4	16.4	**19.2**
T_{max} (°C)	89.3	89.3	91.2	91.4	**90.3**
$Q_{Tmin-20\,°C}$ [MJ/kg]	0.0000	0.0000	0.0098	0.0098	**0.0049**
$Q_{20-30\,°C}$ [MJ/kg]	0.0273	0.0155	0.0273	0.0273	**0.0243**
$Q_{30-40\,°C}$ [MJ/kg]	0.0274	0.0274	0.0274	0.0274	**0.0274**
$Q_{40-50\,°C}$ [MJ/kg]	0.0274	0.0274	0.0274	0.0274	**0.0274**
$Q_{50-60\,°C}$ [MJ/kg]	0.0275	0.0275	0.0275	0.0275	**0.0275**
$Q_{60-70\,°C}$ [MJ/kg]	0.0276	0.0276	0.0276	0.0276	**0.0276**
$Q_{70-80\,°C}$ [MJ/kg]	0.0277	0.0277	0.0277	0.0277	**0.0277**
$Q_{80-Tmax\,°C}$ [MJ/kg]	0.0258	0.0258	0.0311	0.0317	**0.0286**
$Q_{Tmin-Tmax\,°C}$ [MJ/kg]	0.1907	0.1790	0.2058	0.2063	**0.1955**

Appendix H: Heating Time and Heating Rate Calculations

The heating time during the experiment at SIK, *t*, can be determined by using the following variables: mass flow rate, *B*, the volumetric flow rate, *S*, the density, *ρ*, the radius, *r*, the cavity length, *L* and the volume, *V*. The temperature of the BCM is increased from approximately 45 °C to 86 °C in the MW equipment during this experiment. The density was determined during the experimental session and the tube radius and total length of cavity were predetermined. In *Appendix Equation 8-10*, the calculations for determining the heating time in the MW plant at SIK are shown.

$$S[m^3/\min] = \frac{B[kg/\min]}{\rho[kg/m^3]} = \frac{1.031[kg/\min]}{1102[kg/m^3]} = 9.3557\cdot 10^{-4}\, m^3/\min \tag{8}$$

$$V[m^3] = \pi\cdot r^2\cdot L = \pi\cdot 0.01^2\, m^2\cdot 0.842\, m = 0.0003\, m^3 \tag{9}$$

$$\begin{aligned} t[s] &= 60[s/\min]\cdot\frac{V[m^3]}{S[m^3/\min]} = \\ &= 60[s/\min]\cdot\frac{0.0003[m^3]}{9.3557\cdot 10^{-4}[m^3/\min]} = 16.96\, s \approx 17\, s \end{aligned} \tag{10}$$

It is of great interest to know the heating rate for this MW process. To make this calculation, the temperature difference and the heating time need to be known and *Appendix Equation 11* is then used to calculate this heating rate in the MW pilot plant during heating of BCM at SIK.

$$\begin{aligned} &Heating\ rate_{45-86^\circ C}^{microwave\,plant\,at\,SIK}[^\circ C/s] = \frac{\Delta T[^\circ C]}{t[s]} = \\ &= \frac{(86-45)[^\circ C]}{16.96[s]} = 2.417 \approx 2.42\,^\circ C/s \end{aligned} \tag{11}$$

The heating rate during the experiments at Binar Elektronik AB between 29 °C and 85 °C with a heating time of 420 s can also be calculated with *Appendix Equation 11*. This temperature difference and heating time is from Run 6.

$$\begin{aligned} &Heating\ rate_{29-85^\circ C}^{microwave\,plant\,at\,Binar\,Elektronik\,AB}[^\circ C/s] = \frac{\Delta T[^\circ C]}{t[s]} = \\ &= \frac{(85-29)[^\circ C]}{420[s]} = 0.133 \approx 0.13\,^\circ C/s \end{aligned} \tag{11}$$

These values are then compared to the heating rates during heating in the HP tank in the two temperature intervals. An average value of the heating rate of the four batches has been calculated but the values from Batch 551(1) will enact as an example. First, the heating time for 45-86 °C is calculated, see *Appendix Equation 12*.

$$\begin{aligned}
&t_{45-86^{\circ}C}^{Batch551(1)}[s] = (0.5 \cdot t_{40-50^{\circ}C}^{Batch551(1)} + t_{50-60^{\circ}C}^{Batch551(1)} + \\
&+ t_{60-70^{\circ}C}^{Batch551(1)} + t_{70-80^{\circ}C}^{Batch551(1)} + \frac{(86-80\,^{\circ}C)}{(T_{\max} - 80^{\circ}C)} \cdot t_{80-T_{\max}\,^{\circ}C}^{Batch551(1)}) \cdot 60[s/\min] = \\
&= (0.5 \cdot 8.6 + 10.3 + 13.7 + 18{,}9 + 0.64516 \cdot 30.9)[\min] \cdot 60[s/\min] = 4028.1s
\end{aligned} \tag{12}$$

Then, the heating rate in the HP tank, Batch 551(1) is calculated by utilization of *Appendix Equation 11* again.

$$\begin{aligned}
&Heating\ rate_{45-86^{\circ}C}^{Batch551(1)}[^{\circ}C/s] = \frac{\Delta T[^{\circ}C]}{t[s]} = \\
&= \frac{(86-45)[^{\circ}C]}{4028.1[s]} = 0.010 \approx 0.01\,^{\circ}C/s
\end{aligned} \tag{11}$$

Next, the heating time in the HP tank between 29-85 °C is calculated, also by again using *Appendix Equation 12*.

Then, to calculate the heating rate between 29-85 °C in the HP tanks, *Appendix Equation 11* can be used once again.

$$\begin{aligned}
&Heating\ rate_{29-85^{\circ}C}^{Batch551(1)}[^{\circ}C/s] = \frac{\Delta T[^{\circ}C]}{t_{29-85^{\circ}C}^{Batch551(1)}[s]} = \\
&= \frac{(85-29)[^{\circ}C]}{4542.2\ [s]} = 0.0123 \approx 0.012^{\circ}C/s
\end{aligned} \tag{11}$$

The heating rates in the four HP tanks used during these calculations, in the two temperature intervals, are presented in *Appendix Table 11*.

Appendix Table 11: This table presents the heating rates, HR, in the four HP tanks and an average value for each of the two temperature intervals. It is the average values that are presented in the report.

Batch	**551(1)**	**551(2)**	**552**	**553**	**Average**
$HR_{45\text{-}86\ ^{\circ}C}$ [°C/s]	0.010	0.011	0.010	0.011	**0.010**
$HR_{29\text{-}85\ ^{\circ}C}$ [°C/s]	0.012	0.013	0.012	0.012	**0.012**

Appendix I: Annual Energy Requirement during Heating

The energy requirement during heating of butter cream up to 90 °C, known as T_{max} °C, is presented in *Appendix Table 12*, where the energy is presented in both MJ and kWh.

Appendix Table 12: This table shows the energy requirement, *Q*, during butter cream production in the temperature range T_{min}-T_{max} °C. The amount of energy is presented in [MJ] and [kWh].

Batch	**551(1)**	**551(2)**	**552**	**553**	**Average**
Mass [kg]	2648.0	2772.0	2633.0	2637.0	**2672.5**
$Q_{(Tmin-Tmax\ °C)}$ [MJ]	505.02	496.20	541.85	544.14	**521.80**
$Q_{(Tmin-Tmax\ °C)}$[kWh]	140.28	137.83	150.51	151.15	**144.95**

The MJ values are the values presented in the bottom row in *Appendix Table 10,* multiplied with the masses shown above and the kWh values are easily calculated by dividing the MJ values with the factor 3.6.

The different cakes produced at Almondy AB that contain butter cream is presented in *Appendix Table 13* together with the total mass of butter cream that was used during 2010. This utilized butter cream mass is assumed to be equal to the produced butter cream mass during 2010. As mentioned in *Appendix G*, the energy requirement for heating of BCM up to T_{max} °C is 0.1955 MJ/kg.

Appendix Table 13: This table shows the different masses present in the cakes from Almondy AB that contains butter cream. Further, the total mass of butter cream that is used in the cakes during one year (2010) is presented at the bottom. BC is an abbreviation for butter cream. *=IKEA cake and **=Orange taste.

Cake	**Almond**				
Cake weight [kg]	0.35	0.4	0.9	0.4*	0.96*
Mass_{BC}/cake [kg]	0.215	0.265	0.54	0.265	0.6
Produced cakes (2010) [pcs]	406 746	472 194	112 170	971 400	287 850
Mass_{BC}/cake variety [kg]	87450	125131	60572	257421	172710

Cake	**DAIM**				
Cake weight [kg]	0.4	0.45	1	0.4**	1**
Mass_{BC}/cake [kg]	0.16	0.21	0.36	0.16	12 180
Produced cakes (2010) [pcs]	5 846 694	488 696	1 039 032	234 510	360
Mass_{BC}/cake variety [kg]	935471	102626	374051	375216	4384800

TOTAL MASS_{BC} [kg]	**6537755**

The annual energy requirement for heating of butter cream is calculated in *Appendix Equation 13*.

$$Q^{per\ year}_{T_{min}-T_{max}\,^{\circ}C}[GJ] = \frac{Mass_{BC}/year[kg]\cdot Q^{per\ kg}_{T_{min}-T_{max}\,^{\circ}C}[MJ/kg]}{1000[MJ/GJ]} = \tag{13}$$

$$= \frac{6537755[kg]\cdot 0.1955[MJ/kg]}{1000[MJ/GJ]} = 1274.86 \approx 1275\,GJ$$

This calculation shows that approximately 1275 GJ is required to heat all the butter cream that is produced at Almondy AB during one year up to T_{max} °C.

It can be calculated how much of the total energy production from fossil fuels that can be ascribed to the heating of BCM at Almondy AB. First, GJ is converted to TWh, see *Appendix Equation 14*.

$$3.6\cdot 10^{15}\,J = 1\,TWh$$

$$\Rightarrow 1275\cdot 10^{9}\,J = \frac{1275\cdot 10^{9}}{3.6\cdot 10^{15}}\,TWh = 3.54\cdot 10^{-4}\,TWh \tag{14}$$

Then, in *Appendix Equation 15*, this energy amount is compared to the total energy production from fossil fuels in Sweden during 2006, which was 13.2 TWh (Lindholm, 2010).

$$Annual\ energy\ ascribed\ to\ butter\ cream\ heating\,[\%] =$$

$$= \frac{Energy\ requirement\ for\ BCM\ heating}{Energy\ production\ from\ fossil\ fuels} = \tag{15}$$

$$= \frac{3.54\cdot 10^{-4}\,TWh}{13.2\,TWh} \approx 2.68\cdot 10^{-6} = 27\,ppm$$

Appendix J: Power Absorption and Microwave Heating Energy Efficiency

When considering the power absorption during the MW heating at SIK between 45 °C and 86 °C, *Appendix Equation 16* has been used.

$$P_{abs}^{45-86\,°C} = \\ = V\rho c_p \frac{\Delta T}{\Delta t} = 0.0002645\,m^3 \cdot 1102\,kg/m^3 \cdot 2761.59\,J/kg°C \cdot 2.42\,°C/s = \\ = 1947.97\,J/s \approx 1948\,W \tag{16}$$

Here, P_{abs} is the absorbed power [W], V is cavity volume [m^3], ρ is the density [kg/m^3], c_p is the specific heat capacity [J/kg°C] and $\Delta T/\Delta t$ is the heating rate [°C/s]. The specific heat capacity have been estimated at 65.5 °C and the density was measured during the experiment at SIK and is assumed to be constant at 1102 kg/m^3.

This value, 1948 W, is then compared with the forward power value observed on the control panel during the MW heating, 4780 W, see *Appendix Equation 17.*

$$Energy\,efficiency_{45-86\,°C}^{MW\,heating\,at\,SIK}\,[\%] = \frac{Absorbed\ power[W]}{Forward\ power[W]} \cdot 100\% = \\ = \frac{1948[W]}{4780\ [W]} \cdot 100\% = 40.75\% \approx 40.8\% \tag{17}$$

Considering the power absorption during the MW heating at Binar Elektronik AB between 29 °C and 85 °C the mass, m, of BCM [kg] is used instead of the volume and the density and the specific heat capacity is estimated at the median temperature 57 °C. To determine the maximum number of trays that could have been transported through the tunnel during this time period if the tunnel had been filled with BCM filled trays, the following calculation in *Appendix Equation 18* have been performed.

$$Number\,of\,BCM\,trays\,during\,one\,heating\,period = \frac{Tunnel\,length[m]}{Length\,of\,BCM\,tray[m]} = \\ = \frac{4.1m}{0.56\,m} = 7.32\,trays \tag{18}$$

In *Appendix Equation 19*, the average mass in each BCM tray from Run 6 is calculated.

$$m_{BCM}^{average}\,[kg] = \frac{m_{BCM}^{Tray1} + m_{BCM}^{Tray2} + m_{BCM}^{Tray3}}{3} = \frac{0.89 + 0.907 + 0.907}{3} = 0.90133\,kg \tag{19}$$

Thus, the total mass of heated BCM during 420 s if the maximum number of trays had been used is then calculated in *Appendix Equation 20.*

$$m_{BCM}^{one\,heating\,period} = Number\,of\,BCM\,trays \cdot m_{BCM}^{average} = 7.32 \cdot 0.90133 = 6.6\,kg \tag{20}$$

Appendix Equation 16 is then used again to calculate the power absorption.

$$
\begin{aligned}
&P_{abs}^{29-85\,^{\circ}C} = \\
&= V\rho c_p \frac{\Delta T}{\Delta t} = m c_p \frac{\Delta T}{\Delta t} = 6.6\,kg \cdot 2754.36\,J/kg^{\circ}C \cdot \frac{(85-29)\,^{\circ}C}{420\,s} = \\
&= 2423.84\,J/s \approx 2424\,W
\end{aligned}
\tag{16}
$$

This value, 2424 W, is then compared with the forward power value observed on the control panel during the MW heating to obtain the energy efficiency during this MW heating. The forward value here was approximately 9000 W and the calculation is performed with *Appendix Equation 17*.

$$
\begin{aligned}
&Energy\,efficiency_{29-85\,^{\circ}C}^{MW\,heating\,at\,Binar\,Elektronik\,AB}[\%] = \frac{Absorbed\ power[W]}{Forward\ power[W]} \cdot 100\,\% = \\
&= \frac{2424\,[W]}{9000\,[W]} \cdot 100\% = 26.93 \approx 26.9\,\%
\end{aligned}
\tag{17}
$$

Appendix K: Water Losses during Microwave Heating

The mass of BCM in tray 4 was determined prior and after Run 7 during the MW experiments at Binar Elektronik AB, to calculate the water losses during MW heating. This water loss is calculated in *Appendix Equation 21*.

$$m_{water}^{lossduringMW\ heating} = m_{BCM}^{beforeMW\ heating} - m_{BCM}^{after\ MW\ heating}[g] = 1538 - 1512\ g = 26\ g \tag{21}$$

The percentage of water losses is calculated in *Appendix Equation 22*.

$$Water\ loss\ during\ MW\ heating\ [\%] = \frac{m_{water}^{lossduringMW\ heating}[g]}{m_{BCM}^{beforeMW\ heating}[g]} \cdot 100\% = \\ = \frac{26\ g}{1538\ g} \cdot 100\% = 1.69 \approx 1.7\% \tag{22}$$

Appendix L: Energy Efficiency of a Horizontal Processing Tank

The energy efficiency of an HP tank, that is how much of the energy generated by the hot water flowing in the outer shell on the HP tank, that actually is used to heat the BCM inside the HP tank has been calculated in *Appendix Equation 23*. The energy requirement for heating the BCM to its final temperature, presented in *Appendix I*, is approximately 145 kWh. Further, the transferred energy in the process is 647 kWh, which is determined during a measurement of the flow rate and inlet and outlet water temperature in the outer shell on the HP tank.

$$\begin{aligned} &Energy\,efficiency_{Per\,batch}^{T_{min}-T_{max}\,{}^{\circ}C}\,[\%] = \frac{Energy\,requirement\,[kWh]}{Energy\,from\,hot\,water\,[kWh]} \cdot 100 = \\ &= \frac{145\,kWh}{647\,kWh} \cdot 100 = 22.41\,\% \approx 22.4\,\% \end{aligned} \tag{23}$$

This calculation generates an energy efficiency of approximately 22.4 % of an HP tank.