รายงานวิจัยฉบับสมบูรณ์

โครงการ: การศึกษาและพัฒนาแบบจำลองการเกิดตะกรัน ในกระบวนการพาสเจอไรซ์น้ำกะทิ

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สนับสนุนโดยสำนักงานคณะกรรมการการอุดมศึกษา และสำนักงานกองทุนสนับสนุนการวิจัย

สารบัญ

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บทคัดย่อ

การสะสมของตะกรันบนพื้นผิวการถ่ายเทความร้อนในเครื่องแลกเปลี่ยนความร้อนเป็นปัญหาที่พบมากในอุตสาหกรรมอาหาร งานวิจัยที่ผ่านมามุ่งเน้นศึกษาการเกิดตะกรันในกระบวนการพาสเจอไรซ์น้ำนมวัว อย่างไรก็ดีส่วนประกอบของน้ำกะทิมีความแตกต่างจากน้ำนมวัวโดยธรรมชาติ อัตราการเกิดตะกรันจากน้ำกะทิจึงอาจแตกต่างและมีลักษณะเฉพาะที่ไม่สามารถอธิบายได้ด้วยผลการวิจัยสำหรับน้ำนมวัว งานวิจัยนี้จึงได้ทำการศึกษาการเกิดตะกรันของน้ำกะทิที่อุณหภูมิพาสเจอไรซ์ โดยใช้ชุดทดลองเครื่องแลกเปลี่ยนความร้อนแบบแผ่นเพลทผิวเรียบ ที่ถูกออกแบบและจัดทำขึ้นที่สถาบันเทคโนโลยีพระจอมเกล้าพระนครเหนือ ประเทศไทย

ชุดทดลองที่ใช้ได้ถูกออกแบบให้สามารถติดตามผลกระทบของอุณหภูมิและอัตราการไหลของน้ำกะทิต่ออัตราการเกิดตะกรัน ส่วนประกอบที่สำคัญในชุดทดลองได้แก่ เครื่องแลกเปลี่ยนความร้อนแบบแผ่นเพลทผิวเรียบทำจากเหล็กกล้าไร้สนิม ที่มีช่องทางการไหลของน้ำกะทิหนึ่งช่องไหลสวนทางกับช่องทางการไหลของน้ำร้อนจำนวนสองช่อง ในชุดทดลองได้มีการติดตั้งอุปกรณ์วัดและควบคุมอุณหภูมิ ความดัน และอัตราการไหลของน้ำกะทิและน้ำร้อนที่ไหลผ่านเครื่องแลกเปลี่ยนความร้อน โดยผลลัพธ์จากการทดลองสามารถนำไปสู่การคำนวณค่าสัมประสิทธิ์การถ่ายเทความร้อนรวมที่เปลี่ยนแปลงไปกับเวลา ค่าความดันตกคร่อม ปริมาณและส่วนประกอบของตะกรันที่เกิดขึ้น

ในงานวิจัยนี้ได้ศึกษาการเกิดตะกรันของน้ำกะทิที่อุณหภูมิพาสเจอไรซ์ 50-74.5 องศาเซลเซียส และที่อัตราการไหล 2 - 6 ลิตรต่อนาที ข้อมูลสัมประสิทธิ์การถ่ายเทความร้อนรวม และปริมาณตะกรันที่เกิดขึ้นที่เงื่อนไขการทดลองต่างๆ สามารถนำไปสร้างเป็นความสัมพันธ์ในรูปแบบจำลองอัตราการเกิดตะกรันเทียบกับเวลา ($\Delta Bi/\Delta t$ และ $\Delta m/\Delta t$) ซึ่งนำไปสู่ผลสรุปผลกระทบของอุณหภูมิ ที่เมื่ออุณหภูมิของน้ำกะทิมีค่าต่ำลงจะทำให้อัตราการเกิดตะกรันเพิ่มมากขึ้น เนื่องจากการเพิ่มขึ้นของค่าความหนืดของน้ำกะทิ ส่วนผลกระทบเนื่องจากอัตราการไหล พบว่าที่อุณหภูมิต่ำอัตราการไหลที่ต่ำมีผลทำให้อัตราการเกิดตะกรันมีค่ามาก ส่วนที่อุณหภูมิสูงอัตราการไหลมีผลน้อยมากต่ออัตราการเกิดตะกรัน

โดยสรุป งานวิจัยนี้ได้ใช้วิธีการทางวิศวกรรมในการได้มาซึ่งข้อมูลต่างๆ ที่เป็นประโยชน์ต่อการอธิบายการเกิดตะกรันของน้ำกะทิ และแบบจำลองที่ได้สร้างขึ้นจากผลการทดลองสามารถนำไปใช้ในการออกแบบระดับอุตสาหกรรม เนื่องจากการทดลองได้ทำภายใต้สภาวะการดำเนินงานต่างๆ ที่มีความใกล้เคียงกับกระบวนการจริง

Abstract

The deposition of fouling deposit onto the heat transfer surface is a severe problem in food process industries. Most previous work in this area has concentrated on deposition from cow milk fouling at pasteurization temperatures. Since the nature composition of coconut milk is far different from cow milk, thus the rate of fouling due to the coconut milk might have its own characteristics. This research work describes preliminary work to study the problem of coconut milk fouling at pasteurization temperature, using a designed plate heat exchanger section fabricated at King Mongkut's Institute of Technology North Bangkok, Thailand.

To understand how variations in temperature and flowrate affect coconut milk fouling, an apparatus which can be used to closely represent the performance of the real plant was constructed. The significant part of the apparatus is a test section, which composes of four flat stainless steel plates which can form three channels for coconut milk flowing in the middle channel counter-current with two hot water channels. The test section was incorporated with extensive temperature, pressure and flowrate instrumentation, to allow heat transfer coefficients, pressure drop, and deposit mass to be monitored.

Fouling at pasteurization temperatures (50-74.5 °C) and at three different flowrates (2,4 and 6 LPM) is reported. Measurement of the overall heat transfer coefficient and the dry masses of deposit in the product channel was done to obtain empirical models for the evolution of fouling with time ($\Delta Bi/\Delta t$ and $\Delta m/\Delta t$). The effect of temperature was to increase fouling rate when temperature decreased due to an increase of viscosity of coconut milk. The effect of fluid flowrate was also reported. For the operating temperature less than denaturation temperature (70 °C), the effect of flowrate was to increase the fouling rate when the flowrate decreased. However, the effect of flowrate was less significant at higher temperatures.

Throughout the work, the emphasis has been on using engineering methods to obtain data on fouling that may be useful in design and operation of plants. Thus, the approach has been to experiment on, and obtain models of the performance of the apparatus, under conditions of operation that approximate industrial practice.

Acknowledgments

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Executive Summary

Project Title 'Monitoring and Modeling of Coconut Milk Fouling at Pasteurization Temperatures'

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1. Introduction

The formation of solid fouling on heat transfer surface area is often a limiting factor in the operation of heat exchangers, the unit operations where heat is transferred from one fluid to another. Normally, there are two major effects of fouling which are the increase of pressure drop across system and a decrease of the overall heat transfer efficiency of the equipment. Fouling is a common problem in industries involving different types of processes, which may include chemical reaction, mass transport, crystallization and bacterial growth. Generally, the most important consequence of fouling is that plant efficiency is decreased and, therefore, costs are increased. Additional exchanger area is included in the design of plant to take account of the reduction in the heat transfer efficiency due to fouling. It is usually difficult to predict the effects of deposit formation on heat transfer resistance and heat exchanger costs are then increased in two ways. Those are the cost of extra area to compensate for actual fouling, and the cost of extra area for the safety factor. Moreover, fouling leads to increased costs of extra heat and pumping duties required, increased costs of cleaning and maintenance, and usually there is loss of production from a reduced feed rate.

In the food industries, fouling from food fluids is very critical, because the rate of deposit build up on the heat transfer surfaces is often rapid. Mostly, plants shut down for cleaning at least eight hours in every day. Extensive work has been carried out to investigate the characteristics of food fouling. However, developed models of fouling are very dependent on the characteristics of the systems. To obtain an accurate kinetic model of fouling in particular system, it is necessary to monitor and model the heat exchanger thermal performance when fouling occurs. At the present time, thermal treatment of food products is a process, where fouling is a major problem. Any food and drink can be treated by a range of different temperatures according to the properties required by the consumer. In general, heat treatment is given to food fluids to kill pathogenic micro organisms and degrading enzymes in order to increase shelf life, product quality and product safety (sterility).

Thermal treatment of coconut milk is an interesting case in this work, because of its marketing importance. Coconut milk is used in a large variety of Thai dishes, such as the juice in curry and to be part of many Thai desserts and sweets. In the past, coconut milk can be squeezed from coconut body part by hand or squeezing machine, and then, the fresh milk can be added for cooking. Now a day, instant coconut milk has become very popular in both juicy and powder forms due to their convenience in cooking. This kind of coconut milk is produced via thermal treatment processes, which can be separated into two different temperature zones. Firstly, a low temperature pasteurization process is defined as a treatment sufficient to inactivate the enzyme. This is typically achieved by heating the coconut milk to 70-75°C and maintaining at this temperature for 15-20 seconds. The treatment kills all pathogenic organisms, most vegetative organisms, but does not kill spores. Secondly, ultra-high-temperature (UHT) processes are another alternative. These are performed by heating coconut milk to 135-150°C for a few seconds. Unlike pasteurization, these processes kill both vegetative cells and spores. However, after continuous treatment processing, coconut milk must be packaged into sterile containers. The problems of packaging also constitute a separate area of research and development.

In this work, pasteurization process for coconut milk is investigated. At the present time, it is not economical to use pasteurization techniques on coconut milk in containers, because of the significant thermal lag associated with the conduction of heat into the centre of the container. Therefore, the treatment processes have to be performed continuously on the milk in various types of heat exchangers such as plate, tubular and scraped-surface heat exchangers. The heat transfer distance is much less in this equipment, and turbulence produced by flow gives higher heat transfer rates. However, coconut milk is a complex biological fluid, which comprises water, fats, proteins and minerals. After a long running time, some of the compositions can deposit as solid fouling on the heat transfer surface area. This impedes the transfer of heat and increases resistance to fluid flow. Fouling deposits need not be very thick to seriously affect exchanger performance. Many research works have been carried out to investigate the effects of fouling for food fluids such as cow milk, some fruit juices and some vegetable juices. Unfortunately, a wide variety of causes of fouling exist due to different kinds of fluid compositions and different kinds of heat exchangers. Therefore, research in one area of fouling may not give results that are generally applicable. In general, fouling research tries to define the conditions that lead to fouling in a particular process and to relate this to the design and operation parameters, such as time, fluid flow, temperature, heat transfer rates and also to materials selection.

2. Objectives

- To construct a laboratory-scale apparatus for monitoring of fouling of coconut milk at pasteurization temperatures.
- To do experiments by measurement of coconut milk fouling on the generated rig at various operating conditions such as time, fluid velocity, and fluid temperature.
- To correlate the experimental data by means of heat exchanger thermal performance at different rates of fouling.
- To develop mathematical models in order to represent the overall heat transfer coefficient as a function of operating conditions such as time, fluid velocity and fluid temperature.
- To identify the compositions of deposits generated on the heat transfer surface, and to isolate the majority of biological components which cause the fouling in such processes.

3. Methodology

To understand how variations in system parameters affect coconut milk fouling for the pasteurization process, a test section which composes of four flat stainless steel plates is constructed. These plates form three channels for coconut milk flowing in the middle channels counter-current with two hot water channels. This configuration has similarity in the same manner of plate and frame heat exchangers. The test section is incorporated with extensive temperature, pressure and flowrate instrumentation, to allow pressure drops, heat transfer coefficients and deposit mass to be monitored in order to quantify deposit fouling.

The designed apparatus is supported by ancillary equipment, which are a storage tank and a feed tank of coconut milk, coconut milk heater and pump, coconut milk cooling unit, hot water generator and other measuring devices. The apparatus is manufactured in the Department of Chemical Engineering, KMITNB. It is run at the specified operating conditions to measure fouling resistance based on an analysis of the response of heat transfer coefficients and pressure drops. With the experimental data, a fouling model is obtained by multiple linear regression and statistical analysis. It is designed to represent a polynomial function of the process variables, which are fluid flowrate, temperature and time reacted in the system.

Throughout the work, the emphasis is on using engineering methods for the indirect heat transfer to obtain data on coconut milk fouling at pasteurization temperatures (room temperature - 75 °C) that may be useful in design and operation of real plant. Thus, the methodology is to experiment on test rig, and obtain mathematical model of the system performance that may be typically found in industry. Selection of operating conditions is performed that approximate industrial practice, which is most commonly encountered in the literature. In order to have a clear overview of this research work, the procedure can be summarized as following:

A. Literature on food fouling. The literature on food fouling is now extensive. This project concentrates on milk fouling especially coconut milk and its product.

B. Selection of a model solution for the fouling. The solution used in the fouling experiments is the coconut milk extracted from coconut body part, which is obtained via a consistency specified supplier. Compositions, physical and thermal properties of coconut milk are identified by standard methods for food products.

C. Design of the experimental apparatus. The optimal technique to measure coconut milk fouling is selected. The type of apparatus is the most relevant type to the industry, the plate heat exchanger. A three-channel plate heat exchanger (by flat-surface plates) is used to heat coconut milk to the pasteurization temperature (75°C).

D. Construction of the apparatus. The test section of three-channel plate heat exchanger is manufactured in the Department of Chemical Engineering at KMITNB. The other parts of the apparatus are listed and brought in to order to fabricate and assemble the apparatus in the KMITNB Chemical Engineering work shop.

E. Design of the experimental program. The experimental program is designed to monitor temperature-time profiles of the coconut milk channel. The specified conditions cover the ranges of operating parameters in which fouling occurs. However, the apparatus is designed to be as flexible as possible and so experimental configurations can be used to test other ranges of operation.

F. Running of the experiments. A set of experiments is conducted on the apparatus at the Chemical Engineering Department, KMITNB. Time for one run is up to 6 hours at this stage due to available facilities. The total number of test run is designed of 30.

G. Data analysis. The results from experiments are analyzed by multiple linear regression method in order to develop the empirical model. The model represents the effects of process parameters on response variables in the engineering approach. Fouling resistance and the overall heat transfer coefficient at fouled conditions are the response variables in this case, and they are correlated with time, fluid velocity and temperature according to a proper form of mathematical model.

4. Work Schedule

Table 1. The work schedule.

Work\Months	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24
A	→	→										
B		→										
C			→	→								
D					→	→	→					
E							→					
F								→	→	→		
G										→	→	
Reports			→			→			→			→

5. Publication Title

1. The title of the publication is "Monitoring and modeling of coconut milk fouling at pasteurization temperatures". For the international journal, the paper is submitted to the following;

- *Journal of Food Engineering* Impact Factor = 1.085

2. The title of the publication is "Effects of fluid flowrate on coconut milk fouling at pasteurization temperature (70-74.5 °C)". For the national journal, the paper is accepted by the following;

- *Songklanakarin Journal of Science and Technology*

3. The title of the publication is "Experimental device and method for the investigation of coconut milk fouling at pasteurization temperature". For the international conference, the paper is accepted by the following;

- *APCCHE 2006, 27-30 August 2006, Kuala Lumpur, Malaysia*

4. The title of the publication is "Investigation on the role of fat, protein, and minerals present in coconut milk fouling deposit at pasteurization temperature". For the international conference, the paper is submitted to the following;

- *CHEMECA 2006, 17-20 September 2006, Auckland, New Zealand*

CHAPTER 1
INTRODUCTION

1.1 Rationale/Problem Statement

The deposit formation of solid fouling on heat transfer surface areas is often a limiting factor in the operation of heat exchangers, the unit operations where heat is transferred from one fluid to another. Normally, there are two major effects of fouling which lead to an increase of pressure drop across system and a decrease of the overall heat transfer efficiency of the equipment, see Figure 1. Fouling is a common problem in industries involving different types of processes, which may include chemical reaction, mass transport, crystallization, and bacterial growth. Generally, the most important consequence of fouling is that plant efficiency is decreased and, therefore, costs are increased.

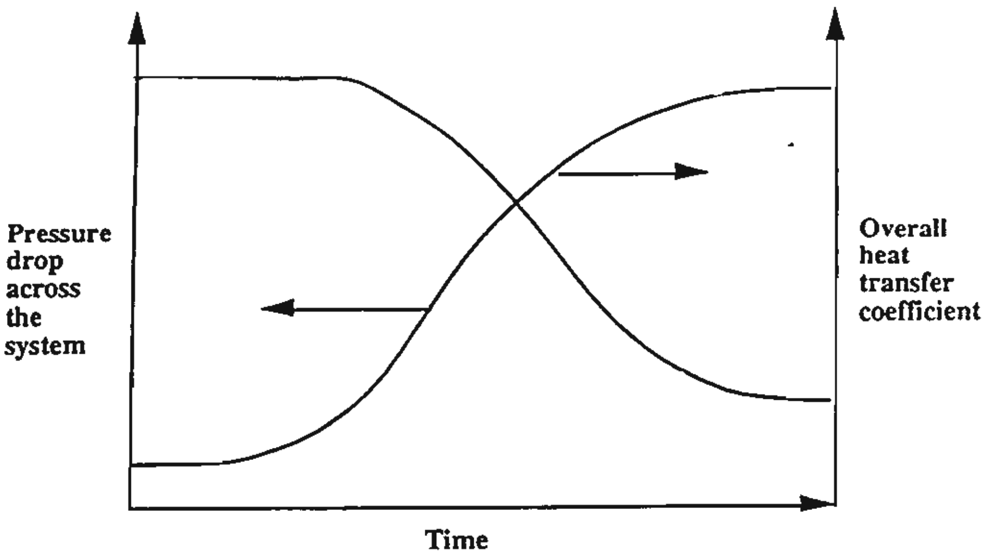


Figure 1 An illustration of the effects of fouling

In the food industries, fouling from food fluids is very critical because the rate of deposit build up on the heat transfer surfaces is often rapid. Mostly, plant shut down for cleaning at least every eight hours in a day (Schreier, 1997). Extensive work has been carried out to investigate the characteristics of food fouling. However, developed models of fouling are very dependent on the characteristics of the systems. To obtain an accurate kinetic model of fouling in particular system, it is necessary to monitor and model the heat exchanger thermal performance when fouling occurs. At the present time, a thermal treatment of food products is a process, in which fouling is a major problem. Any food and drink can be treated by a range of different temperatures according to the properties required by the consumer. In general, the heat treatment is given to food fluids to kill pathogenic microorganisms and degrade enzymes to increase shelf life, product quality, and product safety (sterility) (Burton, 1988).

The thermal treatment of coconut milk is an interesting case in this research work, because of its marketing importance. Coconut milk is the liquid obtained by manual or mechanical extraction of grated coconut meat. It is an important part of many food dishes in Asian and Pacific countries. In the past, coconut milk can be squeezed from coconut body part by hands or squeezing machine, and then, the fresh milk can be added for cooking. Nowadays, immediate coconut milk has become very popular in both juicy and powder forms due to their convenience in cooking. This kind of coconut milk is produced via thermal treatment processes. After passing through heat treatment process, the coconut milk is filled in cans, boxes, soft plastic bags or processed powder forms. To preserve the coconut milk, pasteurization process has been found to be a short- term preservation process in which the coconut milk is heated to pasteurization temperature of 72-75 °C for 20 min (Seow & Gwee, 1997). Normally, the coconut milk pasteurized in soft plastic bags has been found fresher and more convenient for cooking. It has a shelf-life of not more than 5 days (Gwee, 1988). A typical percentage of fat is adjusted depending upon local requirement, which can be in between 15-40%. Heating process normally takes place in a system of indirect plate heat exchangers, which consists of preheating, heating, and cooling sections.

Since the coconut milk is a complex biological fluid, typically composed of fat, protein, carbohydrates, and minerals as a white oil-in-water emulsion, after a long running time, some of the compositions can lose their rheological properties to form deposition on heating surface. This impedes the heat transfer and increases the resistance of the fluid flow. Fouling deposits need not be very thick to seriously affect the exchanger performance (Parry et al., 1981). Some research works have shown significant effect of temperature on the properties and stability of coconut milk. Buccat et al. (1973) reported that the density and pH of coconut milk vary inversely with temperature between 10-80 °C. However, surface tension and viscosity increase steadily with temperature up to 60 °C. For temperature higher than this, they slowly decrease. Vitali et al. (1985) found that coconut milk exhibited mildly pseudoplastic behavior at temperatures of 15-50 °C due to high fat content. Simuang et al. (2004) confirmed the similar result from the experiments at 70-90 °C and fat content of 15-30%, which all coconut milk samples expressed pseudoplastic behavior.

Many research works have been carried out to investigate the effects of fouling for food fluids such as cow milk, fruit juices, and vegetable juices. Unfortunately, a wide variety of causes of fouling exist due to different kinds of fluid compositions and different kinds of heat exchangers. Therefore, research in one area of fouling may not give results that are generally applicable. In general, fouling research tries to define the conditions that lead to fouling in a particular process and to relate this to the design and operation parameters, such as time, fluid flow, temperature, heat transfer rates and also to materials selection (Somerscales, 1981).

1.2 Definition and Types of Fouling

Fouling has been defined as the "deposition of material on heat transfer surface, usually resulting in an increase in the resistance to heat transfer and a subsequent loss of thermal exchange capacity of the heat transfer equipment" (Hewitt, 1992). Fouling deposits need not to be very thick to seriously decline performance of heat exchanger equipment with time (Parry et al., 1981). The presence of a layer of deposit leads to an increase in resistance to heat transfer in addition to that inherent in the exchanger design. Moreover, the deposit surface roughness and the reduction in area available for fluid flow leads to an increase in pressure drop across the exchanger (Bott, 1988 a).

Despite the simplicity of this definition, a wide variety of types of fouling exist according to mechanism as shown in Table 1.

Table 1 The types of fouling

Types of fouling	Description
Precipitation (crystallization) fouling (Bott, 1988 b)	Deposition of dissolved solids with a reverse solubility curve near the surface, e.g. calcium phosphate.
Particulate fouling (Epstein, 1988 b)	Deposition of particles from the bulk, e.g. silt fouling
Chemical reaction fouling (Hewitt, 1992)	Deposition of solid products of chemical reaction on the surface.
Corrosion fouling (Somerscales, 1988)	Formation of corrosion on surface, by direct action or transfer of corrosion products from the bulk.
Biological fouling (Kent, 1988)	Deposition and growth of microorganisms on surface.
Freezing fouling (Hewitt, 1992)	Solidification of a pure liquid in contact with a sub cooled heat transfer surface.
Combined fouling (Hewitt, 1992)	Deposition of particles from the result of two or more of the types described above.

1.3 Economic Consideration of Food Fouling

To examine the cost of fouling to the food industry, an additional exchanger area is included in a design of plant to take an account of the reduction in the heat transfer efficiency due to fouling. It is usually difficult to predict the effects of deposit formation on heat transfer resistance, and heat exchanger costs are then increased in many ways. The costs are classified under four main headings: capital expenditure, fuel costs, maintenance costs and loss of production (Pritchard, 1988).

The capital expenditure is the cost of an extra heat transfer surfaces to allow the fouling, the costs of the extra work associated with the installation of the larger heat exchangers, this due to the provision of more heat transfer surface results in larger and heavier heat exchangers, involves the extra space with stronger foundations, and increases transport and installation charges. The fuel costs are often presented as "Energy Costs". The cost of energy is different according to whether it is the heat generated by combustion of coal, oil or gas in boilers and furnaces, or electricity or process steam in turbines, condensers and heat recovery wheels in electric power plants. Fouling leads to increased costs through the extra heat and pumping duties required. Malignance cost can be divided into two main classes: the costs of removing fouling deposits during planned or unplanned maintenance, and the costs of chemicals or other operating costs of antifouling devices. These costs do not include the additional costs that may arise of an unplanned shutdown, and do not include the result of corrosion associated with fouling. Cost of production loss arises from unwanted plant shut-downs or possibly contamination of the product as a result of fouling. However, the loss of production is only of value if it can be sold so that this cost is initially less important during a downturn in economic activity. Unfilled opportunities, fouling limit the number of possible processes in the food industry. For example, highly viscous materials have very shot process run times such as whipping cream sometimes as little as 5 hours. It difficult to scale up plant or to change designs.

1.4 Thermal Treatment of Food Fluids

Thermal treatment can be separated into two different temperature zones. Firstly, a low temperature pasteurization process is defined as a treatment sufficient to inactivate the enzyme. This is typically achieved by heating the coconut milk to 70-75°C and maintaining at this temperature for 15-20 seconds. The heat kills all pathogenic organisms, most vegetative organisms. However, it does not kill spores (Gotham, 1990). Secondly, ultra-high-temperature (UHT) process is another alternative. This is performed by heating coconut milk to 135-150°C for a few seconds. Unlike pasteurization, these processes kill both vegetative cells and spores. However, after continuous treatment processing, coconut milk must be packaged into sterile containers. The problems of packaging also constitute a separated area of research and development (Burton, 1988). Thermal treatment is given to food fluid to kill pathogenic microorganisms and degrading enzymes so as to increase one or more of shelf life, product quality, process safety (sterility).

Generally, there is a subdivision of pasteurization into two categories (Burton, 1988, Hewitt, 1992).

- Low temperature, long time (LTLT) process. The process is typically achieved by heating product at 63°C for 1800 s.
- High temperature, shot time (HTST) process. The process is typically achieved by heating product at 72-75°C for 15-20 s.

The first process seems to be the better one if product has the highest tendency to foul at high temperature (more than 65°C). However, in terms of improving the efficiency of the whole process, and therefore of saving money, nowadays the food fluid is treated rather in continuous processes than in tanks. That means the HTST process is the favored one and will be investigated in this work.

1.5 Current Technology of Pasteurization Plant

One of the most important requirements of modern pasteurization processes is to be able to control the temperature of products at every stage in the process. Heat in most plants is supplied by stream or hot water, typically raised by combustion of solid fuel, oil or gas, or electricity (Tetra Pak, 1995). For systems using steam or hot water, the heating may be "direct" or "indirect" system.

In the direct system, the two immiscible fluids are in contact with each other. For example, the product is mixed with the steam. In the indirect system, the two fluids are separated by a heat-conducting barrier. In high temperature, shot time (HTST) process, the indirect systems, plate, tubular, and scraped-surface heat exchangers are used, alone or in combination. Typically, plate heat exchangers are the most common type used for food processing. The key features are a source of processing heat such as steam or hot water, a regenerative heat exchanger which transfers heat to the product with the maximum thermal efficiency, and a cooling section to achieve final product cooling before packaging (Schreier, 1997).

There are at least three major plate heat exchanger configurations: the plate and frame heat exchanger, the spiral plate heat exchanger, and the lamella heat exchanger. The common factor among these three configurations is that the heat transfer surface is composed of parallel metal plates kept separated by surface and the heat exchanging fluid flow in the thin channels (Bell, 1981).

The plate heat exchanger (PHE) used in pasteurization processes consists of a pack of stainless steel plates clamped in a frame. The frame may contain several separated sections, in which different stages of treatment such as preheating, final heating, and cooling take place. The plates are corrugated in a pattern designed for optimum heat transfer. The plate pack is compressed in the frame. Supporting points on the corrugations hold the plates apart so that thin channels are formed between them. The liquids enter and leave the channels though ports in the corners. Varying patterns of open and blind ports directs the liquid from one channel to the next. Gaskets round the edges of the plates from the boundaries of the channels and prevent leakage and internal mixing (Tetra Pak, 1995).

The plate heat exchanger is chosen because of the many advantages when compared to the other conventional heat exchangers as following (Narataruksa, 2000).

- High thermal efficiency that means high energy recovery up to 85-90% is common.
- Compact design due to high heat transfer rate per square meter.
- Good working with much closer temperature approach and with much lower flowrate.
- Small weight and less extra space for installation and disassembling due to thin plates.
- Low fouling tendency due to very high turbulence flow in the channels.
- Most economic unit, when expensive materials of construction are required.
- Easy to disassemble for adjusting the number of plates or the heat transfer area.

1.6 Research Objectives

1.6.1 To construct a pilot-scale apparatus for monitoring of fouling of coconut milk at pasteurization temperatures.

1.6.2 To do experiments by a measuring of coconut milk fouling on the generated rig at the operating conditions including time, fluid velocity, and fluid temperature.

1.6.3 To correlate the experimental data by means of heat exchanger thermal performance at different rates of fouling.

1.6.4 To develop statistical models in order to represent the overall heat transfer coefficient as a function of time, fluid velocity and fluid temperature.

1.6.5 To identify the compositions of deposits generated on the heat transfer surface, and to isolate the majority of biological components which cause the fouling in such processes.

CHAPTER 2
THEORIES

2.1 Characteristics of Coconut Milk

Coconut milk is used in a large variety of Thai dishes. In the past, coconut milk can be squeezed from coconut body part (nut) by hand or squeezing machine, and then, the fresh milk can be added for cooking. Coconut milk compares to mother's milk in its chemical balance. It is quite a complete protein food when taken in its natural form. The compositions of the coconut milk in comparison to coconut-cream, meat, dry meat and water are shown in Table 2 (Heritage, 1999).

Table 2 Compositions of the coconut milk in comparison to coconut-cream, meat, dry meat and water (Heritage, 1999).

	Cream	Meat	Dry Meat	Milk	Water
Acid Binding Elements					
Calcium - mgs	15	13	26	16	20
Potassium - mgs	324	256	588	-	147
Sodium – mgs	4	23	-	-	25
Magnesium – mgs	-	46	90	-	28
Iron – mgs	1.8	1.7	3.3	1.6	0.3
Acid Forming Elements					
Phosphorus - mgs	126	95	187	100	13
Chlorine - mgs	-	320	-	-	-
Sulphur - mgs	-	85	-	-	-
Silicon - mgs	-	-	-	-	-
Iodine - mgs	0.009	-	-	-	-
Bromine - mgs	-	-	-	-	-
Vitamin A-I.U.	0	0	0	0	0
Thiamine (B-1) - mgs	0.02	0.05	0.06	0.03	trace
Riboflavin (B-2) - mgs	0.01	0.02	0.04	Trace	trace
Absorbic Acid (C)-mgs	1	3	0	2	2
	Cream	**Meat**	**Dry Meat**	**Milk**	**Water**
Water - percentage	54.1	50.9	3.5	65.7	94.2
Energy - Calories	334	346	662	252	22
Carbohydrates					
Total – grams	8.3	9.4	23	5.2	4.7

Fiber – grams	-	4	3.9	-	trace
Protein - grams	4.4	3.5	7.2	3.2	0.3
Ash – grams	1	0.9	1.4	1	0.6
Fat – grams	32.2	35.3	64.9	24.9	0.2
Fatty Acids					
Total Saturated - grams	28	30	56	22	-
Unsaturated					
Oleic – grams	2	2	5	2	-
Linolic - grams	Trace	Trace	Trace	Trace	-
Organic Acids					
Citric -%	-	-	-	-	-
Malic - %	-	-	-	-	-
PH	-	-	-	-	-
Metab/ React Alkal(acid)	-	6	8.5	7.5	5.04
Digestion Time - hours	-	2.75	3.25	2	-

2.2 Study of Milk Protein Fouling

Fouling from foods shows great variation in its behavior, and pasteurization fouling of coconut milk has not been studied so far. However, there is a report (Table 2) showing that protein, minerals and fat are found in coconut milk. These compositions have been confirmed of their contribution in fouling deposits for cow milk processes. Therefore, it is important to review previous work in the modeling and monitoring of fouling especially of cow milk at pasteurization temperatures.

Burton (1968) classified the milk fouling deposit as Type A for pasteurization process. Type A fouling is a white and voluminous deposit made up of protein (50-60%), minerals (30-35%) and fat (4-8%). Type A deposit starts to form when the temperature about 70 °C, and is a maximum in the range 95-110 °C and decreases in amount at higher temperatures. At the lower end of the temperatures, most of the protein is denatured ß-lactoglobulin, but at the higher end it is predominantly casein (Burton, 1968, Lalande et al., 1984, Tissier et al., 1984). Many people have found the deposit for run times greater than 1 hour, that Type A deposits consist of a protein-rich outer layer and a sublayer, near the heat exchanger surface, that is rich in minerals (Hege and Kessler, 1986 b, Tissier and Lalande, 1986, Daufin et al., 1987, Britten et al., 1988, Foster et al., 1989).

McKenzie (1971) stated that ß-lactoglobulin is the milk protein most sensitive to heating, and it is present in significant amounts (greater than 50%) in pasteurization fouling deposits, substantially greater than its proportion (0.3%) within whole milk. At about 70 °C, there are two separate processes taking place. Denaturation is the first process which is a major change from the original native structure of ß-lactoglobulin. The second process is aggregation in which the unstable configuration of aggregates is stabilized by polymerization with other denatured molecules via intermolecular aggregation (Joly, 1965, Gotham, 1990). Denaturation is essentially reversible, but ß-lactoglobulin aggregation is totally irreversible. The resulting aggregates are insoluble in water (Gotham, 1990) and appearing as the fouling deposit.

2.3 Methods Used to Study Food Fouling

Generally, there are two main areas of studies on food fouling especially for milk treatment processes. The first is concentrated on the investigation of the mechanisms of fouling. This studies the milk protein fouling problem by examining the processes that lead to fouling, the nature of the deposit, and the factors that lead to variations in deposition. Underlying thermal chemistry of milk proteins has been examined to show how protein chemistry causes deposition. From the composition and structure of fouling deposits, the factors that affect deposit formation under the subheadings of biological, chemical and physical factors are identified (Schreier, 1997).

The second areas of milk fouling research are to investigate the effects of fouling deposition on heat transfer and pressure drop. The rate of fouling is a strong function of process variables. It is important to be able to understand the flow and temperature behavior of equipment used to measure fouling. Since the objectives of this work can be counted in the second areas of milk fouling research. The methods used in this area are reviewed.

Hewitt (1992) listed the devices to measure fouling factor for general processes as follows:

A. Constant heat flux devices. The device can be based on either indirect electrical heating or direct resistance heating. Provided the local heat flux, the fluid velocity, bulk temperature, and the measured wall temperature under clean and fouled conditions, the fouling factor can be calculated.
B. Constant wall temperature devices. The device makes use of a boiling liquid or condensing vapor to transfer heat to or from the test fluid. As fouling proceeds, the wall temperature remains constant, and the heat flux decreases. Only average fouling factor over the test section can be determined by this device.
C. Liquid-liquid devices. The fluid being tested may be heated or cooled by another fluid, which should be nonfouling and passed trough the test section at a high mass rate to minimize its temperature change. The condition is in between constant heat flux and constant wall temperature. The device is suitable to study fouling with complex surfaces and complex geometries.

All of the devices suggested by Hewitt (1992) can be constructed in many geometries of heat transfer equipment. Schreier (1997) reported the main geometries of heat exchangers that have been used to study milk fouling previously, namely.

1. Tubular heat exchangers (Lund and Bixby, 1975, Fryer, 1986, Rakes et al., 1986)
2. Plate heat exchangers (Tissier et al., 1984, Lalande et al., 1985, Delplace et al., 1994, Grandison, 1988 a, b, c, De Jong et al., 1992, 1993, 1994)
3. A square duct (Hege and Kessler, 1986 a, b)
4. A single plate (Tissier and Lalande, 1986, Roignant et al., 1983)
5. A heated U-tube apparatus (Burton, 1961)
6. A platinum hot wire apparatus (Burton, 1965)
7. A disc fouling apparatus (Britten et al., 1988, Foster et al., 1989)

8. A couple of two parallel plates and a tapered tube (Fryer et al., 1985, Fryer and Slater, 1987)

2.4 Factors Affecting Deposit Formation

To obtain beneficial results from the research work, the effects of variation in systems parameters on the rate of fouling should be review as following.

A. Fluid characteristic factors. Compositional variations of milk have been reported for the seasonal changes in the amount of deposit formation of milk processing. Burton (1967) suggested that the controlling factor was closely associated with fat content in the milk for the systems using direct injection steam heating. However, fat is found to act as an insignificant factor for indirect systems. The effect of milk pH on deposit formation has also been studied. Skudder et al. (1986) added acid ($pH < 6.6$) or alkali ($pH > 6.8$) to show that the amount of fouling increased markedly at acid pH but was unaffected at alkali pH. The air content of milk is another factor. The deposition is reduced if the air content of milk is reduced. The air content can form bubbles on the heat transfer surface, and this causes severe fouling due to the local stagnation points of flows around bubbles (Fryer, 1986). Lalande and Corrieu (1981) also reported the effects of the NH_3 concentration of the milk on the rate of fouling. This is known that added urea increases milk heat stability and decreases fouling (Robertson and Dixon, 1969, Muir and Sweetsur, 1976, Burton, 1988).

B. Processing time. In a tubular heat exchanger, milk fouling process can be described in three periods. An induction period, the deposit formation has little or no effect on measured parameters. A fouling period, the deposit forms rapidly, and a post-fouling or stationary period, a little extra fouling occurs (Fryer, 1986, Hege and Kessler, 1986 a). For plate heat exchangers, there were some reports stating that there seems to be no induction and post-fouling periods. Fouling deposition increases exponentially at pasteurization temperatures until the PHEs have to be shut down for cleaning (Lalande et al., 1984, Gotham, 1990).

C. Temperature. For milk pasteurization process, the rate of deposit formation increases as the temperature increases above 70 °C (Daufin et al., 1987, Hege and Kessler, 1986 a). Especially in PHEs, fouling has been shown to increase over a limited surface and bulk temperature range up to 100 °C, with a deposit formation profile depending on the fluid type (Fryer, 1986, Hege and Kessler, 1986 a, Rene et al., 1988, Roignant et al., 1986).

D. Fluid flowrate. Fryer and Slater (1985, 1987) stated that it is possible to reduce the mean residence time of fluid, i.e. increase of fluid flowrate, at the hot surface in order to reduce the rate of deposition. They also suggested that the rate of deposit removal can be increased by increase fluid flowrate. As fluid flows over a surface on which a deposit has built up, the shear stresses created by the flow may bring about deposit removal. Paterson and Fryer (1988) concluded that the rate of deposit formation decreased with increasing Reynolds number because of the decrease in the thickness of the laminar sublayer and thus in the amount of heated protein sufficiently close to the hot surface for fouling to occur. However, Belmar-Beiny et al. (1993) performed experiments in tubes and concluded that apart from controlling reaction in the laminar sublayer, reactions in the turbulent core of the flow also affected the rate of fouling. Unlike tubes, it is difficult to relate fouling to flowrate in PHEs since the internal complex flow pattern is designed. This significantly affects the surface shear stress patterns and temperature distribution within the flow channels.

E. Amount of preheating. Preheating milk to 75 °C or above for 10 min or more, can help reducing fouling (Mottar and Moermans, 1988, Kessler and Beyer, 1991). The denaturation of serum proteins especially ß-lactoglobulin, during preheating reduces the formation of proteinaceous deposits later in the process. However, too high preheating temperature will lead to unacceptable fouling in the preheating section itself. An optimum preheating temperature-time range in UHT plant is 76-80 °C for 40-70 s. (Mottar and Moermans, 1988). However, there is no report of preheating temperature-time range for pasteurization processes.

2.5 Selection of a Model Solution for the Experimental Works

2.5.1 Model Fouling Solution

The model coconut milk solution used in the experimental works at King Mongkut's Institute of Technology North Bangkok (KMITNB) was a pasteurized coconut milk, supplied by a local factory (Leader Price) in Bangkok, Thailand. The solution contained normally 99.9 wt % of coconut milk. Microanalysis of its compositions was analyzed by the equipment and methods of the Institute of Food Research and Product Development, Kasetsart University, Thailand. Compositional results of the coconut milk are given in Tables 3 and 4.

Table 3 Composition of the coconut milk solution

Analysis Item(s)	
Moisture, %	82.61
Protein, % (factor 5.30)	2.99
Fat, g/100 ml	17
Carbohydrate, % (by difference)	1.97
Minerals	
Calcium, mg/L	78.81
Iron, mg/L	6.06
Magnesium, mg/L	122.26
Phosphorus, mg/L	414.28
Potassium, mg/L	929.60
Sodium, mg/L	419.33

Table 4 Composition of the coconut milk solution in weight percent (w/w)

Component(s)	Percent* (w/w)
Water	70.57
Protein	2.99
Carbohydrate	1.97
Fat	17.00
Minerals	
Calcium	0.0078
Iron	0.0006
Magnesium	0.0121
Phosphorus	0.0410
Potassium	0.0920
Sodium	0.0415
Others	7.2703

* Calculation based on the density of coconut milk equals to 1000.803 kg/m^3 at 25 °C.

2.5.2 Chemical Analyses of Solution and Deposits

In this work, model coconut milk solution and deposits removed from stainless steel plates were analyzed for the percentages of fat, protein, and minerals by the following techniques. Total protein was found from N content × 6.25 as measured by Kjeldahl technique, digested by BÜCHI Digestion Unit K-242 and BÜCHI Scrubber B-414, and distilled by BÜCHI Distillation Unit K314 (CH-9230 Flawill Switzerland). The Chloroform/Methanol/Water Extraction of fat determination was analyzed by the modified method of Fereidon Shahidi, 2001, using a Sonicator (Branson, 3210, USA), and Centrifuge (Jouan, MR 23i, German). Moisture of coconut milk was analyzed by Karl Fischer Titrator method using a coulometer (METTLER TOLEDO DL 37 KF coulometer, Switzerland). Mineral content was determined by Inductively Coupled Plasma (ICP) (Perkin Elmer model Optima 2000DV, USA).

2.5.3 Physical and Thermal Properties Analysis

Physical and thermal properties of the coconut milk as functions of temperature were also necessary for experimental design and thermal performance calculations. In this work, the coconut milk density and viscosity data were obtained by using a density bottom (BIBBY BORO in 20°C ml, China) and a viscometer K604 CANNON instrument company, USA as shown in Tables 5 and 6, and Figures 2 and 3. The experimental works were done at KMITNB.

Table 5 Density of the coconut milk solution

Temperature (°C)	Density (kg/m^3)
20	1003.3266
30	998.2794
40	997.3999
50	994.1498
60	991.0909
70	985.7378
80	980.2699
90	975.1845

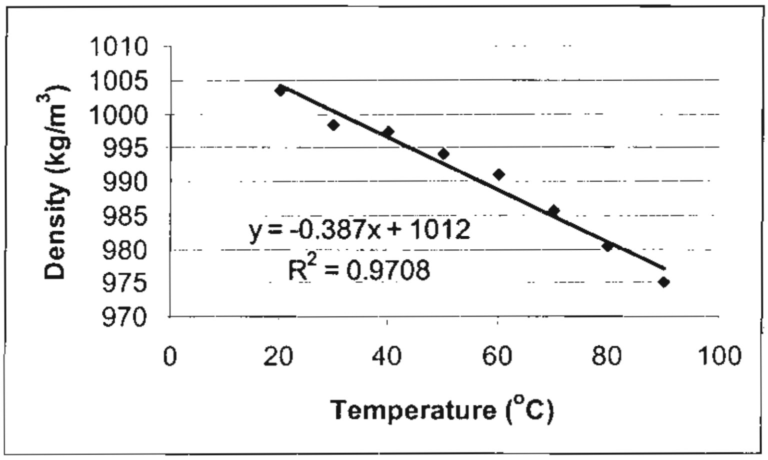


Figure 2 Density of the coconut milk solution

Table 6 Viscosity of the coconut milk solution

Temperature (°C)	Viscosity (kg/m s)
20	0.0020627
30	0.0019995
40	0.0017869
50	0.0014190
60	0.0013389
70	0.0011927
80	0.0008234
90	0.0006243

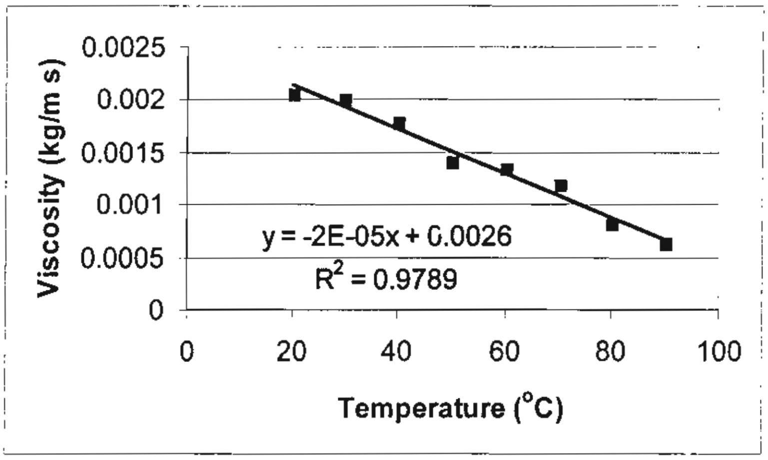


Figure 3 Viscosity of the coconut milk solution

The specific heat capacity and the thermal conductivity of coconut milk solution were obtained by the experimental works done at National Metal and Materials Technology Center (MTEC), National Science and Technology Development Agency, Bangkok, Thailand, as shown in Table 7, and Figure 4.

Table 7 Specific heat capacity of the coconut milk solution

Temperature (°C)	Specific heat capacity (J/kg K)
10	4840
15	4370
20	5350
25	5330
30	5420
35	6120
40	6710
45	6640
50	5690
55	6900

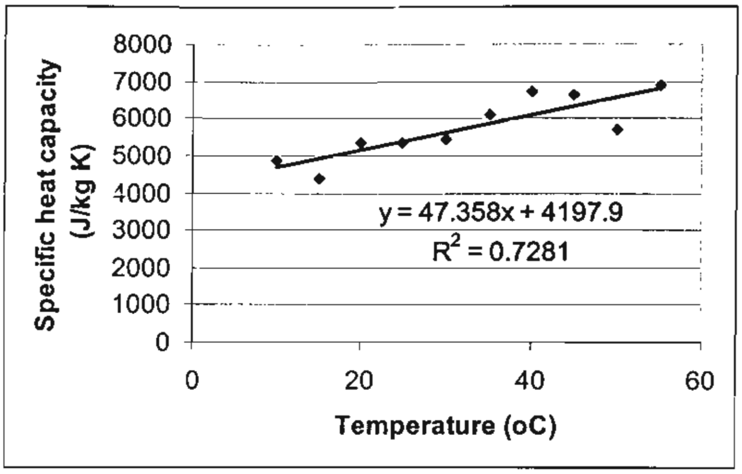


Figure 4 Specific heat capacity of the coconut milk solution

For the thermal conductivity of the coconut milk solution, there was currently no laboratory offering the measuring device in Thailand. However, the composition of the coconut milk (Table 4) have a similarity of the components as a whey protein concentrate (WPC) solution used in the fouling research of Schreier (1997). Comparison of the components in the coconut milk and the WPC solution is shown in Table 8. Therefore, the thermal conductivity data of the WPC solution will be taken as the data for the coconut milk at this stage, see Figure 5.

Table 8 Comparison of the components in the coconut milk and the WPC solution % (w/w)

Component	WPC solution	Coconut milk
Water	87.0	82.61
Fat and carbohydrate	9	6.966
Protein	3.06	2.99
Minerals	0.64	0.1561

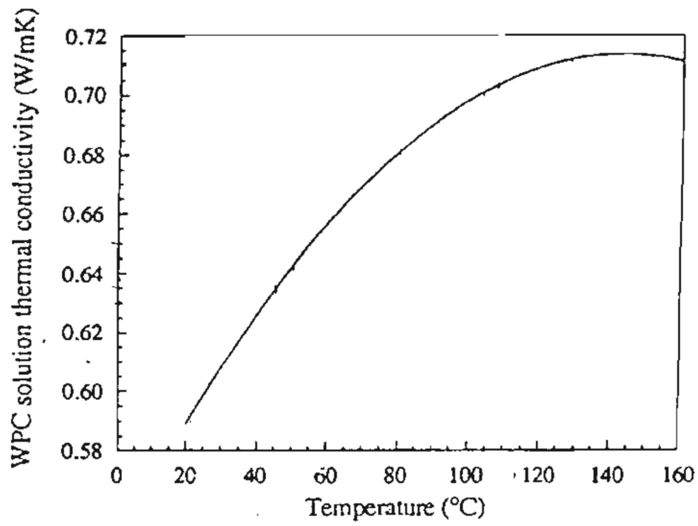


Figure 5 Thermal conductivity data of the WPC solution (Schreier, 1997)

2.5.4 Heating Fluid

The heating fluid in this work is hot water. Normally, the hot water is used to heat up the coconut milk in the practical pasteurization plants. Since the required temperature for pasteurization (up to 75 °C) is in the operating range of sensible heat transfer of liquid water. Acceptable driving force for indirect heating process can be obtained by using the hot water temperature up to its boiling temperature at specified operating pressure. Moreover, the hot water is considered safe in the aspect of contamination, and the cost is cheap compared with other heating fluid.

Physical and thermal properties of the hot water are also necessary for the design of experiments and thermal calculations. In this work, the property data of water were obtained from Handbook of Chemistry and Physics 64th Edition (1983-1984) as shown in Tables 9-12.

Table 9 Density of pure water at 0-100 °C

Temperature (°C)	Density (kg/m^3)	Temperature (°C)	Density (kg/m^3)
0	999.87	45	990.25
3.98	1000.00	50	988.07
5	999.99	55	985.73
10	999.73	60	983.24
15	999.13	65	980.59
18	998.62	70	977.81
20	998.23	75	974.89
25	997.07	80	971.83
30	995.67	85	968.65
35	994.06	90	965.34
38	992.99	95	961.92
40	992.24	100	958.38

Table 10 Viscosity of pure water at 0-100 °C

Temperature (°C)	Viscosity (kg/m s)	Temperature (°C)	Viscosity (kg/m s)
0	0.001787	55	0.0005040
5	0.001519	60	0.0004665
10	0.001307	65	0.0004335
15	0.001139	70	0.0004042
20	0.001002	75	0.0003781
25	0.0008904	80	0.0003547
30	0.0007975	85	0.0003337
35	0.0007194	90	0.0003147
40	0.0006529	95	0.0002975
45	0.0005960	100	0.0002818
50	0.0005468		

Table 11 Specific heat capacity of air-free water at 0-100 °C

Temperature (°C)	Specific heat capacity (J/kg K)	Temperature (°C)	Specific heat capacity (J/kg K)
0	4217.7	55	4182.4
5	4202.2	60	4184.4
10	4192.2	65	4186.8
15	4185.8	70	4189.6
20	4181.9	75	4192.8
25	4179.6	80	4196.4
30	4178.5	85	4200.5
35	4178.2	90	4205.1
40	4178.6	95	4210.3
45	4179.5	100	4216.0
50	4180.7		

Table 12 Thermal conductivity of water

Temperature (°C)	Thermal conductivity (W/m K)
6.85	0.574
16.85	0.592
26.85	0.609
36.85	0.623
46.85	0.637
56.85	0.648
66.85	0.659
76.85	0.668
86.85	0.675
96.85	0.680
106.85	0.684

CHAPTER 3
METHODOLOGY

3.1 Design of the Experimental Apparatus

3.1.1 Selected Type of the Apparatus

Normally, there are two possible ways to monitor fouling in an operating plant which are monitoring the overall behavior of plant or monitoring the local behavior of the plant. To place instrumentation on any part of or the whole plant is expensive and currently impossible in this work, since a case study plant is not in availability. The optimum way to monitor fouling in this situation is to set up the apparatus which can be used to closely represent the performance of the real plant.

To understand how variations in system parameters affect coconut milk fouling for the pasteurization process, a test section which composes of four flat stainless steel plates will be constructed. These plates form three channels for coconut milk flowing in the middle channels counter-current with two hot water channels. This configuration has similarity in the same manner of plate and frame heat exchangers used in pasteurization plants. The test section will be incorporated with extensive temperature, pressure and flowrate instrumentation, to allow pressure drops, heat transfer coefficients and deposit mass to be monitored in order to quantify deposit fouling. This type of the apparatus is so called a liquid-liquid device to measure fouling factor (Hewitt, 1992). The coconut milk will be heated by the hot water with a high mass rate to minimize its temperature change. The condition is in between constant heat flux and constant wall temperature. The device is suggested for a fouling study of complex geometries as PHEs. The diagram of the apparatus and the equipment check list are shown in Figure 6 and Table 13.

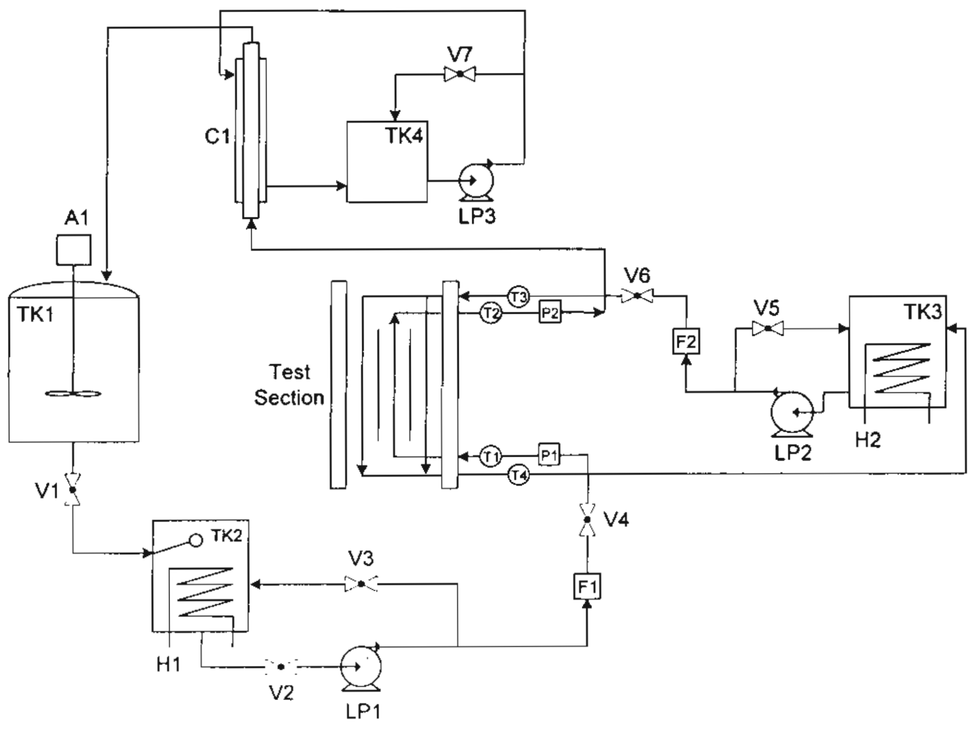


Figure 6 Diagram of the designed apparatus

Table 13 Equipment check list

Item No.	Code	Equipment	Functions
1	A1	Agitator	Low speed motor and turbine impeller for stirring coconut milk in the coconut milk storage tank.
2	C1	Cooler	Double-pipe heat exchanger for cooling coconut milk from the test section.
3	F1	Flowmeter	Flow meter for measuring coconut milk flowrate.
4	F2	Flowmeter	Flow meter for measuring hot water flowrate.
5	H1	Heater	Electric heater for preheating coconut milk.
6	H2	Heater	Electric heater for heating hot water.
7	LP1	Pump	Centrifugal pump for discharging coconut milk.
8	LP2	Pump	Centrifugal pump for discharging hot water.
9	LP3	Pump	Centrifugal pump for discharging cooling water.
10	P1	Pressure sensor and indicator	Analog pressure sensor for measuring inlet pressure of coconut milk.
11	P2	Pressure sensor and indicator	Analog pressure sensor for measuring outlet pressure of coconut milk.
12	T1	Temperature sensor and indicator	Thermocouple and digital temperature indicator for measuring inlet temperature of coconut milk.
13	T2	Temperature sensor and indicator	Thermocouple and digital temperature indicator for measuring outlet temperature of coconut milk.
Item No.	Code	Equipment	Functions
14	T3	Temperature sensor and indicator	Thermocouple and digital temperature indicator for measuring inlet temperature of hot water.
15	T4	Temperature sensor and indicator	Thermocouple and digital temperature indicator for measuring outlet temperature of hot water.
16	TK1	Tank	Storage tank of coconut milk.
17	TK2	Tank	Preheating tank of coconut milk.
18	TK3	Tank	Storage and heating tank of hot water.
19	TK4	Tank	Storage and cooling tank of cooling water.
20	V1	Valve	Grove valve for controlling coconut milk flowrate into coconut milk preheating tank.
21	V2	Valve	Grove valve for controlling coconut milk flowrate to be pumped.
22	V3	Valve	Grove valve for controlling coconut milk bypass.
23	V4	Valve	Grove valve for controlling coconut milk flowrate into test section.
24	V5	Valve	Grove valve for controlling hot water bypass.
25	V6	Valve	Grove valve for controlling hot water flowrate into test section.
26	V7	Valve	Grove valve for controlling cooling water bypass.
27	TS	Test section	Three-channel plate heat exchanger for heat exchanging between hot water and coconut milk.

3.1.2 Design Aspects of the Test Section

To obtain the design of the test section, the heat exchanger calculation must be performed. The objective of the calculation is to know how big the effective area of the exchanger must be in order to be able to transfer the required heat flux according to the indirect heat transfer formula;

$$\dot{Q} = U \cdot A \cdot \Delta T_{ln} \quad (1)$$

Before going to the calculation step by equation (1), the following factors have to be considered for the design of the test section.

- The apparatus has to produce rapid fouling so experiments could be conducted within eight hours, and a statistically significant number of experiments could be completed in the program schedule.

- It is important that experiments be conducted using equipment of a type recognizable by food industry, so that the counter-current flow configuration is selected for plate heat exchanger design.

- A lower limit on the scale of the apparatus will be chosen, but not too small so that results are irrelevant to industry. An upper limit can be obtained by the requirement that the flowrate has to be sufficiently small that it could be managed on a laboratory scale without unreasonable fluid inventories.

- The fluid velocities should be representative of real system. In the design stage, it is nearly impossible and not necessary to consider every detail when calculating a heat exchanger. Therefore, most mathematical models of this stage have simplifying assumptions as following;

1. The thermo-physical properties of the fluid are independent of temperature and pressure.
2. Heat transfer is assumed to take place only between the channels and not between the channel and the ports, or through the seals and gaskets.
3. The heat exchanger is assumed to be insulated from the surrounding.
4. The plates are considered to be thin enough to neglect any axial conduction within.
5. The area is considered to be flat and not corrugated. Since the fluid velocity in the corrugated channels is difficult to be approximated and it strongly depends upon the corrugated patterns which are used to promote the turbulent flow.

3.1.3 Design Procedure

In order to have a clear picture of the detail design of the test section, the calculation steps can be illustrated as follows;

1. The width of the plate (w) is chosen as 0.085 m as the first attempt. Since this size is considered in the range of the small plate heat exchangers used for food industries.
2. The usual length of a plate (L_{ch}) is about 2.5-5 times of the plate width (Haslego and Polley, 2002). In this case, the length of the plate is chosen as 3.5 times of the plate width, which is 0.3 m. The plate pack has a relatively long exchanger area but not the flowrate.
3. The usual thickness of the plate (a) is varied from 0.6 to 1 mm (Hewitt, 1992). In this work, the chosen thickness is 0.6 mm, since there is a commercialized stainless steel sheet (AISI 304) available at 0.6 mm thickness. The plates are considered to be thin enough to neglect any axial conduction.

4. The usual thickness of the plate flow gap (b) is varied from 1.5-5 mm (Hewitt, 1992). In order to have a reasonable coconut milk inventory, the chosen mean plate flow gap for the coconut milk channel is 2 mm. Although a narrow coconut milk channel is required but it should not too narrow due to the thermal expansion problem on the flat metal plates.
5. The thickness of the plate flow gap for the hot water channels is chosen as 16 mm. This value is considered large in comparison to the coconut milk flow gap, since the hot water will be used with a high mass rate to minimize its temperature change. To form the hot water channels, the commercialized cast nylon flat sheet with thickness of 16 mm will be used. This is necessary since the cast nylon sheet can act as an insulator to reduce heat losses from the hot channels to the surrounding.
6. The total heat transfer area of the test section (A_T) can be calculated namely;

$$A_T = 2 \cdot w \cdot L_{ch} = 2(0.085)(0.3) = 0.051 \ m^3 \qquad (2)$$

7. To testify the total heat transfer area calculated in step 6, a calculation program by Microsoft Excel was developed. The program has been used to solve a rating problem for obtaining the thermal performance of the test section. The details of the program are as follows;

   (1) *Required input data.* The required input data are stream operating conditions, stream thermal properties, stream physical properties and heat exchanger data as shown in Tables 14-17.

Table 14 Stream operating conditions

Conditions	Cold Stream (Coconut Milk, C)	Hot Stream (Water, W)
Inlet Temperature, T_{in} (°C)	70	95
Outlet Temperature, T_{out} (°C)	75	Calculated
Volumetric Flowrate, $\dot{V}$ (LPM)	10	Calculated

Table 15 Stream thermal properties

Thermal properties	Cold Stream (Coconut Milk, C)	Hot Stream (Water, W)
Specific Heat Capacity, C_p (J/kg K)	4190.0	4210.3
Thermal Conductivity, λ (W/m K)	0.67	0.68

Table 16 Stream physical properties

Physical properties	Cold Stream (Coconut Milk, C)	Hot Stream (Water, W)
Density, ρ (kg/m^3)	983.9	961.9
Viscosity, μ (kg/m s)	0.00115	0.00030

Table 17 Heat exchanger data

Heat Exchanger Data	Characteristics (Plate, P)
Plate Material	Stainless Steel (AISI 304)
Plate Width, w (m)	0.085
Plate Length, L_{ch} (m)	0.3
Plate Thickness, a (m)	0.0006
Cold Channel Gap, b_c (m)	0.002
Hot Channel Gap, b_w (m)	0.016
Thermal Conductivity, λ_p (W/m K)	16.2

(2) *Problem formulating.* The rating problem is formulated by using the input data shown in Tables 14-17. As seen in Table 14, the heating condition at the highest temperatures of coconut milk (70-75 °C) is set. The coconut milk flowrate of 10 LPM is chosen as the first attempt since it is in the mid-range of the available digital flow meter. The inlet temperature of the hot water is initially specified at 95 °C to minimize the use of the hot water. However, it is necessary also to minimize the temperature change of the hot water. In this work, it should not exceed 1 °C in order to keep the constant surface temperature of the hot side. To solve the problem, the indirect heat transfer formula, equation (1) and the energy balance between the coconut milk and the hot water will be complied to obtain the required flowrate and outlet temperature of the hot water.

(3) *Verification of convective heat transfer coefficients.* To calculate the overall heat transfer coefficient of the system (U), the convective heat transfer coefficients of the coconut side (α_c) and the water side (α_w) must be estimated. In order to run the program, the volumetric flowrate of the hot water can be initially assumed within the range of the available rotameter (15-155 LPM). The details of the calculation are as follows:

- Calculate channel velocity (u) from the volumetric flowrate per channel ($\dot{V}$) and the cross sectional area of the channel (S_{cross}).

$$u = \frac{\dot{V}}{S_{cross}} \tag{3}$$

- Calculate channel hydraulic diameter (d_h) from the cross sectional area of the channel (S_{cross}) and the wetted perimeter of the channel (P_{wetted}).

$$d_h = \frac{4 \cdot S_{cross}}{P_{wetted}} \tag{4}$$

- Calculate Reynolds number (Re) and Prandtl number (Pr).

$$Re = \frac{\rho \cdot u \cdot d_h}{\mu} \tag{5}$$

$$Pr = \frac{C_p \cdot \mu}{\lambda} \tag{6}$$

- Calculate the film heat transfer coefficient of the coconut side (α_c) and the water side (α_w) from the correlation of a flat straight passage (Clark, 1974).

$$Nu = \frac{\alpha \cdot d_h}{\lambda} = 0.036 \cdot Re^{0.8} \cdot Pr^{0.33} \cdot \left(\frac{d_h}{L_{ch}}\right)^{0.054} \tag{7}$$

The correlation can be used in the case of turbulent flow where the channel velocity varies from 0.1 to 3 m/s.

(4) Problem solving. The overall heat transfer coefficient of the system (U) can be calculated from the film heat transfer coefficients of the coconut milk and the hot water sides, namely:

$$\frac{1}{U} = \frac{1}{\alpha_C} + \frac{a}{\lambda_P} + \frac{1}{\alpha_W} \tag{8}$$

If the heat loss to surrounding is insignificant, the heat balance of the system can account only the convective heat transfer from the hot water to the coconut milk.

$$\dot{Q}_W = \dot{Q}_C \tag{9}$$

$$-(\dot{m} \cdot C_p \cdot \Delta T)_W = (\dot{m} \cdot C_p \cdot \Delta T)_C \tag{10}$$

To obtain a pair of the required flowrate and the outlet temperature of the hot water, equation (10) can be solved simultaneously with equation (11), which is a governing equation for indirect counter-current heat transfer.

$$\dot{Q}_{CC} = U \cdot A_T \cdot \Delta T_{ln} \tag{11}$$

where

$$\Delta T_{ln} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \tag{12}$$

$$\Delta T_1 = T_{W,out} - T_{C,in} \tag{13}$$

$$\Delta T_2 = T_{W,in} - T_{C,out} \tag{14}$$

To solve the problem, the Microsoft Excel Solver has been used in this case. The solution which is a combination of the required flowrate and the outlet temperature of the hot water, must be satisfied by equations (10) and (11).

8. The Microsoft Excel program in step 7 was used to solve for the solution of the rating problem illustrated as in Tables 14-17. The results of the calculation are shown in Tables 18, 19 and 20.

Table 18 Verification of convective heat transfer coefficients

Parameters	Coconut Milk, C	Water, W
Volumetric flowrate per channel, $\dot{V}$ (m^3/s)	0.00017	0.00118
Cross sectional area of the channel, S_{cross} (m^2)	0.00017	0.00136
Channel velocity, u (m/s)	0.9804	0.8640
Wetted perimeter of the channel, P_{wetted} (m)	0.174	0.202
Channel hydraulic diameter, d_h (m)	0.0039	0.0269
Reynolds number, Re	3278.0	75232.7
Prandtl number, Pr	7.19	1.84
d_h /L_{ch}	0.0130	0.0898
Nusselt number, Nu	35.46	307.92
Film heat transfer coefficient, α (W/m^2 K)	6079.5	7775.1

Table 19 Calculation of heat exchanger performance

Heat duty required, $\dot{Q}_C$ (W)	3435.5
Outlet temperature of water, $T_{W,out}$ (°C)	94.6
Overall heat transfer coefficient, U (W/m^2 K)	3029.0
Total heat transfer area, A_T (m^2)	0.051
Log mean temperature difference, ΔT_{ln} (°C)	22.2
Indirect counter-current heat duty, $\dot{Q}_{CC}$ (W)	3435.5

Table 20 Stream operating conditions

Conditions	Cold Stream (Coconut Milk, C)	Hot Stream (Water, W)
Inlet Temperature, T_{in} (°C)	70	95
Outlet Temperature, T_{out} (°C)	75	94.6
Volumetric Flowrate, $\dot{V}$ (LPM)	10.0	141.0

The results of the calculations in step 8 have shown that the channel velocities of the hot and cold sides of the test section are in the range of turbulent flow where the channel velocity varies from 0.1 to 3 m/s. The temperature change of the hot water side is less than 1 °C which is considered acceptable. Therefore, the proposed dimensions of the test section will be used as the specifications for the detailed design of the experimental apparatus.

3.1.4 Detailed Design

From the information obtained in the design procedure, the detailed design of the test section can be summarized in Table 21.

Table 21 Detailed design of the test section

Plate Material	Stainless steel (AISI 304)
Plate Thermal Conductivity, λ_p (W/m K)	16.2
End Plate Material	Cast Nylon
End Plate Thermal Conductivity, λ_{ep} (W/m K)	0.3
Plate Width, w (m)	0.085
Plate Length, L_{ch} (m)	0.3
Plate Thickness, a (m)	0.0006
Coconut Channel Gap, b_c (m)	0.002
Hot Water Channel Gap, b_w (m)	0.016
Total Heat Transfer Area, A_T (m^2)	0.051
Internal Flow Arrangement	U-flow / Counter current

Plate arrangement within the test section is shown in Figure 7. The individual plate drawings are illustrated in Figures 8-16 respectively.

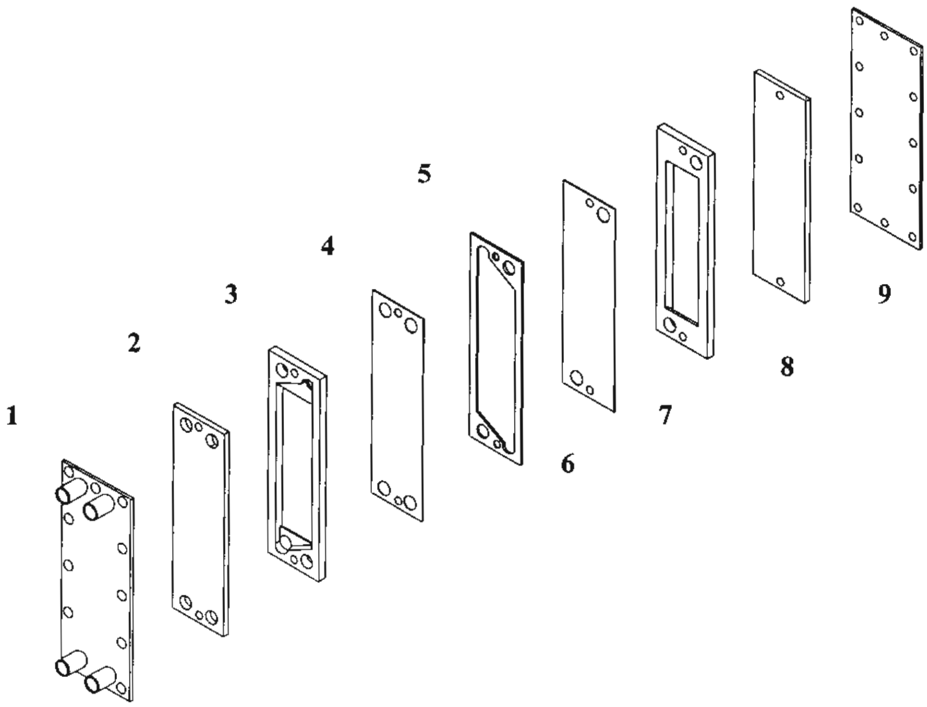


Figure 7 Plate arrangement within the test section (Plate No. 1-9)

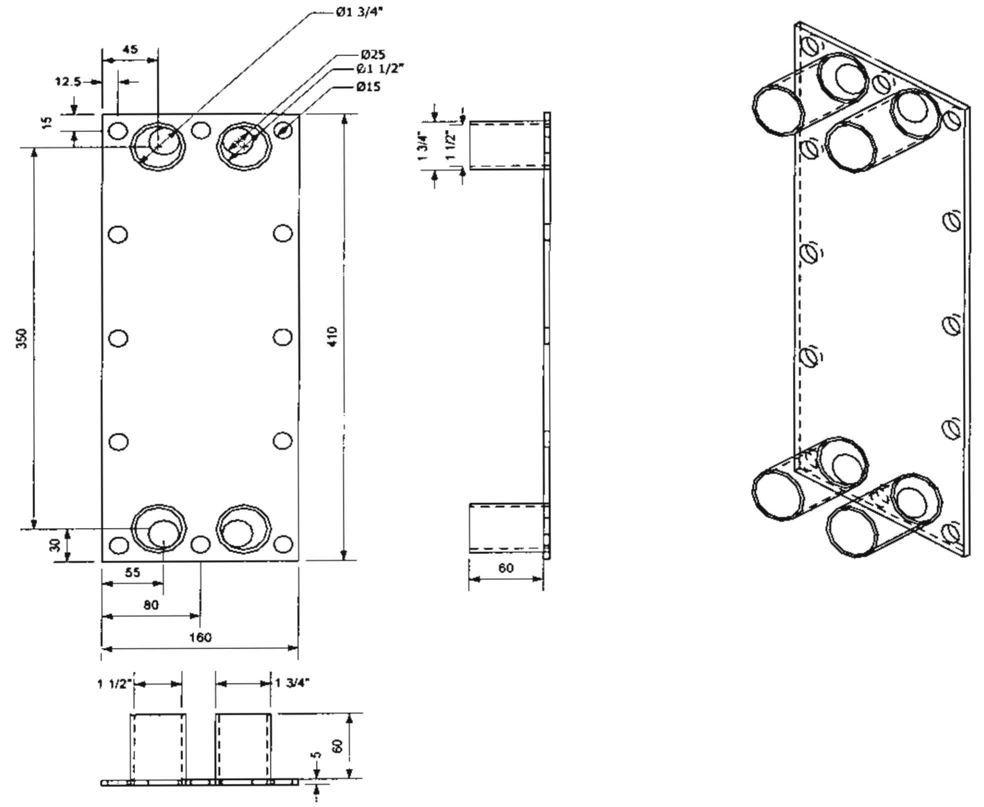


Figure 8 Drawing of Plate No. 1

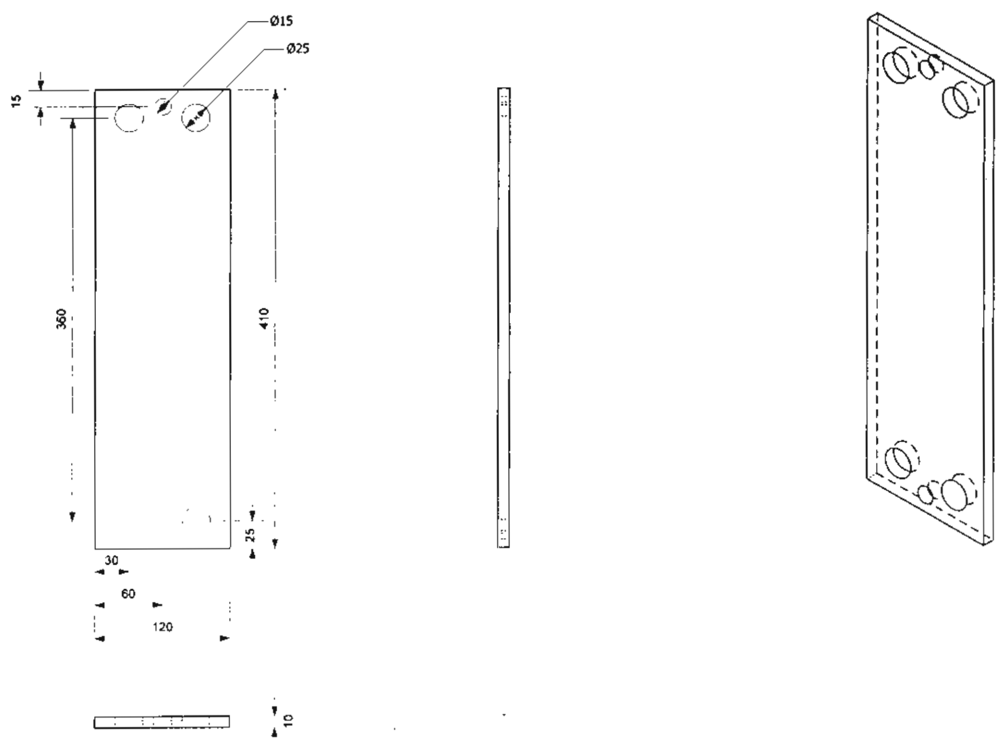


Figure 9 Drawing of Plate No. 2

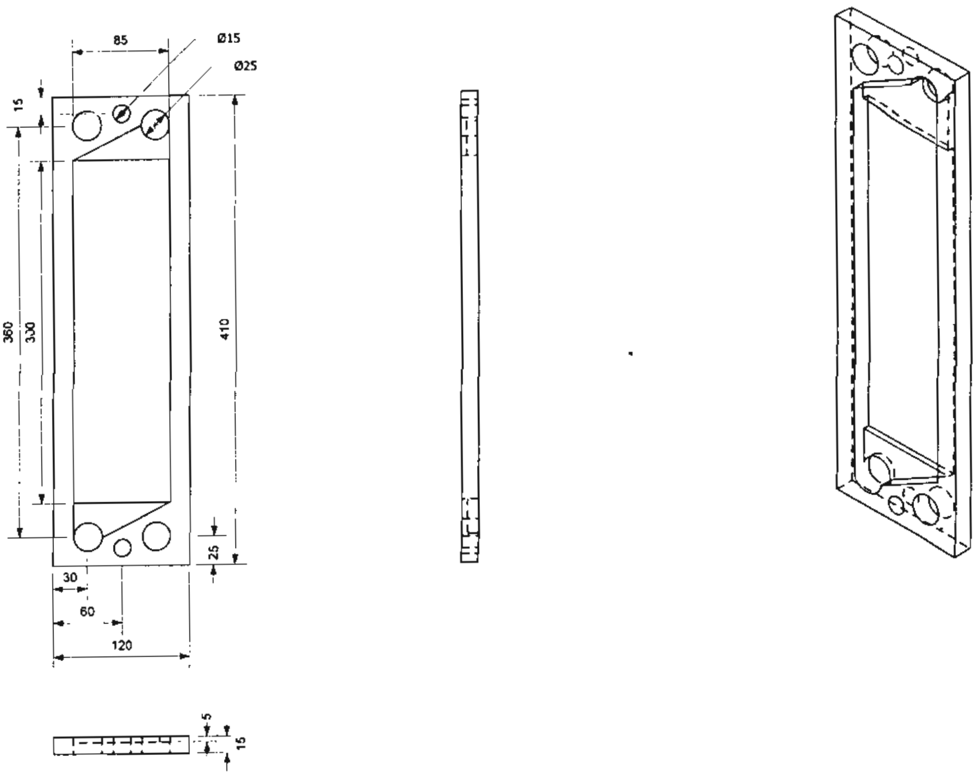


Figure 10 Drawing of Plate No. 3

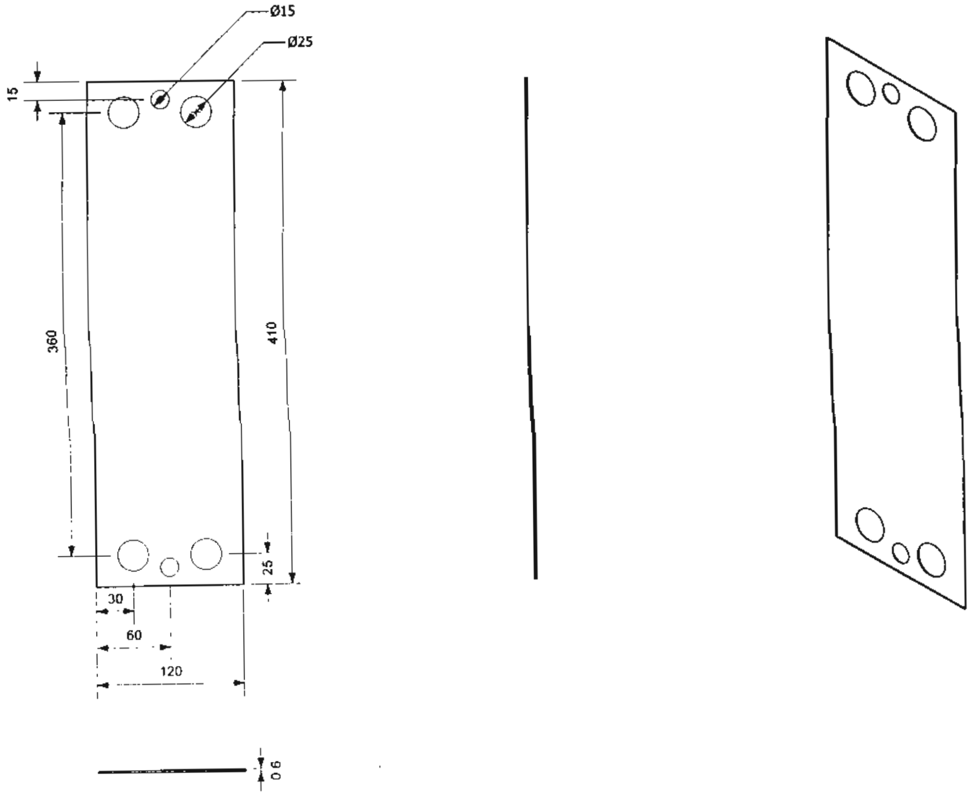


Figure 11 Drawing of Plate No. 4

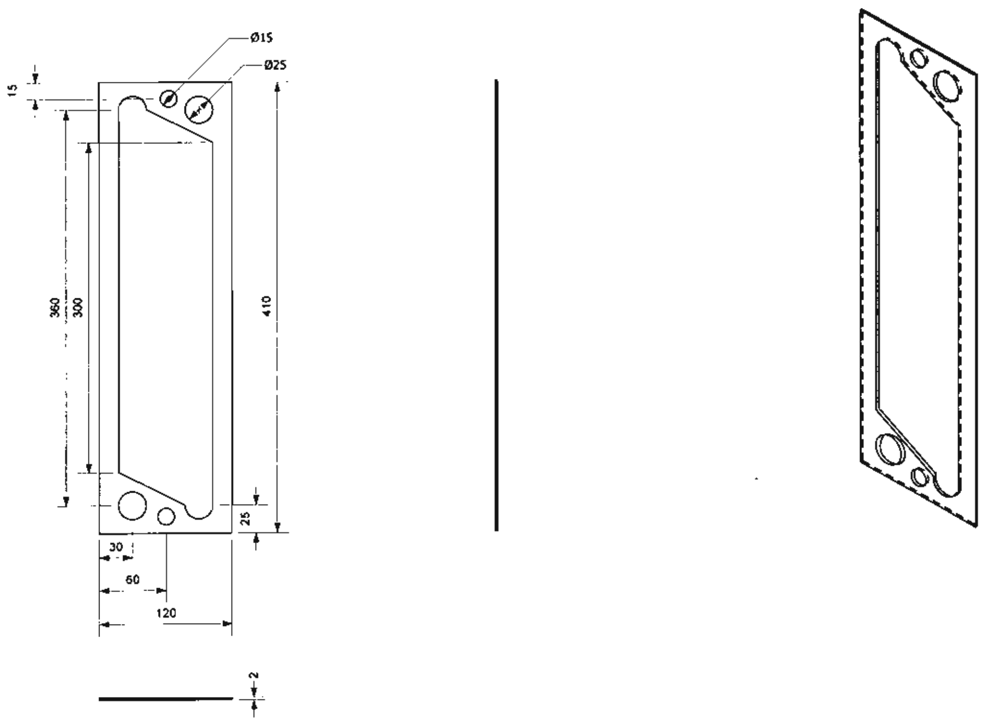


Figure 12 Drawing of Plate No. 5

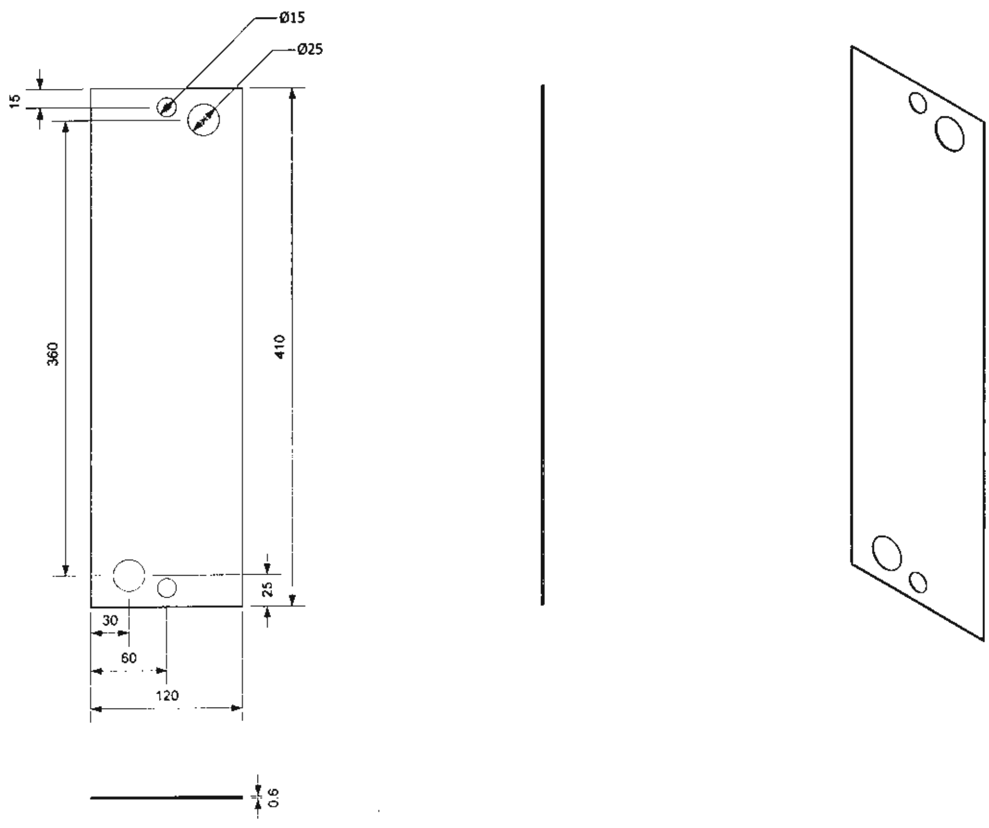


Figure 13 Drawing of Plate No. 6

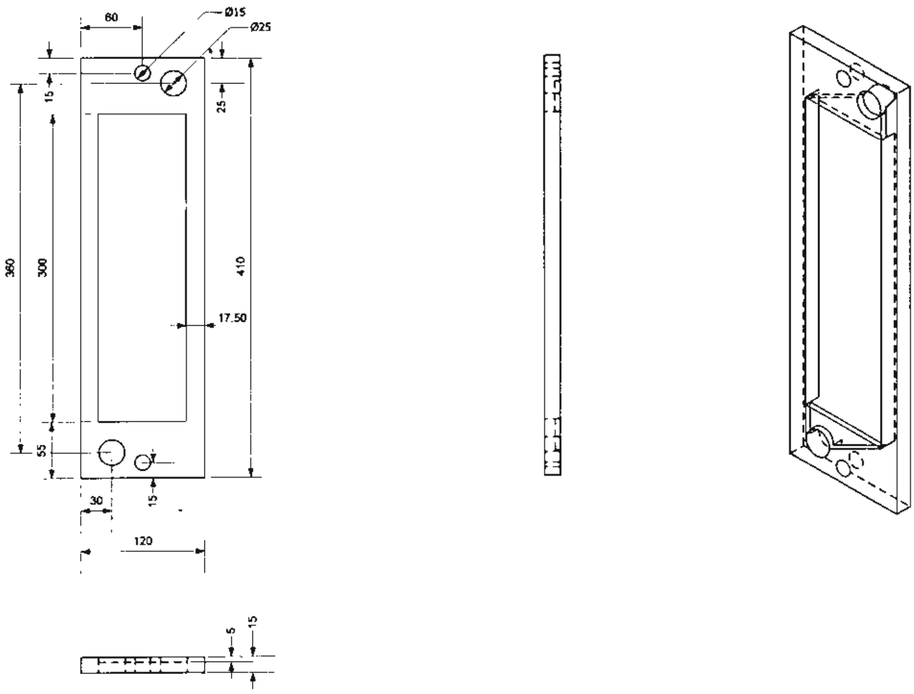


Figure 14 Drawing of Plate No. 7

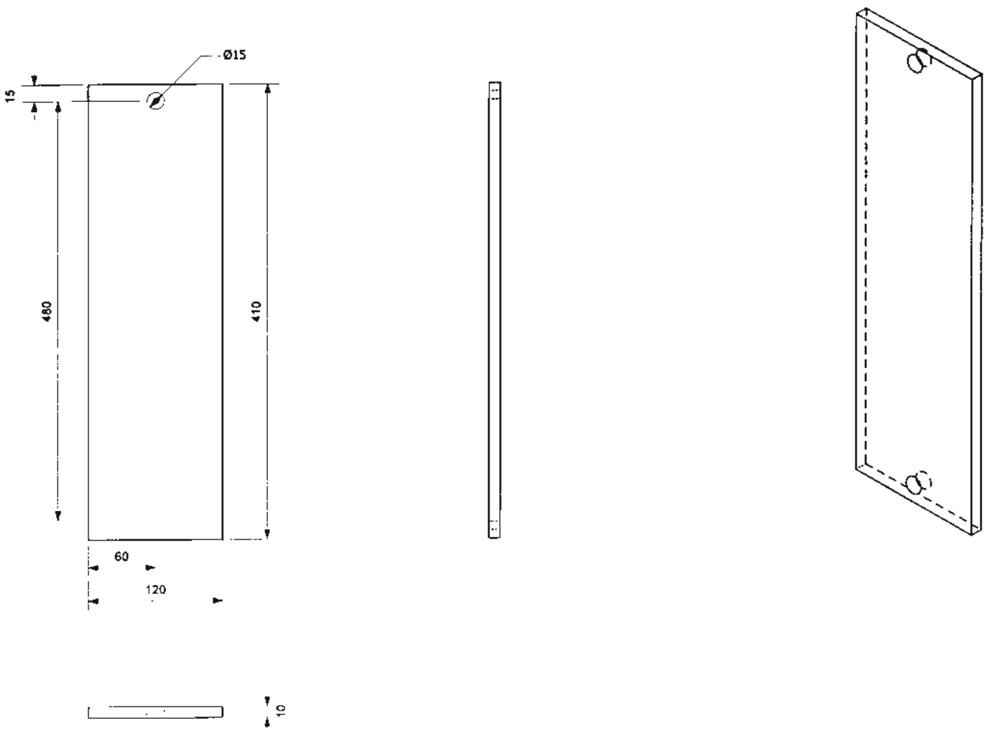


Figure 15 Drawing of Plate No. 8

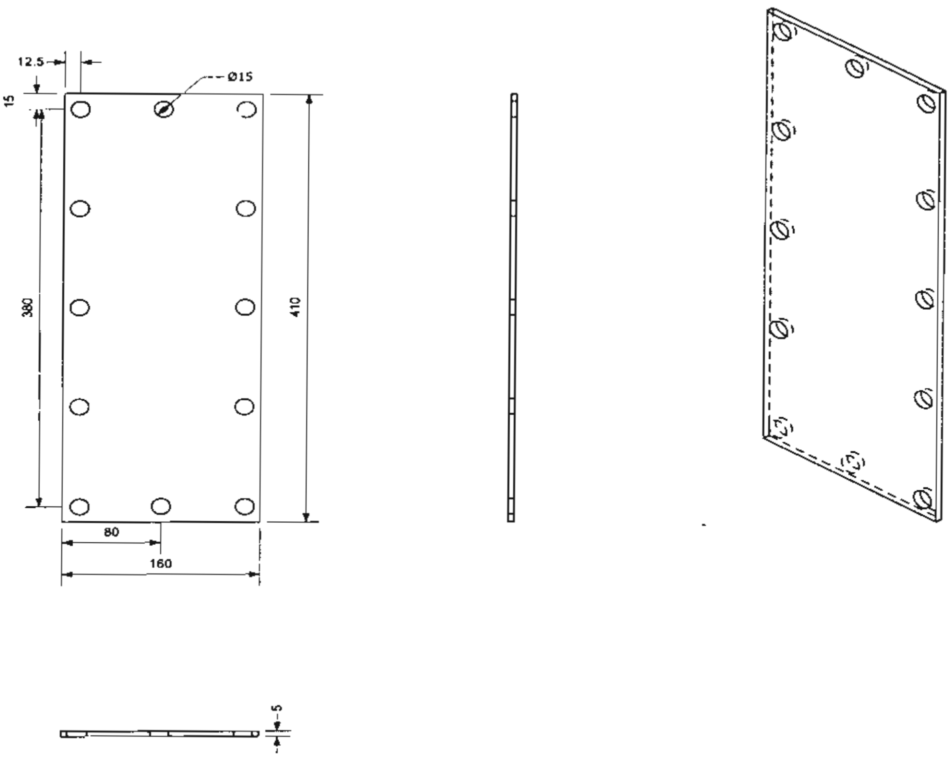


Figure 16 Drawing of Plate No. 9

3.2 Construction of the Apparatus

3.2.1 <u>Specifications of the Equipment</u>

According to the diagram of the designed apparatus in Figure 6, the other parts of the apparatus are listed and specified for their specifications, which are tabulated in Table 22.

Table 22 Specifications of the other equipment

Item No.	Code	Equipment	Specifications
1	A1	Agitator	- Low speed motor 1200/1500 rpm - Turbine impeller diameter 0.3 m, impeller height from the tank bottom 0.26 m, length from motor to impeller 0.7 m, and made with Stainless Steel
2	C1	Cooler	- Double-pipe heat exchanger - Shell inside diameter 1.75 in, shell length 4 m, and made with PVC
3	F1	Flowmeter	- Rotameter - Measure in the range from 0 to 11 LPM - Operating temp. ≤ 90 °C
4	F2	Flowmeter	- Rotameter - Measure in the range from 15 to 155 LPM - Operating temp. ≤ 100 °C
5	H1	Heater	- Electric heater with controller - Maximum controlled temperature at 70 °C - Electrical power 2500 W
6	H2	Heater	- Electric heater with controller - Maximum controlled temperature at 95 °C - Electrical power 2500 W
7	LP1	Pump	- Centrifugal pump made with cast iron

			- Maximum flowrate 110 LPM at pressure 5.3 barg - Discharge pipe diameter 1 in - Operating temp. ≤ 80 °C
8	LP2	Pump	- Centrifugal pump made with stainless steel - Maximum flowrate 250 LPM at pressure2.25 barg - Discharge pipe diameter 1 in - Operating temp. ≤ 100 °C
9	LP3	Pump	- Centrifugal pump made with cast iron - Maximum flowrate 35 LPM at pressure 3.4 barg - Discharge pipe diameter 1 in - Operating temp. ≤ 60 °C
10	P1	Pressure sensor and indicator	- Analog pressure sensor - Measured pressure 1-7 barg
11	P2	Pressure sensor and indicator	- Analog pressure sensor - Measured pressure 1-7 barg

Item No.	Code	Equipment	Specifications
12	T1	Temperature sensor and indicator	- Sensor by thermocouple type PT100 - Measured temperature 0-100 °C at ± 0.1 °C - Digital temperature indicator
13	T2	Temperature sensor and indicator	- Sensor by thermocouple type PT100 - Measured temperature 0-100 °C at ± 0.1 °C - Digital temperature indicator
14	T3	Temperature sensor and indicator	- Sensor by thermocouple type PT100 - Measured temperature 0-100 °C at ± 0.1 °C - Digital temperature indicator
15	T4	Temperature sensor and indicator	- Sensor by thermocouple type PT100 - Measured temperature 0-100 °C at ± 0.1 °C - Digital temperature indicator
16	TK1	Tank	- Cylindrical tank made from plastic with removable lid - Diameter 0.55 m and height 0.855 m - Four baffles at tank wall
17	TK2	Tank	- Cylindrical tank made from stainless sheet with removable lid - Diameter 0.3 m and height 0.425 m - Insulation on with thickness 0.05 m
18	TK3	Tank	- Cylindrical tank made from stainless sheet with removable lid - Diameter 0.3 m and height 0.425 m - Insulation on with thickness 0.05 m
19	TK4	Tank	- Square tank made from foam with removable lid - Width 0.5 m,length 0.4 m, and height 0.425 m
20	V1	Valve	- Grove valve - Inside diameter 1.5 in
21	V2	Valve	- Grove valve - Inside diameter 1.5 in

22	V3	Valve	- Grove valve - Inside diameter 1 in
23	V4	Valve	- Grove valve - Inside diameter 0.5 in
24	V5	Valve	- Grove valve - Inside diameter 1 in
25	V6	Valve	- Grove valve - Inside diameter 1 in
26	V7	Valve	- Grove valve - Inside diameter 1 in
27	TS	Test section	- Three channel plate heat exchanger made with stainless steel 304 and cast nylon - Rubber gasket with 2 and 3 mm. thickness - Single-pass counter current flow configuration - Connecting pipe size (ID) 1.5 in - Dimension see plate drawing

3.2.2 Fabrication of the Apparatus

The test section and the other parts of the apparatus were assembled together according to the designed piping and instrumentation diagram (Figure 6). The fabricated rig is illustrated by Figures 17-21.

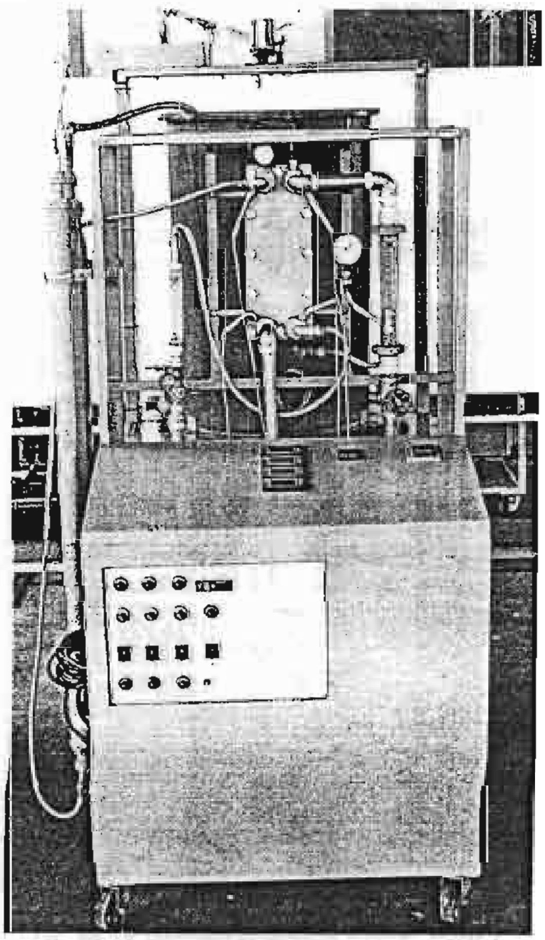


Figure 17 Photograph of the apparatus (Front view)

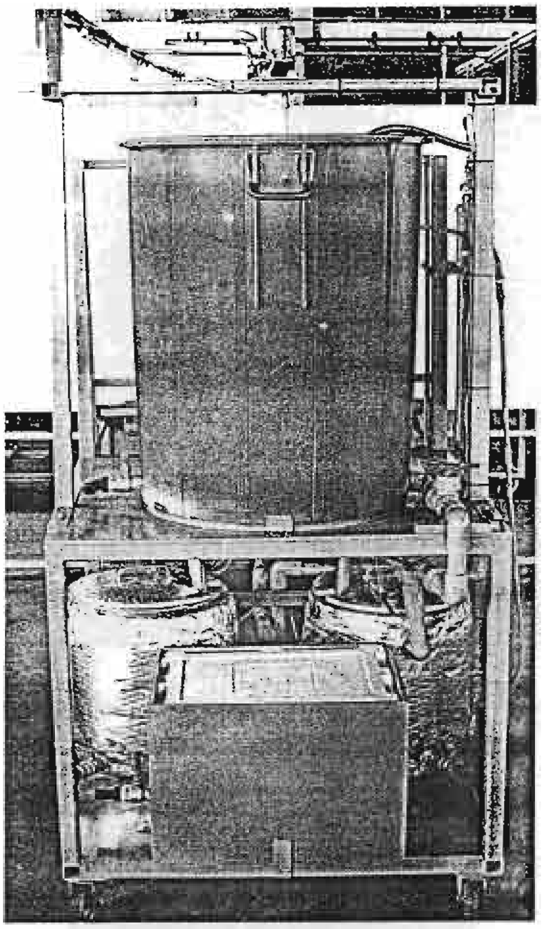


Figure 18 Photograph of the apparatus (Back view)

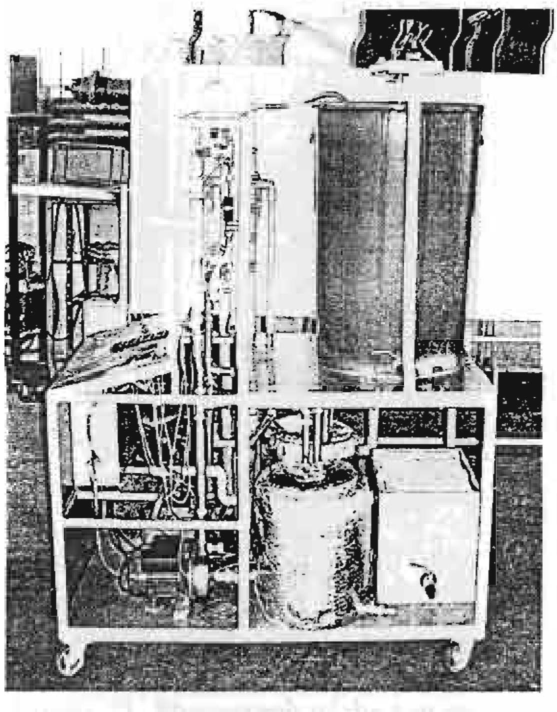


Figure 19 Photograph of the apparatus (Side view)

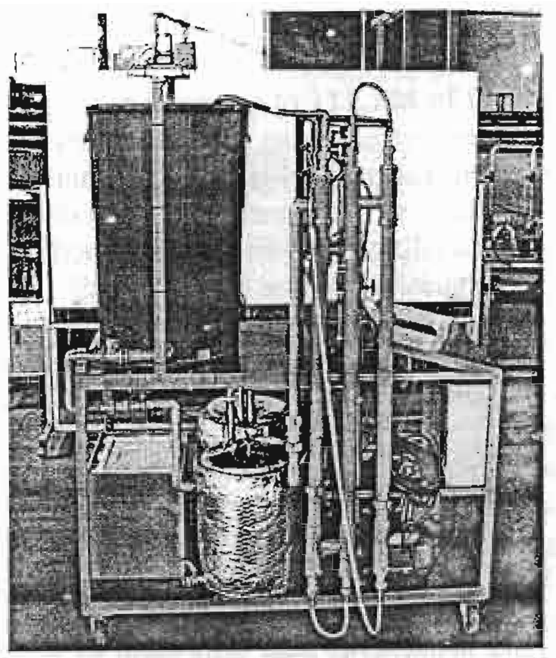


Figure 20 Photograph of the apparatus (Side view)

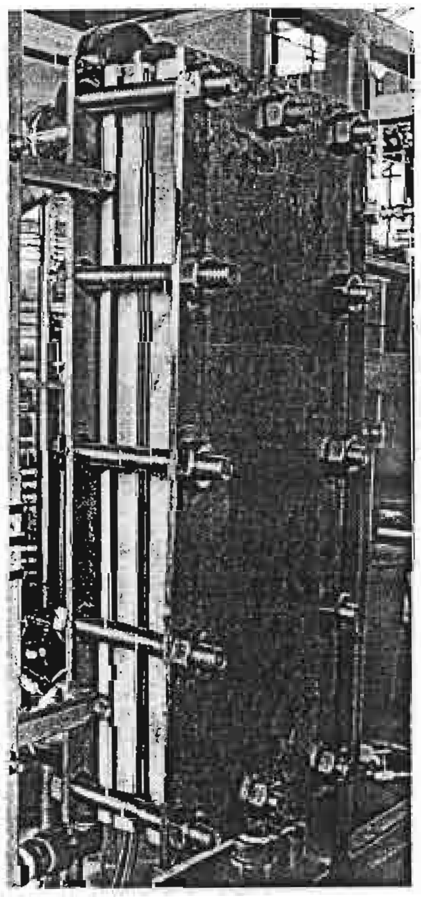


Figure 21 Photograph of the test section

3.2.3 Apparatus Description

The apparatus was designed to use up to 11 LPM of fouling fluid, i.e. coconut milk, heating the product to temperature within the pasteurization range. The test section is a plate heat exchanger with three channels in counter-current flow arrangement. The coconut milk channel is in the middle of two hot water channels. The total heat transfer area is 0.051 m^2. The heat input to the test section is provided by a water heater, which can deliver hot water at up to 95 °C and 155 LPM. Excess heat is removed through a closed circuit cooling water system, linked to a cooling chamber.

To measure fouling, the apparatus incorporated extensive instrumentation to allow temperature, pressure and flowrate to be measured and recorded throughout the experiments. Calibrated rotameters were provided in both the coconut milk and hot water circuits to measure fluid flowrate. Platinum resistance thermometers were placed as probes in the pipe work connecting inlet and outlet positions of the test section. Incorporated pressure gauges allowed the measurement of the effects of fouling on pressure drop in the coconut milk side. At present time, all data readings will have to be recorded by hand every one minute. Manipulation of this data can be done after each experiment via spreadsheet and graphical program, in which a heat balance and fouling rate analysis can be performed.

All temperature data are displayed by built-in liquid crystal indicators which can display all outputs in real time. The data can be used to calculate heat flows in the test section using the physical and thermal property data for coconut milk and water given in section B. Heat balance of the test section can be estimated by the heat flows of the hot and cold sides of the test section. By neglecting the heat losses, the heat balance of the test section is namely;

$$\left(\dot{m} \cdot C_p \cdot \Delta T\right)_C = -\left(\dot{m} \cdot C_p \cdot \Delta T\right)_W \tag{15}$$

Although C_p is a function of the temperature, it is not constant within each plate channel. The assumption has been made so that the specific heat capacities of two fluids are linear in temperature over the temperature ranges in the channels. Therefore, the linear average of C_p is used in the calculation of equation (15).

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Measurement Accuracy

The details of all the measurement equipment on their accuracy are described as follows:

A. Temperature sensor inaccuracy. The resistance temperature detector type Pt100 with digital temperature indicators, were specified tolerance of ±0.1 °C.

B. Flowrate errors. The coconut milk flowmeter, a rotameter calibrated with water, has the accuracy of ±5% of FSD. Extensive commissioning tests were made in order to calibrate the rotameter for coconut milk. The test method was to measure a flowrate by pumping heated coconut milk with a specified volume and collecting a time. Repeated runs were made for a whole range of operating temperatures. The results have been presented between the read flowrate and the actual flowrate as in Figures 22.

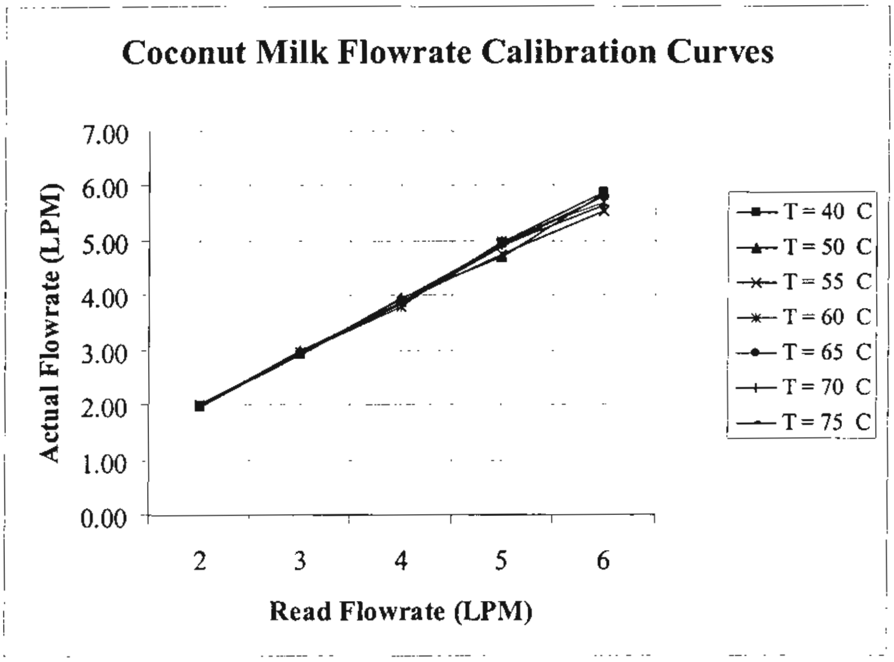


Figure 22 Coconut milk flowrate calibration curves

The calibration data between read flowrate and actual flowrate of coconut milk from Figure 22 gives a good straight line fit with a regression coefficient approaching to 1, namely:

For T = 40 °C	$y = 0.983x + 0.973$	$R^2 = 0.9992$	(16)
For T = 50 °C	$y = 0.954x + 1.024$	$R^2 = 0.9972$	(17)
For T = 55 °C	$y = 0.887x + 1.167$	$R^2 = 0.9986$	(18)
For T = 60 °C	$y = 0.947x + 1.039$	$R^2 = 0.9955$	(19)
For T = 65 °C	$y = 0.962x + 1.034$	$R^2 = 0.9992$	(20)
For T = 70 °C	$y = 0.924x + 1.102$	$R^2 = 0.9969$	(21)
For T = 75 °C	$y = 0.966x + 0.992$	$R^2 = 0.9995$	(22)

Where y : The actual flowrate of coconut milk, LPM
x : The read flowrate of coconut milk, LPM

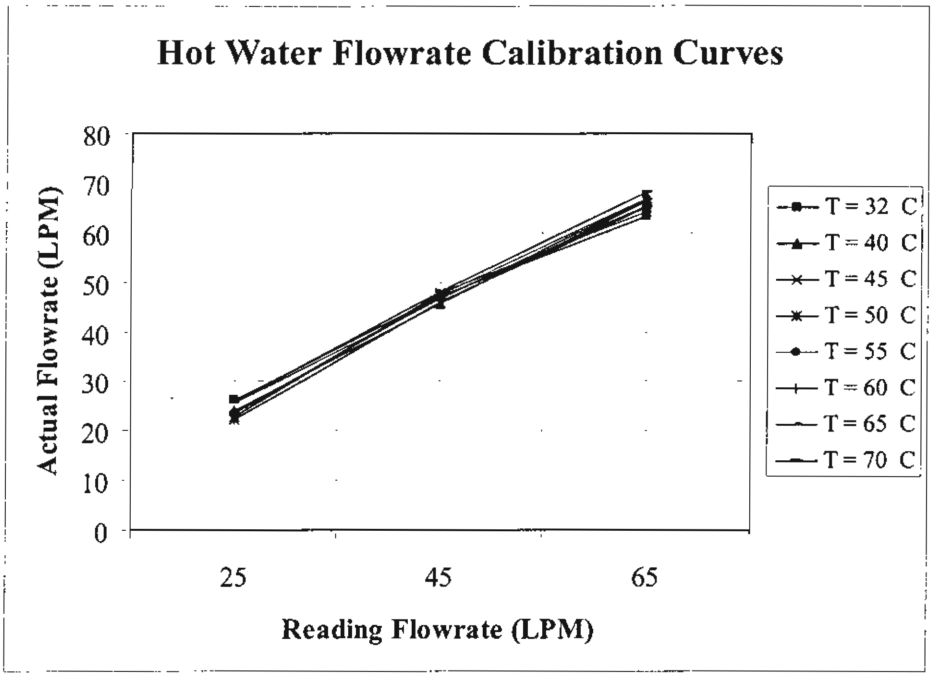


Figure 23 Hot water flowrate calibration curves

The calibration data between read flowrate and actual flowrate of hot water from Figure 23 gives a good straight line fit with a regression coefficient approaching to 1, namely:

For T = 32 °C	$y = 18.61x + 8.3067$	$R^2 = 0.9945$	(23)
For T = 40 °C	$y = 21.14x + 2.96$	$R^2 = 0.9997$	(24)
For T = 45 °C	$y = 20.675x + 3.65$	$R^2 = 0.9967$	(25)
For T = 50 °C	$y = 21.345x + 1.7367$	$R^2 = 0.9959$	(26)
For T = 55 °C	$y = 21.84x + 2.2133$	$R^2 = 0.9963$	(27)
For T = 60 °C	$y = 20.865x + 3.6367$	$R^2 = 0.9963$	(28)
For T = 65 °C	$y = 20.41x + 5.4$	$R^2 = 0.9999$	(29)
For T = 70 °C	$y = 21.105x + 5.19$	$R^2 = 0.9991$	(30)

Where y : The actual flowrate of hot water, LPM
x : The read flowrate of hot water, LPM

The hot water flowmeter, a rotameter calibrated with water, has the accuracy of ±3% of FSD.

C. Effect of temperature and flowrate inaccuracies on the overall heat transfer coefficient, U. The expected errors in U resulting from inaccuracies of coconut milk flowrate, hot water flowrate, and temperature measurements can be calculated by exploiting the combination of errors.

The clean overall heat transfer coefficient of the test section was derived as follow:

$$U = \frac{\dot{Q}_C}{A_T \cdot \Delta T_{ln}} \tag{31}$$

where

$$\dot{Q}_C = (\dot{m} \cdot C_p \cdot \Delta T)_C \tag{32}$$

$$\Delta T_{ln} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \tag{33}$$

$$\Delta T_1 = T_{W,out} - T_{C,in} \tag{34}$$

$$\Delta T_2 = T_{W,in} - T_{C,out} \tag{35}$$

$$\Delta T_C = T_{C,out} - T_{C,in} \tag{36}$$

Equation (31) can be written in terms of the independent variables of which U is a function:

$$U = \frac{\dot{m}_C \cdot C_{pC} \cdot \Delta T_C \cdot \ln \frac{\Delta T_1}{\Delta T_2}}{A_T \cdot (\Delta T_1 - \Delta T_2)} = f\ (\dot{m}_C, T_{C,in}, T_{C,out}, T_{W,in}, T_{W,out}) \tag{37}$$

In this work, the operator ε is used to express the error. The error in U, εU, can be related to the measurement errors in $\dot{m}_C, T_{C,in}, T_{C,out}, T_{W,in}, \text{and}\, T_{W,out}$ as follows:

$$(\varepsilon U)^2 = \left(\frac{\partial f}{\partial \dot{m}_C} \varepsilon \dot{m}_C\right)^2 + \left(\frac{\partial f}{\partial T_{C,in}} \varepsilon T_{C,in}\right)^2 + \left(\frac{\partial f}{\partial T_{C,out}} \varepsilon T_{C,out}\right)^2 + \left(\frac{\partial f}{\partial T_{W,in}} \varepsilon T_{W,in}\right)^2 + \left(\frac{\partial f}{\partial T_{W,out}} \varepsilon T_{W,out}\right)^2 \tag{38}$$

By manipulation of equation (37), the following equations can be obtained.

$$\frac{\partial f}{\partial \dot{m}_C} = \frac{C_{pC} \cdot \Delta T_C \cdot \ln \frac{\Delta T_1}{\Delta T_2}}{A_T \cdot (\Delta T_1 - \Delta T_2)} \tag{39}$$

and

$$\frac{\partial f}{\partial T_{C,in}} = \frac{\dot{m}_C \cdot C_{pC}}{A_T} \left[\frac{-(\Delta T_1 - \Delta T_2)\left(\frac{\Delta T_C}{\Delta T_1} + \ln \frac{\Delta T_1}{\Delta T_2}\right) + \Delta T_C \cdot \ln \frac{\Delta T_1}{\Delta T_2}}{(\Delta T_1 - \Delta T_2)^2} \right] \tag{40}$$

$$\frac{\partial f}{\partial T_{C,out}} = \frac{\dot{m}_C \cdot C_{pC}}{A_T}\left[\frac{(\Delta T_1 - \Delta T_2)\left(\frac{\Delta T_C}{\Delta T_2} + \ln\frac{\Delta T_1}{\Delta T_2}\right) - \Delta T_C \cdot \ln\frac{\Delta T_1}{\Delta T_2}}{(\Delta T_1 - \Delta T_2)^2}\right] \quad (41)$$

$$\frac{\partial f}{\partial T_{W,in}} = \frac{\dot{m}_C \cdot C_{pC}}{A_T}\left[\frac{(\Delta T_1 - \Delta T_2)\left(-\frac{\Delta T_C}{\Delta T_2}\right) + \Delta T_C \cdot \ln\frac{\Delta T_1}{\Delta T_2}}{(\Delta T_1 - \Delta T_2)^2}\right] \quad (42)$$

$$\frac{\partial f}{\partial T_{W,out}} = \frac{\dot{m}_C \cdot C_{pC}}{A_T}\left[\frac{(\Delta T_1 - \Delta T_2)\left(\frac{\Delta T_C}{\Delta T_1}\right) - \Delta T_C \cdot \ln\frac{\Delta T_1}{\Delta T_2}}{(\Delta T_1 - \Delta T_2)^2}\right] \quad (43)$$

D. Pressure measurement errors. Inlet and outlet pressures of the coconut milk channel were measured by Bourdon type pressure gauges with accuracy of ±1% FSD.

4.2 Design of the Experimental Program

4.2.1 Initial Experiments: Thermal Characterization

To test accuracy and repeatability of the operation, a series of initial experiments were conducted using a heat transfer between hot and cold water, see Table 23 Experimental design for thermal characterization.

Table 23 Experimental design for thermal characterization

Experiment number	$T_{c,in}$ (°C)	$T_{c,out}$ (°C)	F_c (LPM)	$T_{h,in}$ (°C)	$T_{h,out}$ (°C)	F_h (LPM)
1	40	45	2	59	58.5	20.7
2	50	55	2	68	67.5	22.3
3	60	65	2	77	76.5	22.2
4	70	75	2	86	85.6	22.7
5	40	45	4	59	58.7	59.6
6	50	55	4	68	67.7	64.4
7	60	65	4	77	76.7	64.2
8	70	75	4	86	85.7	66.0
9	40	45	6	59	58.7	117.9
10	50	55	6	68	67.7	127.7
11	60	65	6	77	76.8	127.9
12	70	75	6	86	85.8	132.5

Listed conditions for the experiments in Table 23 were obtained from the simulation program by specifying the inlet and outlet temperatures and flowrate of the cold side. The constraints of the simulations were considered namely, the difference of the inlet and outlet temperatures of the hot side was not more than 1 °C, and the flowrate of the hot side was in the readable range of the measuring device, 15-155 LPM.

In the real operations, the conditions for the cold side had been kept as the simulated conditions in Table 23. Also, the inlet temperatures of the hot side were specified as seen in the same table. The only degree of freedom for the experiments was the hot water flowrate, in which it had been adjusted to obtain the specified cold conditions for each experimental run. The overall heat transfer coefficient and the heat balance were calculated for each run. The values of the heat balance and the overall heat transfer coefficient in each run are shown in Tables 24 and 25 respectively. Calculations are given in Appendix B.

Table 24 The heat balance of the experiments for thermal characterization

Experiment number	$T_{h,in}$ (°C)	$T_{h,out}$ (°C)	F_h (LPM)	$\dot{Q}_h$ (W)	$\dot{Q}_c$ (W)	Heat Balance (%)
1	59	58.2	17.5	960.8	694.1	72
2	68	67.2	16.0	874.9	692.7	79
3	77	76.2	16.5	898.6	690.5	76
4	86	85.1	15.0	915.3	687.6	75
5	59	58.6	55.0	1,509.3	1,388.3	91
6	68	67.7	60.0	1,230.1	1,385.5	112
7	77	76.7	65.0	1,327.4	1,380.9	103
8	86	85.6	58.0	1,572.6	1,375.2	87
9	60	59.8	107.5	1,474.4	2,082.4	140
10	69	68.8	110.0	1,502.8	2,078.2	137
11	78	77.8	113.0	1,537.6	2,071.4	134
12	87	86.8	113.0	1,531.2	2,062.8	134

The values of heat balance for experiment numbers 1-4 are much less than 100%. This happened due to the imbalance of a small flowrate of the cold side, i.e. 2 LPM comparatively to a large flowrate of the hot channels. The heat losses to the environment in these cases then become very high. For experiment numbers 9-12, the values of heat balance are much higher than 100%. This can be counted as the error due to the temperature reading. As the temperature changes of the hot stream are very small, i.e. 0.2 °C for those runs, more significant numbers of the temperature values should have been recorded. The heat balance can then approach to very reasonable values. However, this error is considered insignificant to the calculations of the overall heat transfer coefficient (U) to be shown in the next table. Since the values of U were obtained from the net amount of energy that the cold channel received from the hot, namely:

$$U = \frac{\dot{Q}_c}{A_T \cdot \Delta T_{ln}} \tag{44}$$

where

$$\dot{Q}_c = (\dot{m} \cdot C_p \cdot \Delta T)_c \tag{45}$$

Table 25 The overall heat transfer coefficients of the experiments for thermal characterization

Experiment number	$\dot{Q}_c$ (W)	ΔT_{ln} (°C)	U (W/m^2 K)	±εU (W/m^2 K)	% εU
1	694.1	16.0	850.2	49.6	5.80
2	692.7	15.0	905.4	52.6	5.81
3	690.5	14.0	967.4	56.4	5.82
4	687.6	12.9	1,041.8	60.7	5.83
5	1,388.3	16.2	1,681.2	97.8	5.80
6	1,385.5	15.2	1,783.8	103.6	5.81
7	1,380.9	14.2	1,904.0	111.1	5.82
8	1,375.2	13.2	2,048.1	118.5	5.83
9	2,082.4	17.3	2,361.7	137.2	5.79
10	2,078.2	16.3	2,502.7	145.1	5.80
11	2,071.4	15.3	2,659.0	153.9	5.81
12	2,062.8	14.3	2,835.3	164.4	5.82

The values of the overall heat transfer coefficient shown in Table 25 are considered in the range of practical values found in the real plants for pasteurization processes, i.e. not less than 820 W/m^2 K (Schreier, 1997). The combination of errors in temperature sensor and fluid flowmeter readings give a total measurement error in the overall heat transfer coefficient measurements by applying equations (38)-(43). Absolute error and error in percentage of the overall heat transfer coefficient are tabulated in the same table. The errors are not greater than ±6% for all experimental runs.

Not only the thermal performance has been investigated for the initial experiments, but also the pressure drops across the cold channel was measured for each run as shown in Table 26.

Table 26 Pressure drops across the cold channel of the initial experiments

Experiment number	ΔP (kg/cm^2)
1	0.09
2	0.09
3	0.09
4	0.1
5	0.11
6	0.11
7	0.12
8	0.12
9	0.13
10	0.13
11	0.15
12	0.16

Initial experiments have shown that the test section can perform an indirect heat transfer between two hot channels with nearly constant temperatures and a middle cold channel with a temperature difference around +5 °C. The applicable range of the cold side temperature is 40 to 75 °C, and of the hot side is limited to not more than 90 °C due to stability of material used to form channels. For the experiments shown here, it is possible to monitor both the overall heat transfer coefficient and pressure drops in the development of fouling in the test section. Similar operating conditions will then be applied for the main experimental program in the next section.

4.2.2 Main Experimental Program

The main experimental program aims to investigate the effects of variations in process variables on the test section, i.e. coconut milk flowrate and heating temperature, and then to analyze the effects. This is the first engineering step in gaining a good understanding of a development of coconut milk fouling at pasteurization temperatures. This kind of work does not attempt to understand the kinetic causes of fouling. However, the obtained data can be useful in subsequent kinetic work.

Since a fouling phenomenon is a function of more than one process variables, it is common practice to assess the significance of each separately. For example, carrying out experiments to measure fouling rate at a set of different flowrates for the same heating temperature conditions, should give us a chance to analyze the effects of product Reynolds number on fouling rate at the specific temperature interval. By using the strategy termed "*changing one separate factor at a time*", the main experimental program for this work can then be designed by varying the following process parameters:

(a) Coconut milk flowrate (2, 4, 6 LPM),
(b) Inlet temperature of coconut milk (40, 50, 60, 70 °C) with temperature difference around +5 °C.

The main experimental conditions to investigate the significance of the two process variables on the system response are listed in Table 27.

Table 27 Experimental design for investigation of the significance of the two process variables on the system response

Experiment number	Coconut milk flowrate (LPM)	Coconut milk temperature	
		Inlet (°C)	Outlet (°C)
1	2	40	45
2	2	50	55
3	2	60	65
4	2	70	75
5	4	40	45
6	4	50	55
7	4	60	65
8	4	70	75
9	6	40	45
10	6	50	55
11	6	60	65
12	6	70	75

The data collected from the main experiments will be analyzed by using a statistical method. The aim is to determine which of the selected process variables significantly affect the chosen response variables as following:

a) rate of increase of Biot number ($\Delta Bi/\Delta t$),
b) rate of pressure drop increase ($\Delta (\Delta P)/ \Delta t$), and

c) rate of deposition of foulant ($\Delta m/\Delta t$) in the test section.

To obtain the response variables, each experimental run must yield the measuring data of temperature and flowrate on both coconut milk and hot water sides, pressure drop on the coconut milk side, and foulant mass on the coconut milk side by weighing. Biot number is used throughout this work as a dimensionless fouling factor, whilst the rate of increase of pressure drop is chosen as a simple measure of fouling development. Similarly, average deposition rate is referred as a simple first indicator of fouling development in the test section.

4.3 Running of the Main Experiments

Attempting to perform the experiments with the conditions proposed in Table 27, there was a problem concerning to the temperature difference of the coconut milk in some experimental runs. Maximum flowrate of the hot water cannot heat the coconut milk up to +5°C. This can be explained by the difference in thermal and physical properties of coconut milk from water, which was used for the initial test runs. However, to maintain the number of experimental runs, the coconut milk temperature difference of around +4.5°C can be achieved for all the runs. Therefore, the new conditions for the main experiments are shown in Table 28.

Table 28 New experimental design for investigation of the significance of the two process variables on the system response

Experiment number	Coconut milk flowrate (LPM)	Coconut milk temperature	
		Inlet (°C)	Outlet (°C)
1	2	50	54.5
2	2	60	64.5
3	2	70	74.5
4	4	50	54.5
5	4	60	64.5
6	4	70	74.5
7	6	50	54.5
8	6	60	64.5
9	6	70	74.5

In Table 28, the experimental runs with 40°C inlet temperature of coconut milk were canceled. This results from the difficulty of bringing the coconut milk temperature in the storage tank back to the set point of the inlet temperature. Very high rate of cooling was needed in this case, and the rig cannot cope with the operation at this conditions.

After, a set of experiments had been conducted on the apparatus at the Chemical Engineering Department, KMITNB. The results can be shown next.

4.3.1 Rate of Decrease of the Overall Heat Transfer Coefficient in the Test Section

4.3.1.1 Coconut milk inlet and outlet temperatures are 50°C and 54.5°C respectively.

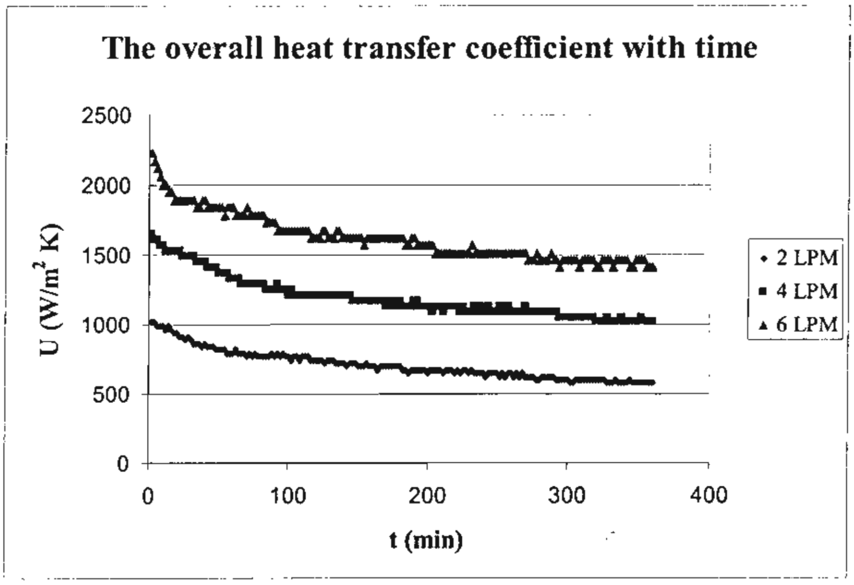


Figure 24 Comparison of heat transfer coefficients in the test section for the coconut milk temperature of 50°C to 54.5°C

4.3.1.2 Coconut milk inlet and outlet temperatures are 60°C and 64.5°C respectively.

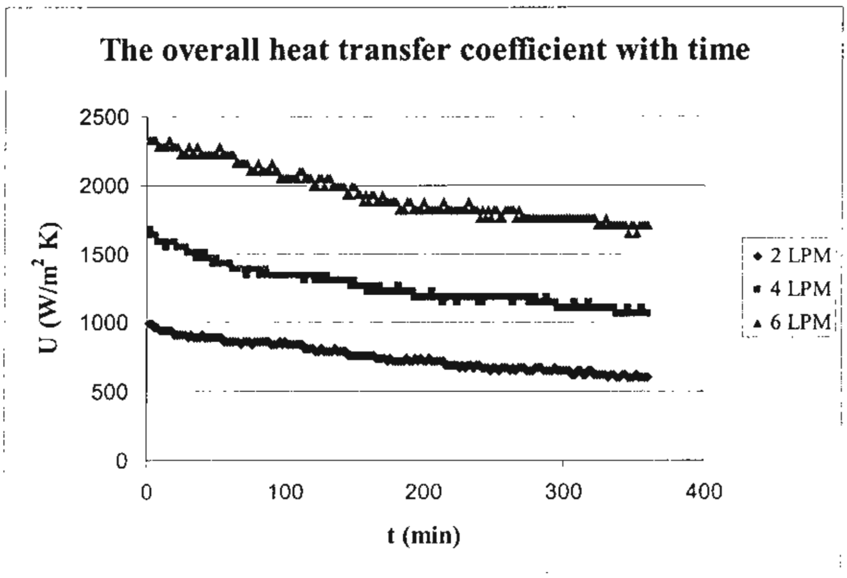


Figure 25 Comparison of heat transfer coefficients in the test section for the coconut milk temperature of 60°C to 64.5°C

4.3.1.3 Coconut milk inlet and outlet temperatures are 70°C and 74.5°C respectively.

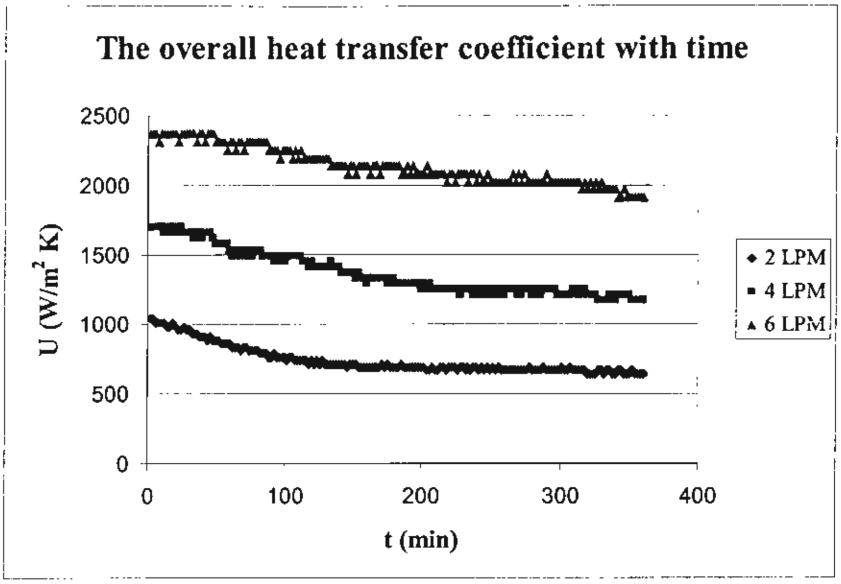


Figure 26 Comparison of heat transfer coefficients in the test section for the coconut milk temperature of 70°C to 74.5°C

Rates of decrease of the overall heat transfer coefficients in the test section are shown in Figures 24-26. Two phases of fouling phenomena were observed during the experiments for 6 hours. Firstly, a fouling period occurred in which the overall heat transfer coefficient decreased rapidly with time. The fouling period lasting approximately two hours was followed by a post-fouling period where the overall heat transfer coefficient decreased slowly. The evolution of the overall heat transfer coefficients did not show the first phase of fouling phenomena, i.e. an induction period, reported by Fryer (1986) and Delplace et al. (1994). Apart from the difference in food fouling which their study was for fouling by whey proteins solutions, the observed variation in the overall heat transfer coefficients may be due to differences in flow geometries. However, there may be a period after startup where the induction period occurred but was not classified due to the inaccuracy of measurement systems.

4.3.2 Rate of Increase of the Fouling Factor in the Test Section

4.3.2.1 Coconut milk inlet and outlet temperatures are 50°C and 54.5°C respectively.

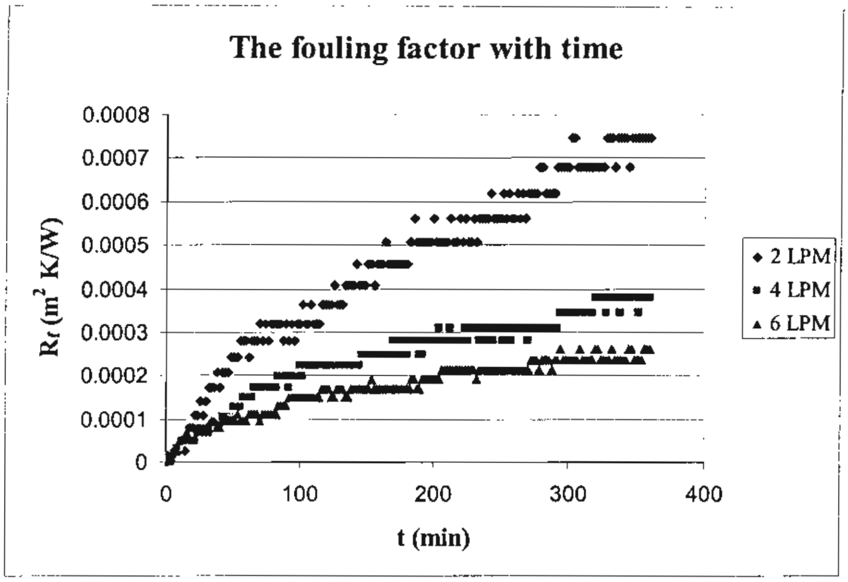


Figure 27 Comparison of the fouling factor in the test section for the coconut milk temperature of 50°C to 54.5°C

4.3.2.2 Coconut milk inlet and outlet temperatures are 60°C and 64.5°C respectively.

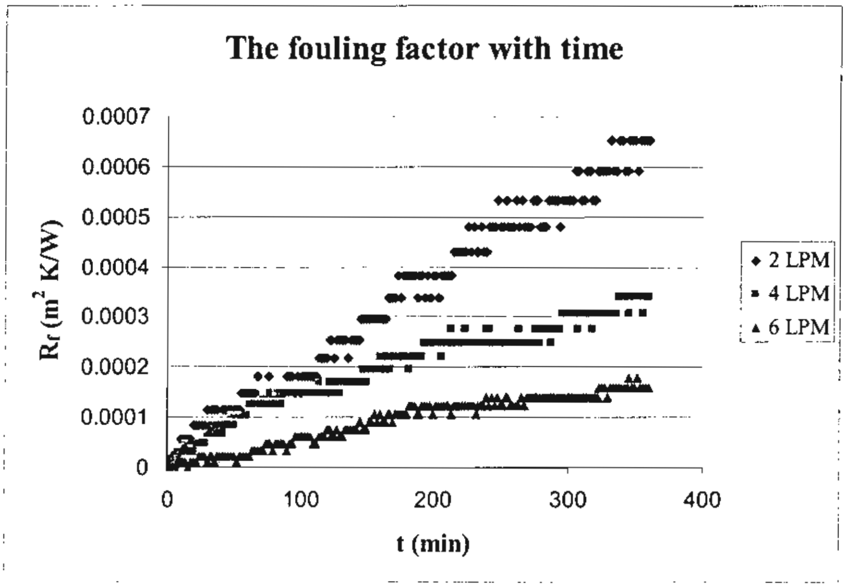


Figure 28 Comparison of the fouling factor in the test section for the coconut milk temperature of 60°C to 64.5°C

4.3.2.3 Coconut milk inlet and outlet temperatures are 70°C and 74.5°C respectively.

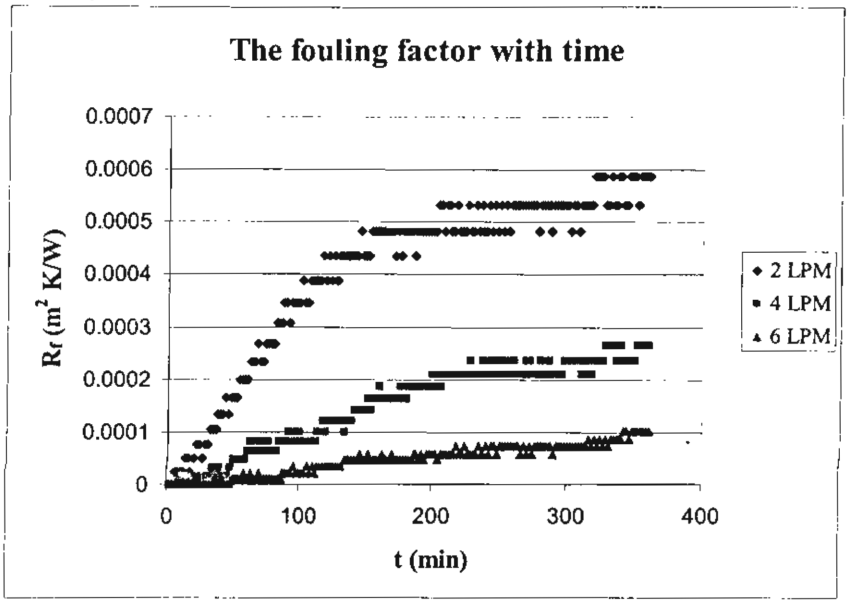


Figure 29 Comparison of the fouling factor in the test section for the coconut milk temperature of 70°C to 74.5°C

Rate of increase of the fouling factor in the test section are shown in Figures 27-29. Same fouling phenomena can be seen from the plots between fouling factor with time. Values of the fouling factor at the sixth hour were tabulated in Table 29. The values of the fouling factor increased when the coconut milk flowrate decreased. This confirmed the results obtained from the study of fouling from whey protein solutions (Fryer and Slater, 1985, 1987; Paterson and Fryer, 1988; Gotham, 1990 and Belmar-Beiny et al., 1993). The rate of deposit formation decreased with increasing Reynolds number. This was caused by the decrease in the thickness of the laminar sublayer and thus in the amount of heated material sufficiently close to the heating surface for fouling to occur.

4.3.3 Rate of Increase of the Biot Number in the Test Section

In this work, rate of change of Biot number was used to present the effects of fluid flowrate and temperature on fouling rate, the Biot number can be written, namely;

$$Bi = U_0 \times R_f \tag{46}$$

From equation (46) the Biot number is a product of the overall heat transfer coefficient for clean condition and fouling factor. After the deposition of fouling onto heat transfer surface, it represents an additional resistance to the heat transfer, and thus results in a decreasing performance of the heat exchanger. To measure the overall degradation of the specified system, a fouling factor is usually verified. Fouling factors should always been obtained experimentally by determining the values of U for both clean and dirty conditions as follows:

$$R_f = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}} \tag{47}$$

The overall heat transfer coefficient of the system (U) can be calculated from the collecting data, i.e. fluid temperature and time, or theoretically estimated from film heat transfer coefficients of the hot and cold sides, namely:

$$\frac{1}{U} = \frac{1}{\alpha_C} + \frac{a}{\lambda_P} + \frac{1}{\alpha_W} \tag{48}$$

The film heat transfer coefficients of the cold side (α_c) and the hot side (α_w) are incorporated in the Nusselt number.

$$Nu = \frac{\alpha \cdot d_h}{\lambda} \tag{49}$$

By referring to the formula of Biot number from equation (46), it can be said that the formula has been fitted to a general term of Biot number by the following equation.

$$Bi = \frac{h \cdot a}{\lambda} \tag{50}$$

where the heat transfer coefficient (h) stands for the overall heat transfer coefficient (U), and the thermal resistance (a/λ) can be represented by the fouling factor (R_f), see equations (47) and (48).

4.3.3.1 Coconut milk inlet and outlet temperatures are 50°C and 54.5°C respectively.

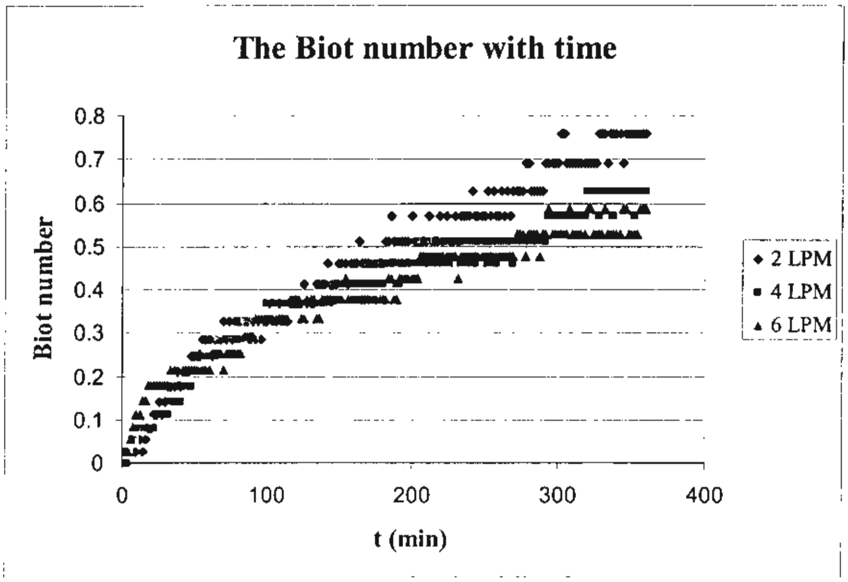


Figure 30 Comparison of the Biot number in the test section for the coconut milk temperature of 50°C to 54.5°C

4.3.3.2 Coconut milk inlet and outlet temperatures are 60°C and 64.5°C respectively.

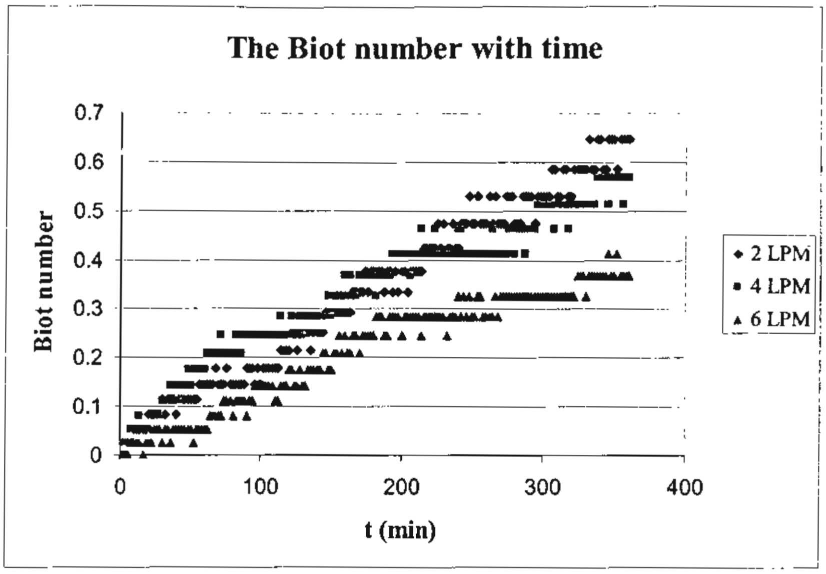


Figure 31 Comparison of the Biot number in the test section for the coconut milk temperature of 60°C to 64.5°C

4.3.3.3 Coconut milk inlet and outlet temperatures are 70°C and 74.5°C respectively.

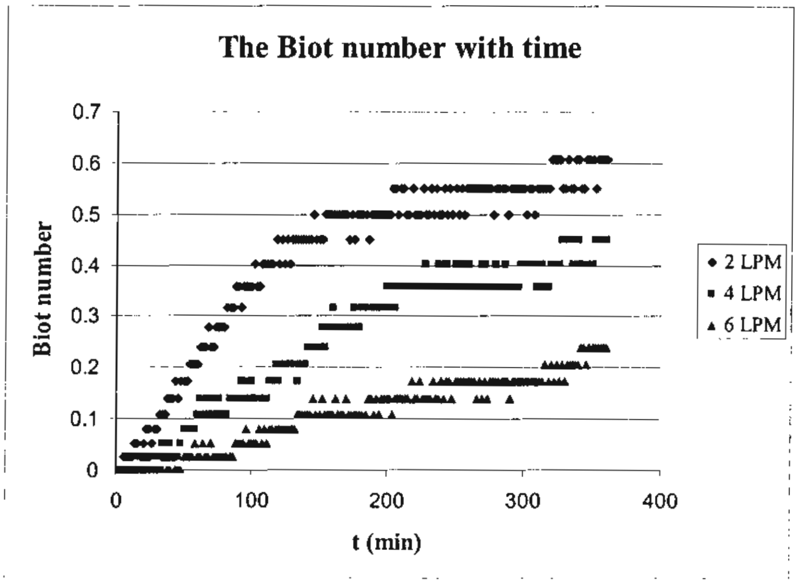


Figure 32 Comparison of the Biot number in the test section for the coconut milk temperature of 70°C to 74.5°C

Rate of increase of the Biot number in the test section are shown in Figures 30-32. Rate of increase of the Biot number are similar to rate of increase of the fouling factor. Values of the Biot number at the last two hour were also tabulated in Table 29.

Table 29 Experimental data for the thermal performance analysis

Run number	Coconut milk flowrate (LPM)	Coconut milk temp. (°C)	$U_{t=0\ min}$ ($W/m^2\ K$)	$U_{t=6\ hr}$ ($W/m^2\ K$)	$R_{f,\ t=6\ hr}$ ($m^2\ K/W$)	$\Delta Bi/\Delta t$ (t=4-6 hr) (1/min)
1	2	50-54.5	1016.1	578.1	0.00075	0.00169
2	2	60-64.4	990.8	601.4	0.00065	0.00154
3	2	70-74.6	1035.3	643.8	0.00059	0.00063
4	4	50-54.4	1653.1	1016.0	0.00038	0.00139
5	4	60-64.5	1675.2	1068.1	0.00034	0.00138
6	4	70-74.6	1700.9	1173.6	0.00026	0.00062
7	6	50-54.4	2232.3	1407.5	0.00026	0.00079
8	6	60-64.5	2333.9	1706.1	0.00016	0.00071
9	6	70-74.6	2367.7	1908.9	0.00010	0.00065

At the same values of coconut milk flowrate, the values of the fouling factor increased when the coconut milk inlet temperature decreased. This fouling phenomenon was not reported in the works done for fouling from whey protein solutions. The reasons for this variation should come from the difference in the chemical compositions of the coconut milk from cow milk. Samson et al. (1971) and Balachandran and Arumughan (1992) reported that 80% of proteins in coconut endosperm can be classified as albumins and globulins. Hagenmaier et al. (1972a) stated that about 30% of the protein in coconut milk is dissolved in the aqueous phase. Undissolved protein is an emulsifying agent for the fat globules. In coconut milk, each fat globule is bordered by the aqueous protein solution (Gonzalez et al., 1990). Seow & Goh (1994) described that the range of temperature 50-130 °C can reflect the complex protein structure. Two peaks or denaturation temperatures of coconut milk protein were found at about 92 and 110 °C respectively. Seow & Gwee (1997) stated that heating coconut milk at high sterilizing temperature can destroy heat labile proteins. This follows by fat globules tending to aggregate and the liquid containing less single small fat globules to resist the flow. Chiewchan et al. (2005) confirmed from their rheological studies that the coconut milk exhibited pseudoplastic behavior (viscosity decrease with increasing velocity gradient) with the flow behavior index (n) between 0.719 and 0.971. Heat treatment of the coconut milk resulted in the aggregating of fat globules and this caused the reduction of apparent viscosity.

For the rate of change of Biot number listed in Table 29, some phenomena were observed.

- At the same temperature conditions (50-54.5°C and 60-64.5°C), rate of change of Biot number increased when coconut milk flowrate decreased.
- At the same temperature conditions (70-74.5°C), rate of change of Biot number was almost independent from coconut milk flowrate.
- At low temperature conditions (50-54.5°C and 60-64.5°C), rate of change of Biot number was much higher than that of the high temperature conditions (70-74.5°C).
- At the same flowrate conditions, rate of change of Biot number increased when the coconut milk inlet temperature decreased.

To find out the reasons behind these phenomena, composition analysis of the deposit formation was made as following:

Table 30 Composition analysis of the deposit formation (% w/w)

Component(s)	Coconut milk solution	Coconut milk fouling		
		50-54.5 (°C)	60-64.5 (°C)	70-74.5 (°C)
Protein	2.990	4.638	5.863	7.963
Fat	17.000	35.543	25.689	21.877
Minerals				
Calcium	0.0078	1.4000	1.9427	1.5603
Iron	0.0006	0.0114	0.0021	0.0258
Magnesium	0.0121	3.1930	4.2987	4.2883
Phosphorus	0.0410	0.6458	0.8432	0.8918
Potassium	0.0920	0.0207	0.0331	0.0393
Sodium	0.0415	5.9830	7.9050	7.0370

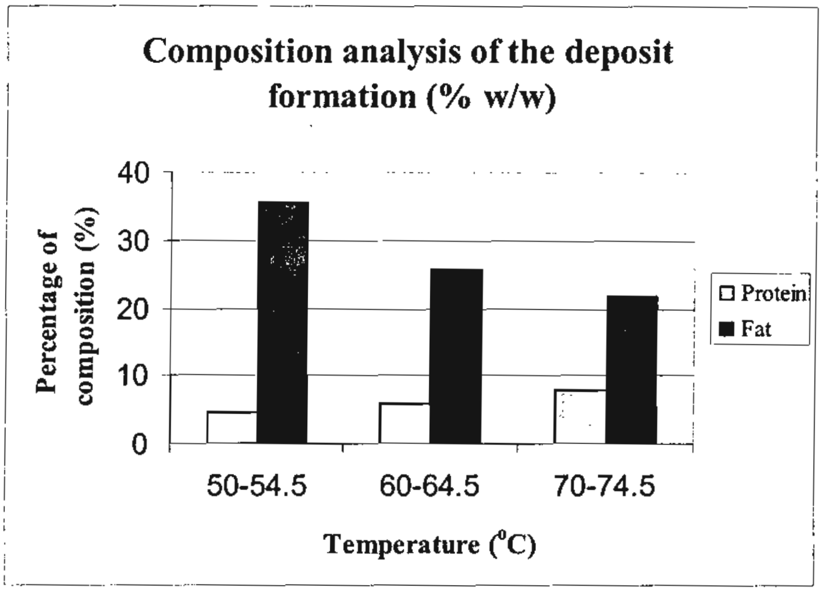


Figure 33 Composition analysis of the deposit formation (% w/w)

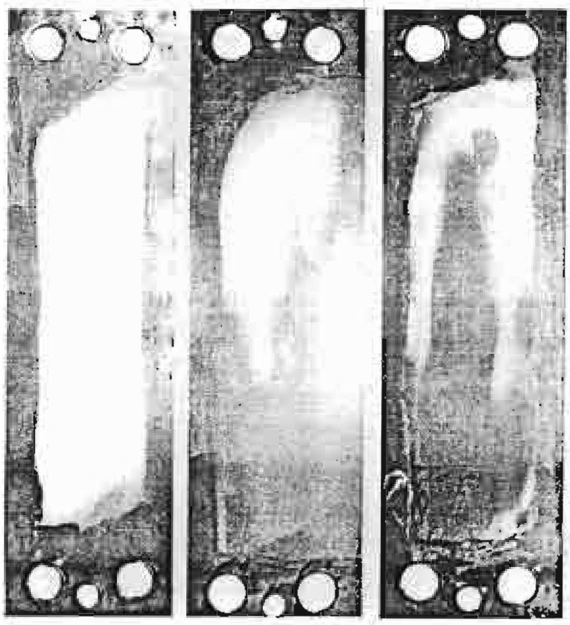
With this information, the coconut milk protein also acted as an important factor for coconut milk fouling at pasteurization temperatures. Although, it did not appear as a majority mass of the foulant as in the cow milk fouling (50-60% protein), see Table 30. Its stability at low temperatures caused an increase in fluid viscosity due to very fine fat particles resisting the flow. This caused the increase in the thickness of the laminar sublayer and thus in the amount of heated fat, protein, and mineral sufficiently closed and attached to the heating surface for fouling to occur. The result can also be confirmed by looking at the weight percents of protein and fat which were analyzed as in Table 30. Figure 33 showed the tendency of protein and fat when temperature increased. Higher value of weight percent of protein in the deposit has been found when the coconut milk inlet temperature increased. However, at the lower inlet temperature, larger value of weight percent of fat has been reported. This can be concluded at this stage that denaturation of protein in coconut milk can cause fouling by two mechanism. Firstly at high temperature approximately from 70 °C, the structure of protein is altered by the processes of denaturation and aggregation to form deposit formation. Attached fat onto metal surface happens to be less significant at higher temperature, since the aggregating of fat globules causes the decrease of fluid viscosity. The fat particles can easily flow through the channel. Secondly at low temperature, heat labile proteins are hardly destroyed. This is considered as the adverse effect on system performance where food fluid containing naturally high weight percent of fat like coconut milk. Stability of small fat globules due to undestroyed protein acting as an emulsifying agent results in high resistance to the flow and thus permits the fat for a quick adhesion rate onto heating surface.

Coming to the conclusions, rate of change of Biot number at different temperature was found relevant to the amount of fat and protein found on the heating surface. Two different phenomena on the causes of coconut milk fouling had been written, namely.

- Fouling at low temperature conditions (50-54.5°C and 60-64.5°C), rate of change of Biot number increased when flowrate of coconut milk decreased, see in Table 29. Higher value of weight percent of fat in the deposit was found, see in Table 30. This was caused by the precipitation fouling from fat dominated the chemical reaction fouling from protein.
- Fouling at high temperature conditions (70-74.5°C), rate of change of Biot number was not much different when the flowrate was varied, see in Table 29. Higher value of weight percent of protein in the deposit was found, see in Table 30. This was caused by the chemical reaction fouling from protein began to dominate the precipitation fouling from fat.

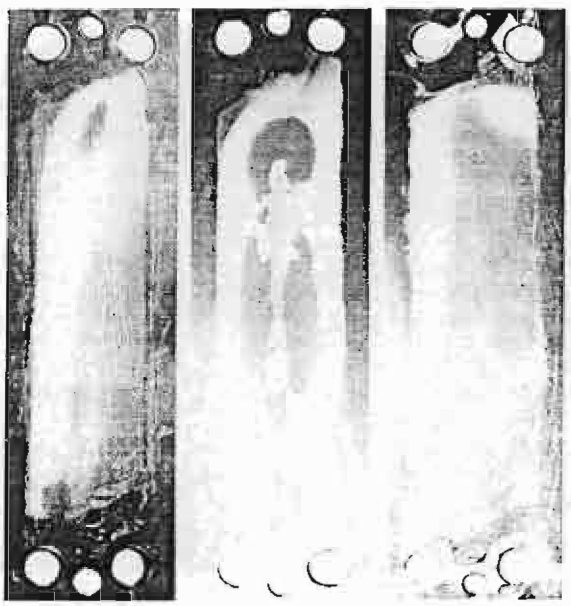
4.4 Characterization of Coconut Milk Fouling Deposit

At the end of each experiment, the test section was dismantled. A Picture of the fouled plate for a coconut milk inlet temperature and flowrate of 50, 60, and 70°C and 2, 4, and 6 LPM was taken, see Figure 34-36. From the figure, fouling of the experimental plates was visible to the naked eye as a white spongy deposit. Location of this deposit seemed confined to areas where the fluid residence time was higher. In some parts of the plates at this range of temperature, the white spongy deposit was found coated by translucent layer of foulant which was suspected as an aggregation of fat particles. Scanning electron microscopy (SEM), (LEO 1455VP, USA) permitted observation of the deposit surface on the plate for clean plate and operating temperature of 50-54.5, 60-64.5, 70-74.5 °C and flowrate of 4 LPM, see Figure 37-40. As can be seen from the scanning electron micrograph, the mineral particles are embedded in the protein and fat layers. Further study is needed to verify for an initial and subsequent layers of the deposit, which can lead to understanding of the interaction between protein, fat and mineral adsorption onto metal surface.



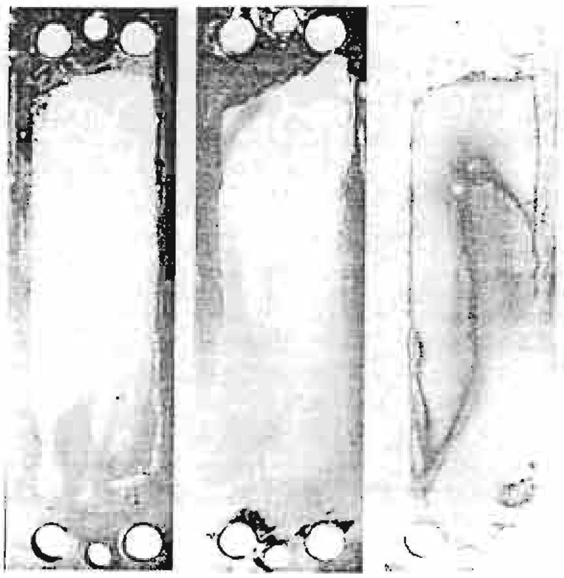
2 LPM 4 LPM 6 LPM

Figure 34 Photograph of the deposit on stainless steel plates for the heating condition from 50°C to 54.5°C at flowrate of 2, 4, and 6 LPM



2 LPM 4 LPM 6 LPM

Figure 35 Photograph of the deposit on stainless steel plates for the heating condition from 60°C to 64.5°C at flowrate of 2, 4, and 6 LPM



2 LPM 4 LPM 6 LPM

Figure 36 Photograph of the deposit on stainless steel plates for the heating condition from 70°C to 74.5°C at flowrate of 2, 4, and 6 LPM

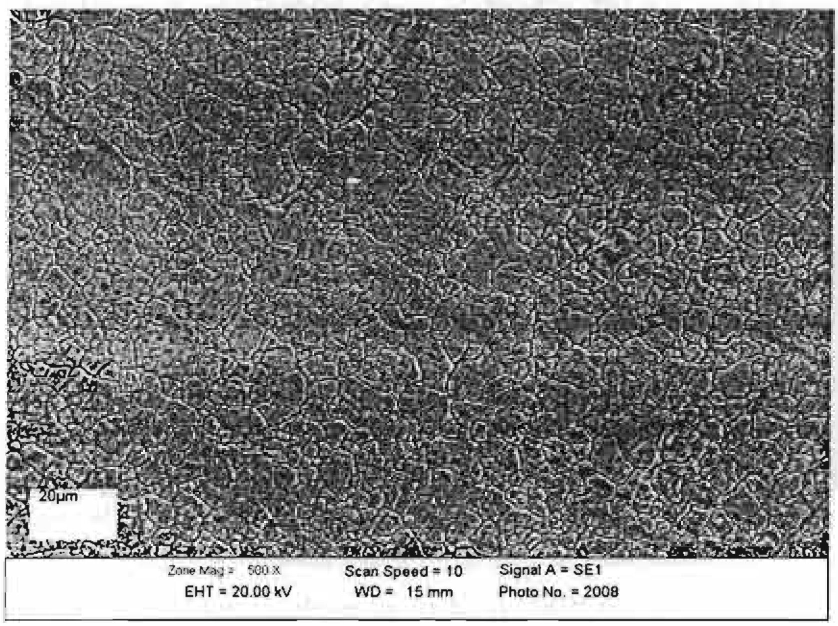


Figure 37 The foulant analysis by SEM at 500X for clean condition

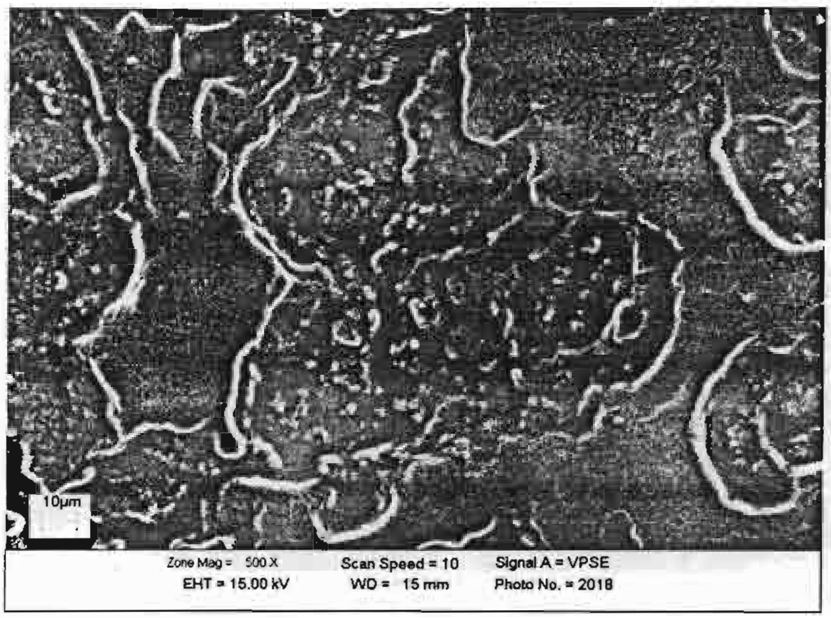


Figure 38 The foulant analysis by SEM at 500X for the heating condition from 50°C to 54.5°C and flowrate of 4 LPM

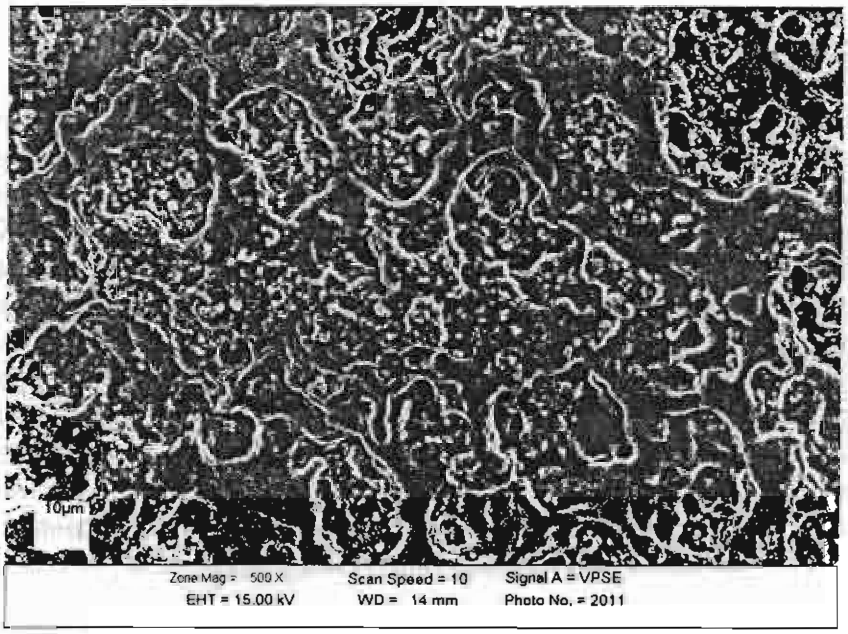


Figure 39 The foulant analysis by SEM at 500X for the heating condition from 60°C to 64.5°C and flowrate of 4 LPM

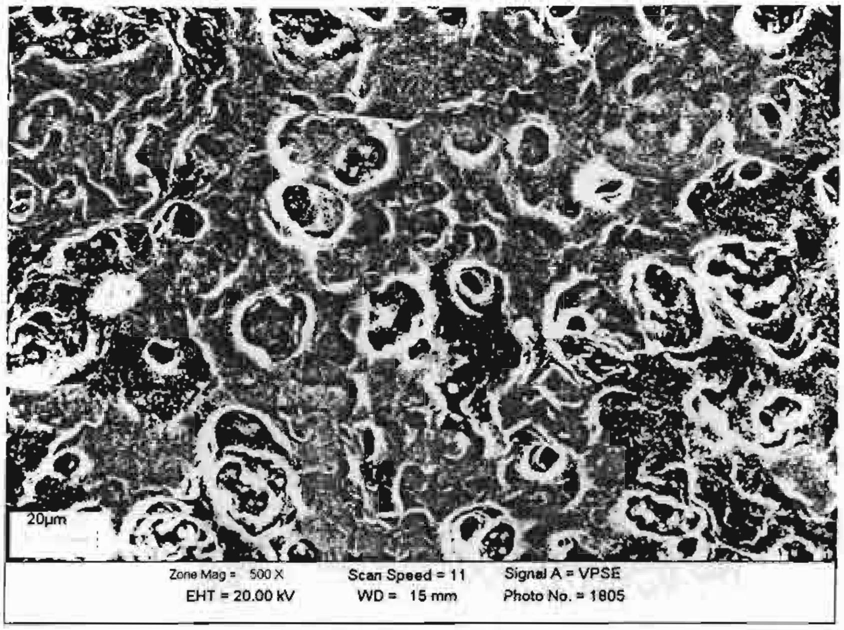


Figure 40 The foulant analysis by SEM at 500X for the heating condition from 70°C to 74.5°C and flowrate of 4 LPM

By assuming that the composition of deposit is dependent only on fluid temperature, the composition analysis of the deposit is also reported in Table 30. The analysis has shown that the highest percent of fat was found at the lowest coconut milk temperature (50-54.5 °C). In contrast, the highest percent of protein was found at the highest coconut milk temperature (70-74.5 °C). This confirms that the analysis results of the decrease in heat transfer performance already mentioned are reasonable. Denaturation of protein was the important mechanism in the development of coconut milk fouling. However, the analysis has shown also the compositions by minerals. Sodium, Magnesium, Calcium, and Phosphorus were found for their significant contributions in the deposit mass respectively. Visser and Jeurnink (1997) reviewed that the formation of Ca and P in the deposit formed in the dairy industry was insoluble calcium phosphate particles. They also stated that protein denaturation and aggregation, respectively, and calcium phosphate particle formation are two different processes that follow different kinetics. The build up of minerals and protein in a foulant may keep on independently. However, original amount of minerals in the solution is also important. Different amounts of minerals in coconut milk fluid are usually found due to variety, geographical location, and maturity of the nut. Therefore, the compositions of deposit by minerals in this work can not be related to any impact on the rate of fouling. Future work is needed to prove that the process of mineral formation is truly independent from the processes of particle aggregation by denatured protein and fat.

4.5 Coconut Milk Fouling Model

4.5.1 Experimental Data for the Deposition of Rate of Increase of Biot Number

A detail analysis of the data from the experiments was undertaken in order to determine which of the process variables, i.e. fluid temperature and flowrate, significantly affect the thermal performance of the test section. Rate of increase of Biot number for the last two hour ($\Delta Bi/\Delta t$), was chosen as a response variable. Plot of $\Delta Bi/\Delta t$ against coconut milk temperatures and flowrate can be seen in Figure 41. The effects of coconut milk temperature and flowrate on the rate of change of Biot number have been confirmed as the effects of these two variables on the fouling factor at the sixth hour. By using a statistical program, a simple model for this set of data can be developed as a polynomial form; namely.

$$\Delta Bi / \Delta t = -2.83\times10^{-3} + 2.19\times10^{-4}T - 5.76\times10^{-4}F - 2.48\times10^{-6}T^2 - 3.21\times10^{-5}F^2 + 1.15\times10^{-5}TF \quad (51)$$

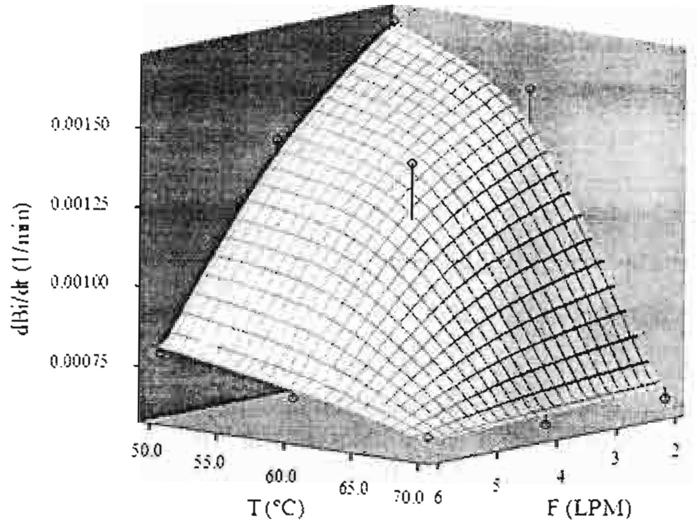


Figure 41 Rate of increase of Biot number for the last two hour, ΔBi/Δt against coconut milk temperature and flowrate

Plot of ΔBi/Δt response surface against coconut milk temperatures and flowrate can be seen in Figure 41 with the R-Square value of 95%. From the plot, the effect of flowrate on fouling rate is less significant for the coconut milk inlet temperature of 70 °C. However, it is apparent that the effect of flowrate becomes considerable for the lower temperature conditions. This is due to the change of rheological property of coconut milk which is highly a function of temperature explained in the previous section.

4.5.2 Experimental Data for the Pressure Drop Analysis

Since, inlet and outlet pressure gauges of this work are Bourdon-tube pressure gauge. Bourdon-tube pressure gauges are simple, rugged, reliable, and cheap; they are the most widely use type of industrial pressure gauge. But this work, the via of plate channels is less than that in the industries; the value of pressure drop (ΔP) is then very small. Therefore, average pressure drop, $\Delta P_{average}$ for the total 6 hours are presented instead. The average pressure drop at flowrate of 6 LPM is higher than flowrate of 2, and 4 LPM. The value of average pressure drop, $\Delta P_{average}$ for the total 6 hours were shown in Table 31.

Table 31 Average pressure drop, $\Delta P_{average}$ for the total 6 hours

Run number	Coconut milk flowrate (LPM)	Coconut milk temp. (t=0 min) Inlet - Outlet (°C)	$\Delta P_{average}$ (t=0-6 hr) (kg/cm^2)
1	2	50-54.5	0.14
2	2	60-64.4	0.15
3	2	70-74.6	0.12
4	4	50-54.4	0.13
5	4	60-64.5	0.14
6	4	70-74.6	0.22
7	6	50-54.4	0.17
8	6	60-64.5	0.41
9	6	70-74.6	0.23

From the pressure measurements, the rate of increase of pressure drop was also monitored as a simple measure of the development of fouling. However, there was only one coconut milk channel in this work and that resulted in a very small pressure drop on the coconut milk side. It is difficult to look at the effects of temperature and flow on the deposition rate by the pressure drop information. Therefore, the details have not been reported here.

4.5.3 Experimental Data for the Deposition of Foulant Analysis

Rate of increase of deposit mass for the six hours ($\Delta m/\Delta t$), was also chosen as a response variable, see Table 32. Plot of $\Delta m/\Delta t$ against coconut milk temperatures and flowrate can be seen in Figure 42 with the R-Square value of 94%. The effect of coconut milk flowrate on the rate of change of deposit mass has been shown. The effect of flowrate is to increase fouling as the flowrate decreases. However, the effect of coconut milk temperature on the rate of change of deposit mass has not been clear. This may happen due to the difference in the deposit compositions from the experiments at different coconut milk temperatures, see Table 30. Therefore, measuring the deposit mass in this case cannot well represent the effect of coconut milk temperature on the fouling rate. By using a statistical program, a simple model for this set of data can be developed as a polynomial form; namely.

$$\Delta m/\Delta t = 2.80 - 4.02\times10^{-2}T - 2.72\times10^{-1}F + 2.48\times10^{-4}T^2 - 4.92\times10^{-3}F^2 + 3.25\times10^{-3}TF \quad (52)$$

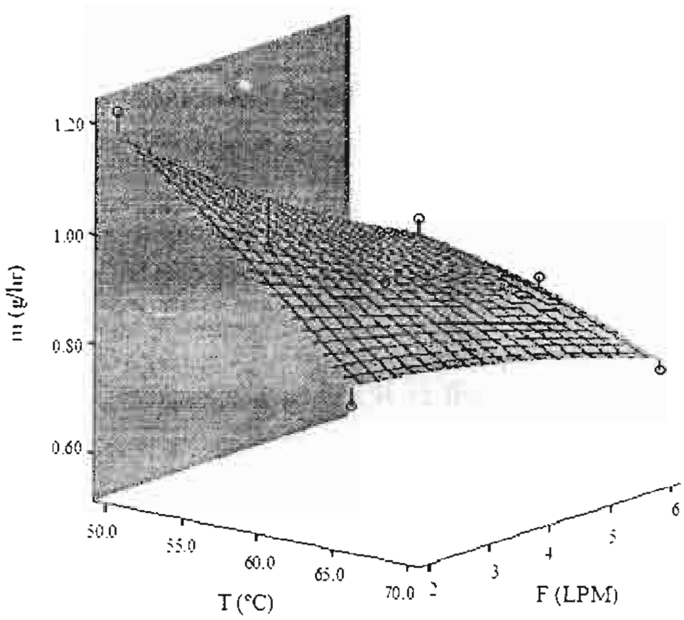


Figure 42 Rate of deposition of foulant for the total 6 hours, $\Delta m/\Delta t$ against coconut milk temperature and flowrate

Table 32 Average rate of deposition of foulant, $\Delta m/\Delta t$ for the total 6 hours

Run number	Coconut milk flowrate (LPM)	Coconut milk temp. (°C)	m_{total} (t=0-6 hr) (g)	$\Delta m/\Delta t$ (t=0-6 hr) (g/hr)
1	2	50-54.5	6.231	1.039
2	2	60-64.4	6.177	1.030
3	2	70-74.6	6.840	1.140
4	4	50-54.4	5.396	0.899
5	4	60-64.5	5.368	0.895
6	4	70-74.6	5.772	0.962
7	6	50-54.4	4.058	0.676
8	6	60-64.5	4.453	0.742
9	6	70-74.6	4.311	0.719

4.6 Comparison Between the Experimental Data and Fouling Model from Literatures

The most important factor affecting the rate of cow milk deposit formation at pasteurization temperature is the fluid flowrate. Fryer & Slater (1985, 1987) stated that it is possible to increase of fluid flowrate at the hot surface in order to reduce the rate of deposition. They also suggested that the rate of deposit removal can be increased by increase fluid flowrate. As fluid flows over a surface on which a deposit has built up, the shear stresses created by the flow can promote deposit removal. Paterson & Fryer (1988) and Belmar-Beiny et al. (1993) concluded that the rate of deposit formation decreased with increasing Reynolds number. This was caused by the decrease in the thickness of the laminar sublayer and thus in the amount of heated protein sufficiently close to the heating surface for fouling to occur. Lund & Bixby (1975) presented that fouling of 1.25 inch diameter stainless steel tubing with egg albumin was solely dependent on fluid flow correlated by equation (53). The equation was obtained by applying the constant heat flux conditions. Ratio of the overall heat transfer coefficient at clean and fouled conditions (U_0/U) was a function of the fluid Reynolds number (Re) and time (t) as following.

$$\frac{U_0}{U} = \exp\left[U_0 t\left(1.62\,\mathrm{Re}^{-0.72} - 8.33\times 10^{-4}\right)\right] \quad (53)$$

Fryer and Slater (1984) and Fryer (1986) carried out the fouling experiments for skimmed milk to a stainless steel tube in which the wall temperature was held constant (90°C – 110°C). The initial rate of increase of fouling factor (R_f) with fluid Reynolds number (Re) was formulated as in equation (54), where R is the universal gas constant and T_{fi} is the temperature at the deposit/fluid interface.

$$\frac{\Delta R_f}{\Delta t} = \left(\frac{(4.85\pm 0.4)}{\mathrm{Re}}\times 10^{13}\exp\left(\frac{-(87\pm 6)\times 10^3}{RT_{fi}}\right)\right)\times\left(\frac{1}{U_0}\right) \quad (54)$$

With the difference in the native compositions between cow milk and coconut milk and the difference in the flow configuration, research in the area of protein solution fouling to a tube may not give results that are generally applicable for coconut milk fouling to a plate heat exchanger. Therefore, the effects of fluid flowrate on the rate of fouling are reported and compared with the effects found for cow milk fouling. The information obtained from the study could be used as a guideline for developing of coconut milk pasteurization process, and could be useful for a mechanistic study of coconut milk fouling.

The values of the overall heat transfer coefficient (U) obtained from the experimental works were plotted in comparison with the values obtained from the empirical model presented by Lund & Bixby (1975) (equation (53)) as seen in Figures 43-45. Trend of the U with t obtained from the model has presented also the fouling period and the post-fouling period. Predicted values of U are found pretty much less than that obtained from the experimental works. This can be explained from the difference in the flow configurations between fluid flow in a tube (model) and in a plate channel (experimental works). At the same flowrate, a plate heat exchanger channel gives a higher overall heat transfer coefficient than that of a tubular exchanger for liquid-liquid operations (Narataruksa, 2000). Another main reason is that the egg albumin solution was used to correlate the model not the coconut milk solution. With the unique compositions of coconut milk, it is better to correlate an empirical equation by using a statistical program on the values of U from the experiments. The formulated model (coconut milk model) is in the non-linear regression form with the R-Square value of 96%, see equation (55). The model plots with the experimental data can be seen in Figures 43-45.

$$\frac{Uo}{U} = -3.43\times 10^{-6}t^2 + 4.46\times 10^{-4}t\cdot \mathrm{Re} - 4.34\times 10^{-4}t\cdot U_0 + 3.32\times 10^{-3}t - 9.64\times 10^{-2}\mathrm{Re} + 9.36\times 10^{-2}U_0 + 1.21 \quad (55)$$

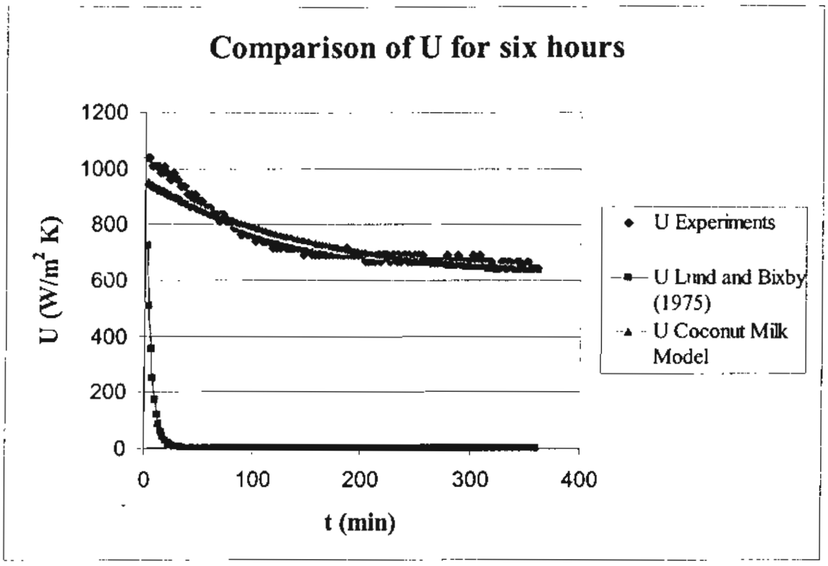


Figure 43 Comparison of the overall heat transfer coefficients obtained from the experiments and the models at flowrate 2 LPM

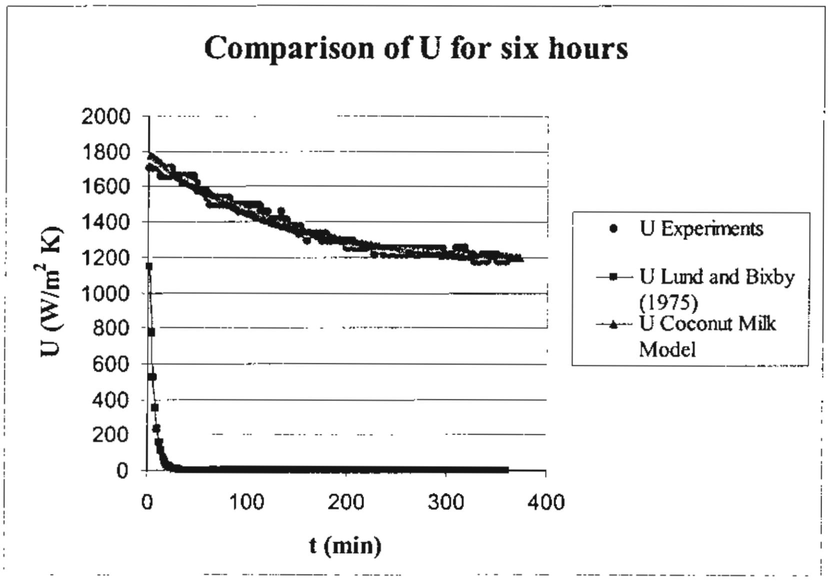


Figure 44 Comparison of the overall heat transfer coefficients obtained from the experiments and the models at flowrate 4 LPM

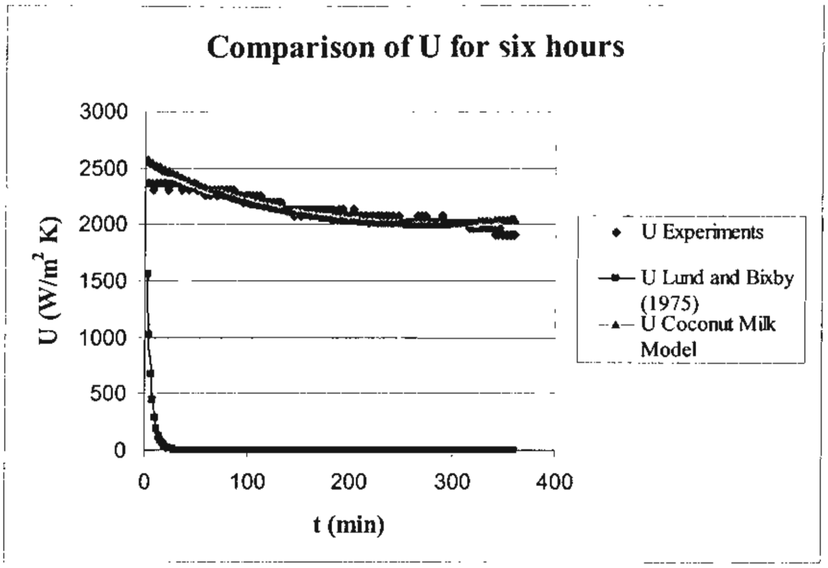


Figure 45 Comparison of the overall heat transfer coefficients obtained from the experiments and the models at flowrate 6 LPM

The initial rates of increase of the fouling factor ($\Delta R_f/\Delta t$) obtained from the experimental works at 0-2 hours were plotted in comparison with the rates obtained from the empirical model presented by Fryer (1986) (equation (54)) as seen in Figure 46. From the Figure, the initial rate of increase of the fouling factor decreases when the Reynolds number (flowrate) increases. Both the experimental data and the data predicted by the model agree with this phenomenon. This actually confirms that decreasing in the thickness of the laminar sublayer by using more flowrate, results in the less amount of heated material sufficiently close to the heating surface for fouling to occur. The system performance can be monitored of this effect by recording the evolution of the U as seen in previous section.

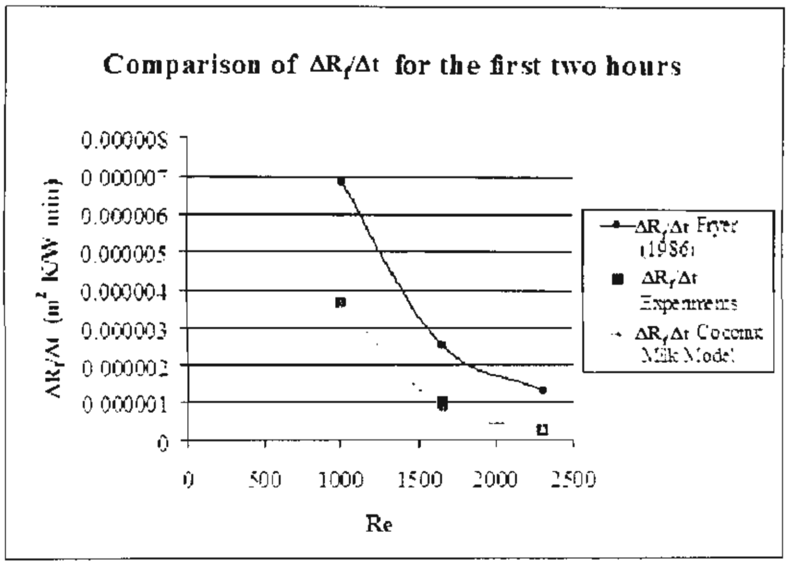


Figure 46 Comparison of the initial rate of increase of fouling factor from the experiments and the models

However, the skimmed milk model gave the higher rate of increase of fouling factor than that obtained from the experiments. The difference in flow configuration and the difference in composition of fouling fluid are the main reason for this. Next section with characterization of the deposit, difference in the deposit composition (cow milk and coconut milk) will confirm that there is a need of the unique model to explain the coconut milk fouling. Here, to present the experimental data, the coconut milk model is formulated in the non-linear regression form with the R-Square value of 99%, see equation (56). The model plot with the experimental data can be seen in Figure 46.

$$\frac{\Delta R_f}{\Delta t} = 1.95\times 10^{-6}\,\mathrm{Re} + 1.89\times 10^{-6}\,U_0 + 6.28\times 10^{-6} \qquad (56)$$

CHAPTER 5
CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

5.1.1 Literature Survey on the Food Fouling Research

In this work, pasteurization process for coconut milk is investigated. Since coconut milk is a complex biological fluid. After a long running time, some of the compositions can deposit as solid fouling on the heat transfer surface area. This impedes the transfer of heat and increases resistance to fluid flow. Many research works have been carried out to investigate the effects of fouling for food fluids such as cow milk. Unfortunately, a wide variety of causes of fouling exist due to different kinds of fluid compositions and different kinds of heat exchangers. Therefore, research in one area of fouling may not give results that are generally applicable.

From literature survey, fouling has been defined as the deposition of material on a heat transfer surface. A wide variety of types of fouling exist according to mechanism such as precipitation fouling, particulate fouling, and chemical reaction fouling. The types of fouling that normally occur in the heat exchanger equipment for food industries can be chemical reaction, crystallization, biofouling, particulate, and corrosion fouling. The removal of fouling depositions and requirements for product sterility means that plant requires frequent and expensive cleaning. Many works concerning milk protein fouling were reviewed here. This included methods used to study fouling from whey protein, factors affecting deposit formation, and characterization of fouling from whey protein solution. The information was used as the experiences for working on the coconut milk fouling investigation.

5.1.2 Selection of a Coconut Milk Model Solution

The model solution used in fouling experiments at KMITNB is a pasteurized coconut milk, supplied by Leader Price, Bangkok, Thailand. An analysis of the solution was done by Institute of Food Research and Product Development, Kasetsart University, Thailand. To confirm the analysis, percent of fat, protein, and mineral were rechecked by experimental works done at the Department of Chemical Engineering at KMITNB. The results show that selected coconut milk solution has a high fat content (17%), protein (2.99%), and minerals such as potassium (0.09%), sodium (0.04%), and phosphorus (0.04%). Physical and thermal properties of the solution as a function of temperature had been investigated. The data has been used for the calculations of the heat transfer coefficient of the test section.

5.1.3 Design of the Experimental Apparatus

To understand how variations in system parameters affect coconut milk fouling for the pasteurization process, a test section which composes of four flat stainless steel plates was constructed. These plates formed three channels for coconut milk flowing in the middle channels counter-current with two hot water channels. This configuration has similarity in the same manner of plate and frame heat exchangers used in pasteurization plants. The test section was incorporated with extensive temperature, pressure and flowrate instrumentation, to allow pressure drops, heat transfer coefficients and deposit mass to be monitored in order to quantify deposit fouling. The coconut milk was heated by the hot water with a high mass rate to minimize its temperature change. The condition was in between heat flux and constant wall temperature. By performing the heat exchanger calculation, the effective area of the test section was 0.051 m^2.

The apparatus was designed to use 2, 4, and 6 LPM of coconut milk solution, heating the milk to temperature with in the pasteurization range (50-74.5°C). The heat input to the test section was provided by a water heater, which can deliver hot water at up to 90°C and 90 LPM. Excess heat was removed though a closed circuit cooling water system, linked to a cooling chamber. To measure fouling, the apparatus incorporated extensive instrumentation to allow temperature, pressure and flowrate to be measured and record throughout the experiments. Calibrated rotameters were provided in both the coconut milk and hot water circuits to measure fluid flowrate. Platinum resistance thermometers were placed as probes in the pipework connecting inlet and outlet positions of the test section. Incorporated pressure gauges allowed the measurement of the effects of fouling on pressure drop in the coconut milk side.

5.1.4 Initial Experiments: Thermal Characterization

To test accuracy and repeatability of the operation, a series of initial experiments were conducted using a heat transfer between hot and cold water. The values of heat balance for the experiments were between 72-134%. This happened due to the imbalance of a small flowrate of the cold side, i.e. 2-4 LPM comparatively to a large flowrate of the hot channels (40-90 LPM). However, this error is considered insignificant to the calculations of the overall heat transfer coefficient (U). Since the values of U were obtained from the net amount of energy that the cold channel received from the hot.

The values of the overall heat transfer coefficient were considered in the range of practical values found in the real plants for pasteurization processes (850-2,835 W/ m^2 K). The combination of errors in temperature sensor and fluid flowmeter readings gave a total measurement error in the overall heat transfer coefficient measurements. Error in percentage of the overall heat transfer coefficient was not greater than ±6% for all experimental runs.

5.1.5 Main Experiments: Effects of Fluid Flowrate and Temperature on Fouling Rate

Two phases of fouling phenomena were observed during the experiments for 6 hours. Firstly, a fouling period occurred in which the overall heat transfer coefficient decreased rapidly with time. The fouling period lasting approximately two hours was followed by a post-fouling period where the overall heat transfer coefficient decreased slowly. The evolution of the overall heat transfer coefficients did not show the first phase of fouling phenomena, i.e. an induction period. However, there may be a period after startup where the' induction period occurred but was not classified due to the inaccuracy of measurement systems.

In this work, the results show that the values of the fouling factor increased when the coconut milk flowrate decreased. This was caused by the increase in the thickness of the laminar sublayer and thus in the amount of heated material sufficiently close to the heating surface for fouling to occur. On the other words, increasing of fluid Reynolds number resulted in the high rate of heat transfer, and thus the heating surface temperature decreased. In term of chemical reaction fouling by protein denaturation, lower heating surface temperature retarded the kinetic rate of reaction. The system in this case returned a slow rate of deposit formation.

At the same values of coconut milk flowrate, the values of the fouling factor increased when the coconut milk inlet temperature decreased. This fouling phenomenon was not reported in the works done for fouling from whey protein solutions. The reasons for this variation should come from the difference in the chemical compositions of the coconut milk from cow milk. Previous research work about coconut milk stated that undissolved protein in coconut milk is an emulsifying agent for the fat globules to resist the flow. This causes the reduction of apparent viscosity, and thus the thickness of laminar sublayer reduces. Fouling rate at the high temperature conditions therefore tends to be less than that of the low temperature conditions.

5.1.6 Microanalysis of the Foulant

The coconut milk protein acted as an important factor for coconut milk fouling at pasteurization temperatures. Its stability at low temperatures caused an increase in fluid viscosity due to very fine fat particles resisting the flow. This caused the increase in the thickness of the laminar sublayer and thus in the amount of heated fat, protein, and mineral sufficiently closed and attached to the heating surface for fouling to occur. The result can be confirmed by looking at the weight percents of protein and fat which were analyzed. Higher value of weight percents of protein in the deposit has been found when the coconut milk inlet temperature increased. However, at the lower inlet temperature, larger value of weight percents of fat has been reported. This can be concluded at this stage that denaturation of protein in coconut milk can cause fouling by two mechanisms at different temperatures. At high temperature (from 70°C), the process of denaturation and aggregation of heat labile proteins is found significant. Attached fat onto metal surface happens to be less significant, since the aggregating of fat globules causes the decrease of fluid viscosity. The fat particles can easily flow though the channel. At low temperature, heat labile proteins are hardly destroyed. This is considered as the adverse effect on system performance where food fluid containing naturally high weigh percent of fat like coconut milk. Stability of small fat globules due to undestroyed protein acting as an emulsifying agent results in high resistance to the flow and thus permits the fat for a quick adhesion rate onto heating surface.

5.2 Future Work

The work in this report has suggested many future works suitable for further development. In the area of test section global monitoring and modeling, the effects of temperatures from 50°C down to 4°C and with flowrate varied should be studied. Also the effects of native properties of the coconut milk, i.e. percents of fat, protein and some minerals, and pH are worth to be investigated on the rate of fouling. Another area is to develop kinetic model used to calculate an amount of protein reacted at different operating time. This model could be coupled with mass transfer models for the deposition of fat and minerals onto heat transfer surface. These theoretical models should finally be proved by experimental data. Last area, the local fouling monitor and cleaning behavior of the plant, a great interest to industry, needs to be investigated systematically.

APPENDIX A

Example of raw experimental data for condition number 1; heating condition of coconut milk from 50°C to 55°C

Hot water flowrate = 85 LPM   Inlet temperature of hot water = 70 °C
Coconut milk flowrate = 2 LPM   Inlet temperature of coconut milk = 50 °C
Average rate of deposition of foulant (Δm/Δt) = 1.039 g/hr

Time (min)	$T_{c,out}$ (°C)	$T_{h,out}$ (°C)	ΔP (kg/cm^2)	Q_c (W)	U (W/m^2 K)	R_f (m^2 K/W)	Bi
2	54.5	69.8	0.14	914.8	1016.1	0.00000	0.00000
4	54.5	69.8	0.13	914.8	1016.1	0.00000	0.00000
6	54.4	69.9	0.15	894.5	990.4	0.00003	0.02588
8	54.4	69.8	0.12	894.5	990.4	0.00003	0.02588
10	54.4	69.8	0.12	894.5	990.4	0.00003	0.02588
12	54.3	69.8	0.12	874.2	965.0	0.00005	0.05296
14	54.4	69.8	0.13	894.5	990.4	0.00003	0.02588
16	54.3	69.9	0.12	874.2	965.0	0.00005	0.05296
18	54.2	69.9	0.12	853.9	939.6	0.00008	0.08132
20	54.2	69.9	0.11	853.9	939.6	0.00008	0.08132
22	54.1	69.9	0.12	833.5	914.5	0.00011	0.11106
24	54.1	69.9	0.12	833.5	914.5	0.00011	0.11106
26	54.0	69.8	0.11	813.2	889.5	0.00014	0.14228
28	54.1	69.9	0.12	833.5	914.5	0.00011	0.11106
30	54.0	69.9	0.13	813.2	889.5	0.00014	0.14228
32	53.9	69.9	0.12	792.9	864.7	0.00017	0.17509
34	53.9	69.9	0.14	792.9	864.7	0.00017	0.17509
36	53.9	69.9	0.14	792.9	864.7	0.00017	0.17509
38	53.8	69.9	0.13	772.5	840.0	0.00021	0.20962
40	53.9	69.9	0.13	792.9	864.7	0.00017	0.17509
42	53.8	69.9	0.15	772.5	840.0	0.00021	0.20962
44	53.8	69.9	0.14	772.5	840.0	0.00021	0.20962
46	53.8	69.9	0.14	772.5	840.0	0.00021	0.20962
48	53.7	69.9	0.14	752.2	815.5	0.00024	0.24601
50	53.7	69.9	0.14	752.2	815.5	0.00024	0.24601
52	53.7	69.9	0.15	752.2	815.5	0.00024	0.24601
54	53.7	69.9	0.15	752.2	815.5	0.00024	0.24601
56	53.6	69.9	0.15	731.9	791.1	0.00028	0.28441
58	53.6	69.9	0.14	731.9	791.1	0.00028	0.28441
60	53.6	69.9	0.14	731.9	791.1	0.00028	0.28441
62	53.7	69.9	0.13	752.2	815.5	0.00024	0.24601
64	53.6	69.9	0.14	731.9	791.1	0.00028	0.28441
66	53.6	69.9	0.15	731.9	791.1	0.00028	0.28441
68	53.6	69.9	0.13	731.9	791.1	0.00028	0.28441
70	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
72	53.6	69.9	0.13	731.9	791.1	0.00028	0.28441
74	53.5	69.9	0.13	711.5	766.8	0.00032	0.32500

Time (min)	$T_{c,out}$ (°C)	$T_{h,out}$ (°C)	ΔP (kg/cm²)	Q_c (W)	U (W/m² K)	R_f (m² K/W)	Bi
76	53.6	69.9	0.13	731.9	791.1	0.00028	0.28441
78	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
80	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
82	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
84	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
86	53.5	69.9	0.13	711.5	766.8	0.00032	0.32500
88	53.6	69.9	0.14	731.9	791.1	0.00028	0.28441
90	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
92	53.6	69.9	0.12	731.9	791.1	0.00028	0.28441
94	53.5	69.9	0.13	711.5	766.8	0.00032	0.32500
96	53.6	69.9	0.13	731.9	791.1	0.00028	0.28441
98	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
100	53.5	69.9	0.15	711.5	766.8	0.00032	0.32500
102	53.4	69.9	0.14	691.2	742.8	0.00036	0.36796
104	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
106	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
108	53.4	69.9	0.14	691.2	742.8	0.00036	0.36796
110	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
112	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
114	53.5	69.9	0.13	711.5	766.8	0.00032	0.32500
116	53.4	69.9	0.14	691.2	742.8	0.00036	0.36796
118	53.4	69.9	0.13	691.2	742.8	0.00036	0.36796
120	53.4	69.9	0.13	691.2	742.8	0.00036	0.36796
122	53.4	69.9	0.14	691.2	742.8	0.00036	0.36796
124	53.4	69.9	0.13	691.2	742.8	0.00036	0.36796
126	53.3	69.9	0.15	670.9	718.8	0.00041	0.41353
128	53.4	69.9	0.15	691.2	742.8	0.00036	0.36796
130	53.4	69.9	0.15	691.2	742.8	0.00036	0.36796
132	53.4	69.9	0.15	691.2	742.8	0.00036	0.36796
134	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
136	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
138	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
140	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
142	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
144	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
146	53.3	69.9	0.13	670.9	718.8	0.00041	0.41353
148	53.3	69.9	0.13	670.9	718.8	0.00041	0.41353
150	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
152	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
154	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
156	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
158	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
160	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
162	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193

Time (min)	$T_{c,out}$ (°C)	$T_{h,out}$ (°C)	ΔP (kg/cm^2)	Q_c (W)	U (W/m^2 K)	R_f (m^2 K/W)	Bi
164	53.6	69.9	0.13	731.9	791.1	0.00028	0.28441
166	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
168	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
170	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
172	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
174	53.5	69.9	0.13	711.5	766.8	0.00032	0.32500
176	53.6	69.9	0.14	731.9	791.1	0.00028	0.28441
178	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
180	53.6	69.9	0.12	731.9	791.1	0.00028	0.28441
182	53.5	69.9	0.13	711.5	766.8	0.00032	0.32500
184	53.6	69.9	0.13	731.9	791.1	0.00028	0.28441
186	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
188	53.5	69.9	0.15	711.5	766.8	0.00032	0.32500
190	53.4	69.9	0.14	691.2	742.8	0.00036	0.36796
192	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
194	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
196	53.4	69.9	0.14	691.2	742.8	0.00036	0.36796
198	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
200	53.5	69.9	0.14	711.5	766.8	0.00032	0.32500
202	53.5	69.9	0.13	711.5	766.8	0.00032	0.32500
204	53.4	69.9	0.14	691.2	742.8	0.00036	0.36796
206	53.4	69.9	0.13	691.2	742.8	0.00036	0.36796
208	53.4	69.9	0.13	691.2	742.8	0.00036	0.36796
210	53.4	69.9	0.14	691.2	742.8	0.00036	0.36796
212	53.4	69.9	0.13	691.2	742.8	0.00036	0.36796
214	53.3	69.9	0.15	670.9	718.8	0.00041	0.41353
216	53.4	69.9	0.15	691.2	742.8	0.00036	0.36796
218	53.4	69.9	0.15	691.2	742.8	0.00036	0.36796
220	53.4	69.9	0.15	691.2	742.8	0.00036	0.36796
222	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
224	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
226	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
228	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
230	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
232	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
234	53.3	69.9	0.13	670.9	718.8	0.00041	0.41353
236	53.3	69.9	0.13	670.9	718.8	0.00041	0.41353
238	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
240	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
242	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
244	53.3	69.9	0.14	670.9	718.8	0.00041	0.41353
246	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
248	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
250	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193

Time (min)	$T_{c,out}$ (°C)	$T_{h,out}$ (°C)	ΔP (kg/cm²)	Q_c (W)	U (W/m² K)	R_f (m² K/W)	Bi
252	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
254	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
256	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
258	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
260	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
262	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
264	53.2	69.9	0.15	650.6	695.0	0.00045	0.46193
266	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
268	53.2	69.9	0.14	650.6	695.0	0.00045	0.46193
270	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
272	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
274	53	69.9	0.14	609.9	647.8	0.00056	0.56838
276	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
278	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
280	53.1	69.9	0.15	630.2	671.4	0.00051	0.51344
282	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
284	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
286	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
288	53.0	69.9	0.15	609.9	647.8	0.00056	0.56838
290	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
292	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
294	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
296	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
298	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
300	53.0	69.9	0.14	609.9	647.8	0.00056	0.56838
302	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
304	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
306	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
308	53.0	69.9	0.15	609.9	647.8	0.00056	0.56838
310	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
312	53.0	69.9	0.15	609.9	647.8	0.00056	0.56838
314	53.1	69.9	0.13	630.2	671.4	0.00051	0.51344
316	53.1	69.9	0.14	630.2	671.4	0.00051	0.51344
318	53.0	69.9	0.15	609.9	647.8	0.00056	0.56838
320	53.1	69.9	0.15	630.2	671.4	0.00051	0.51344
322	53.0	69.9	0.14	609.9	647.8	0.00056	0.56838
324	53.0	69.9	0.14	609.9	647.8	0.00056	0.56838
326	53.0	69.9	0.14	609.9	647.8	0.00056	0.56838
328	53.0	69.9	0.15	609.9	647.8	0.00056	0.56838
330	52.9	69.9	0.15	589.6	624.5	0.00062	0.62711
332	53.0	69.9	0.15	609.9	647.8	0.00056	0.56838
334	53.0	69.9	0.14	609.9	647.8	0.00056	0.56838
336	53.0	69.9	0.14	609.9	647.8	0.00056	0.56838
338	52.7	69.9	0.16	548.9	578.1	0.00075	0.75757

Time (min)	$T_{c,out}$ (°C)	$T_{h,out}$ (°C)	ΔP (kg/cm^2)	Q_c (W)	U (W/m^2 K)	R_f (m^2 K/W)	Bi
340	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757
342	52.7	69.9	0.14	548.9	578.1	0.00075	0.75757
344	52.8	69.9	0.15	569.2	601.2	0.00068	0.69001
346	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757
348	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757
350	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757
352	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757
354	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757
356	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757
358	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757
360	52.7	69.9	0.15	548.9	578.1	0.00075	0.75757

APPENDIX B
HEAT TRANSFER COEFFICIENT ERROR ANALYSIS

B.1 Calculation of the Clean Overall Heat Transfer Coefficient and Heat Balance

The calculations of described here were performed during the commissioning run, for condition 1 to determine the accuracy of heat transfer measurements in the PHE apparatus. The clean overall heat transfer coefficients for each section were calculated using the basis of heat flow to the coconut milk in the test section, calculated as:

$$U = \frac{\dot{Q}_C}{A_T \cdot \Delta T_{ln}} \tag{57}$$

Condition of Run No. 1

Cold Fluid				
Inlet Temp. (°C)	Outlet Temp. (°C)	Flowrate (LPM)	ρ (kg/m³)	C_p (J/kg K)
50	55	2	996.587	4179.05
Hot Fluid				
Inlet Temp. (°C)	Outlet Temp. (°C)	Flowrate (LPM)	ρ (kg/m³)	C_p (J/kg K)
59	58.2	17.5	984.240	4183.60

Calculate mass flowrate of hot and cold fluid as follows:

$$\dot{m}_c = 2\frac{L}{min}\cdot\frac{1}{60}\frac{min}{s}\cdot\frac{1}{1000}\frac{m^3}{L}\cdot 996.587\frac{kg}{m^3} = 0.033\frac{kg}{s} \tag{58}$$

$$\dot{m}_h = 17.5\frac{L}{min}\cdot\frac{1}{60}\frac{min}{s}\cdot\frac{1}{1000}\frac{m^3}{L}\cdot 984.24\frac{kg}{m^3} = 0.287\frac{kg}{s} \tag{59}$$

Calculate heat duty required.

$$\dot{Q}_C = (\dot{m}\cdot C_p \cdot \Delta T)_C \tag{60}$$

$$\begin{aligned}\dot{Q}_C &= \dot{m}\cdot C_p \cdot \left(T_{C,out} - T_{C,in}\right) \\ &= 0.033\frac{kg}{s}\cdot 4179.05\frac{J}{kg\cdot K}\cdot(55-50)K \\ &= 690.13\frac{J}{S}\end{aligned} \tag{61}$$

$$\begin{aligned}\dot{Q}_h &= \dot{m}\cdot C_p \cdot \left(T_{h,in} - T_{h,out}\right) \\ &= 0.287\frac{kg}{s}\cdot 4183.60\frac{J}{kg\cdot K}\cdot(59-58.2)K \\ &= 960.78\frac{J}{S}\end{aligned} \tag{62}$$