ORIGINAL ARTICLE

Effects of fluid flowrate on coconut milk fouling at pasteurization temperature (70ºC - 74.5ºC)

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Abstract

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Effects of fluid flowrate on coconut milk fouling at pasteurization temperature (heating from 70ºC to 74.5ºC) were investigated. A test section equipped with four flat plates forming one coconut milk channel and two hot water channels was constructed with the total heat transfer area of 0.051 m^2. Three different flowrates of coconut milk (2, 4 and 6 litres per minute (LPM)) were studied. Monitoring of the overall heat transfer coefficient (U) with time (t) and the rate of increase of the fouling resistance (dRf/dt) was done for all experimental runs. The results illustrated that there were two fouling periods: a fouling period and a post-fouling period, where the rate of increase of the fouling resistance of the fouling period was found to be

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higher than that of the post-fouling period. The effects of fluid flowrate were found to increase the fouling rate when the flowrate decreased. Published fouling models by protein solutions were unable to predict accurately the fouling rate for coconut milk. Non-linear regression models were then provided by using the experimental data to illustrate the effects of fluid flowrate on coconut milk fouling. The role of protein and fat on coconut milk fouling was explained according to microanalysis of the deposit and chemistry data of the coconut milk from previous research.

Key words : coconut milk, fouling, heat exchanger, pasteurization process

บทคัดย่อ

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ผลกระทบของอัตราการไหลของของไหลที่มีต่อการเกิดตะกรันของน้ำกะทิ สำหรับกระบวนการพาสเจอร์ไรเซชัน (70-74.5°C)

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บทความนี้มีจุดมุ่งหมายในการศึกษาผลกระทบของอัตราการไหลของของไหลที่มีต่อการเกิดตะกรันของน้ำกะทิที่อุณหภูมิการพาสเจอร์ไรเซชัน (70-74.5°C) โดยในส่วนที่ทำการทดสอบใช้เครื่องแลกเปลี่ยนความร้อนแบบแผ่นเพลทผิวเรียบที่มีจำนวนช่องทางการไหล 3 ช่องทางการไหล กำหนดให้น้ำกะทิไหลเข้าในช่องทางการไหลตรงกลางสวนทางกับน้ำร้อนจำนวน 2 ช่องทางการไหล และมีพื้นที่การถ่ายเทความร้อนรวม 0.051 ตร.เมตร ทำการทดลองโดยปรับเปลี่ยนอัตราการไหลเป็น 2, 4 และ 6 ลิตร/นาที โดยผลลัพธ์แสดงได้จากความสัมพันธ์ระหว่างค่าสัมประสิทธิ์การถ่ายเทความร้อนและค่าอัตราการเพิ่มขึ้นของความต้านทานการเกิดฟาวลิ่งของน้ำกะทิกับเวลา พบว่าการเกิดฟาวลิ่งสามารถแบ่งออกได้เป็น 2 ช่วงคือ ช่วง fouling period และ ช่วง post-fouling period ซึ่งอัตราการเพิ่มขึ้นของความต้านทานการเกิดฟาวลิ่งในช่วง fouling period จะสูงกว่าในช่วง post-fouling period ผลกระทบของอัตราการไหลคืออัตราการเกิดฟาวลิ่งเพิ่มขึ้นเมื่ออัตราการไหลลดลงต่อมาได้ทำการเปรียบเทียบค่าที่ได้จากการทดลองและจากแบบจำลองของสารละลายโปรตีนชนิดอื่น (จากสัตว์) พบว่าแบบจำลองของสารละลายโปรตีนชนิดอื่นไม่สามารถใช้ในการทำนายอัตราการเกิดฟาวลิ่งของน้ำกะทิ แบบจำลองการถดถอยแบบไม่เป็นเชิงเส้นของน้ำกะทิจึงถูกสร้างขึ้นโดยใช้ข้อมูลจากการทดลอง ส่วนบทบาทของโปรตีนและไขมันของน้ำกะทิที่มีต่อการเกิดตะกรัน สามารถอธิบายได้จากการวิเคราะห์เชิงจุลภาคของตะกรันของน้ำกะทิและจากข้อมูลขององค์ประกอบทางเคมีจากผลงานวิจัยก่อนหน้านี้

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Coconut milk is the liquid obtained by manual or mechanical extraction of grated coconut meat. Coconut milk is an important ingredient of many foods of Asian and Pacific regions including curry, deserts and sweets. In general, thermal treatment is given to food fluid to kill pathogenic micro-organisms and degrading enzyme in order to increase shelf life, product quality and product safety (Burton, 1988). Heating process normally takes place in a system of indirect plate heat exchangers, which consists of preheating, heating, and cooling sections. After passing through heat treatment process, the coconut milk is filled in cans, boxes, soft plastic bags or processed powder forms. Pasteurization process has been found to be a short-term preservation process in which the coconut milk is heated to pasteurization temperature of 72-75ºC for 20 min (Seow and Gwee, 1997). Normally, coconut milk pasteurized in soft plastic bags has been found to be fresher and more convenient for cooking. It has a shelf life of not more than 5 days (Gwee, 1988).

Coconut milk is a complex biological fluid, typically composed of fat, protein, carbohydrates, and minerals as a milky white oil-in-water emulsion; a percentage of fat is adjusted depending upon local requirement in between 15-40%. At high temperature (more than room temperature), some components can lose their rheological properties and/or denature to form a deposit on the heating surface. The deposit formation on heat exchanger surface in this case is called coconut milk fouling. As with other food fouling, the rate of deposit build up is quite rapid. The most important consequence is that heat transfer efficiency is decreased and, therefore, costs are increased. 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 10-80ºC. However, surface tension and viscosity increase steadily with temperature up to 60ºC. For temperature higher than this, they slowly decrease. Vitali *et al.* (1985) found that coconut milk exhibited mildly pseudoplastic behavior at temperatures of 15-50ºC due to high fat content. Simuang *et al.* (2004) obtained a similar result from the experiments at 70-90ºC and fat content of 15-30%, in which all coconut milk samples expressed pseudoplastic behavior.

Fouling from foods shows significant variation in behavior and coconut fouling has not been studied in depth as have other food products, such as cow milk fouling. Previous research works have described mainly on cow milk fouling. The low temperature cow milk deposit (type A) can form as a soft, white and voluminous material and it is made up of protein (50-60%), minerals (30-35%) and fat (4-8%) (Burton, 1968). In this deposit form, most of the protein is denatured β-lactoglobulin at the lower end of the temperature range, but at the higher end it is predominantly casein (Tissier *et al.*, 1984, Lalande *et al.*, 1985). A deposit starts to form when the temperature is about 70ºC and most of protein is denatured β-lactoglobulin at or near the heating surface leading to deposit formation via chemical reaction fouling. The deposit can be found for run times greater than 1 hour, and the type A deposit consists of a protein-rich outer layer and a mineral-rich inner layer near the heat exchanger surface (Tissier and Lalande, 1986; Daufin *et al.*, 1987; Britten *et al.*, 1988; Foster *et al.*, 1989). Gotham (1990) stated that two separate processes take place. Denaturation from the original native structure of β-lactoglobulin is the first, reversible, process. However, the second process of aggregation is totally irreversible and results in the fouling deposit on the heat transfer surface.

The most important factor affecting the rate of cow milk deposit formation at pasteurization temperature is the fluid flowrate. Fryer and Slater (1985, 1987) stated that it is possible to increase the 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 increasing 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 and 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 and Bixby (1975) reported that fouling of 1.25 inch diameter stainless steel tubing with egg albumin was solely dependent on fluid flow correlated by equation (1). 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.

$$\frac{U_0}{U} = \exp\left[U_0\, t\, (1.62\,\mathrm{Re}^{-0.72} - 8.33\times10^{-4})\right] \qquad (1)$$

Fryer and Slater (1984) and Fryer (1986) carried out the fouling experiments for skimmed milk in a stainless steel tube in which the wall temperature was held constant (90ºC - 110ºC). The initial rate of increase of fouling resistance (Rf) with fluid Reynolds number (Re) was formulated as in equation (2), where R is the universal gas constant and T_{fi} is the temperature at the deposit/ fluid interface.

$$\frac{dR_f}{dt} = \left(\frac{(4.85 \pm 0.4)}{\text{Re}} \times 10^{13} \exp\left(\frac{-(87 \pm 6) \times 10^{3}}{RT_{fi}} \right) \right) \times \left(\frac{1}{U_0} \right) \quad (2)$$

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 aim of this work is to apply a fouling monitoring technique to measure fouling globally on the test section using conventional plant instrumentation. 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.

Materials and Methods

1. Experimental Apparatus

To understand how variation in fluid flowrate affects coconut milk fouling in the pasteurization process, fouling experiments were carried out on the apparatus presented in Figure 1. The apparatus consists of a test section and ancillary equipment, which are a storage tank (170 litres) and feed tank (40 litres) of coconut milk, coconut milk heater and pump, coconut milk cooling unit, hot water generator and the temperature and flowrate measuring devices. The test section was designed to be a similar is a plate and frame heat exchanger used in pasteurization plants. It was

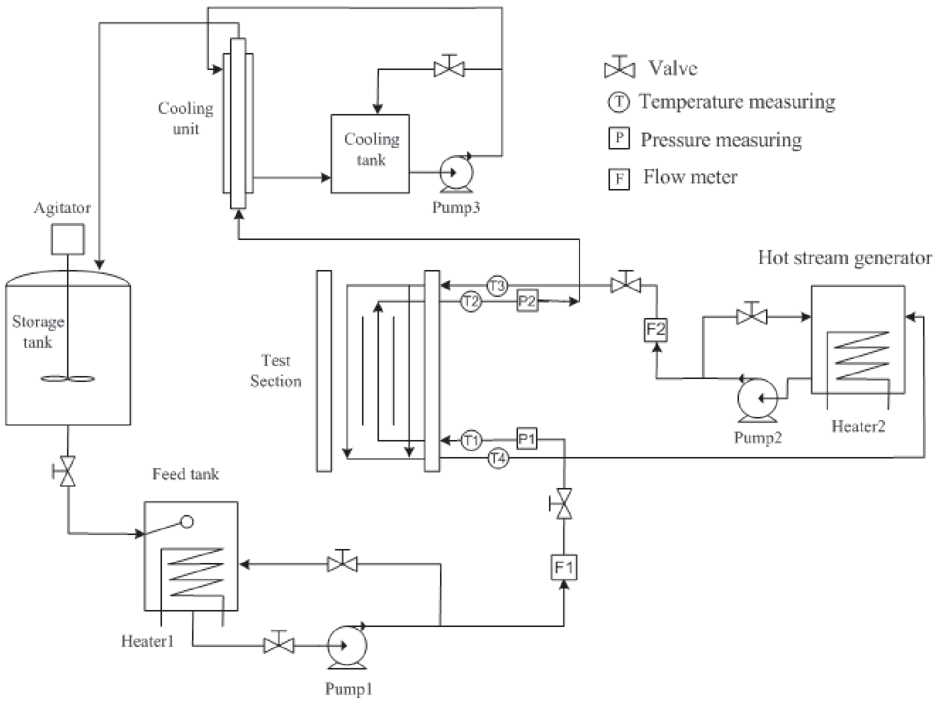

Figure 1. Diagram of the apparatus

composed of four flat stainless steel plates which can form three channels for coconut milk flowing in the middle channels counter-current with two hot water channels (see detailed design in Table 1). In order to minimize the temperature change of the hot water, its high mass rate was used. The difference of the inlet and outlet temperatures of the hot side was controlled to not more than 0.5ºC. This type of the apparatus is the so called liquid-liquid device to measure fouling resistance (Hewitt, 1992).

2. Model fouling solution

The model coconut milk solution used in the experimental works was a pasteurized coconut milk, supplied by a local factory in Bangkok, Thailand. The solution contained normally 99.9 wt % of coconut milk. Its composition was analyzed by the equipment and methods described in the next section. Compositional analysis results of the solution are tabulated in Table 2.

3. 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

Table 1. 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 Milk Channel Gap, b_c (m)	0.002
Hot Water Channel Gap, bw (m)	0.016
Total Heat Transfer Area, AT (m^2)	0.051
Internal Flow Arrangement	U-flow / Counter current

Table 2. Compositions of the coconut milk solution (% w/w)

Component(s)	**Percent* (w/w)**
Water	70.57
Protein	2.99
Fat	17.00
Minerals	
Calcium	0.0078
Iron	0.0006
Magnesium	0.0121
Phosphorus	0.0410
Potassium	0.0920
Sodium	0.0415
Others	9.2450

***Calculation based on the density of coconut milk equals to 1000.803 kg/m³ at 25ºC.**

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). Water content 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).

4. 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 bottle (BIBBY BORO in 20ºC ml, China) and a viscometer (K604 CANNON instrument company, USA). 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.

5. Experimental design

Heating conditions were investigated at pasteurized temperature range in which the inlet temperature of coconut milk was assigned at 70ºC and the outlet temperature was set at 74.5ºC at clean conditions. The coconut milk flowrate was set at 2, 4, and 6 LPM, see Table 3. The heat input to the test section was provided by an electric water heater and centrifugal pump, which can deliver hot water at up to 95ºC and 100 LPM. To obtain those conditions, the inlet temperature of the hot water was fixed and the hot water flowrate was adjusted according to the difference of the hot water temperatures of 0.5ºC at the maximum. Data reading of the temperature and flowrate was recorded for 6 hours in all runs. The overall heat transfer coefficient was calculated by using the thermal performance data for each run. After each run, the test section was dismantled in order to remove the deposit for weighing and analysis of its composition.

6. Data analysis

The temperature data collected from the experiments was analyzed by using a basic equation governing the heat transfer between the hot water channels to coconut milk channel.

$$\dot{Q}_{milk} = U \cdot A \cdot LMTD \tag{3}$$

where $\dot{Q}_{milk}$ was determined by the product of the coconut milk heat capacity, flowrate and its temperature change. The LMTD (Log Mean Temperature Difference) was the thermal driving force calculated from the input and output temperature of the hot and cold fluids. The unknown heat transfer coefficient, U was determined as a function of time from equation (3), in which heat losses were negligible. The error in percentage of

Table 3. Experimental design for investigation of the effect of the coconut milk flowrate on the fouling rate

Experiment number	Coconut milk flowrate (LPM)	Coconut milk temperature		Hot water temperature (ºC)
		Inlet (ºC)	Outlet (ºC)	
1	2	70	74.5	90
2	4	70	74.5	90
3	6	70	74.5	90

the overall heat transfer coefficient due to measurement error was not greater than ±6% for all experimental runs. To determine significant effect of coconut milk flowrate onto the fouling rate, a rate of increase of fouling resistance (dR_f/dt) for the first and last two hours of each experimental run was chosen. The fouling resistance was calculated by the following equations;

$$R_f = \frac{1}{U_t} - \frac{1}{U_{t=0\,\mathrm{min}}} \tag{4}$$

Results and Discussion

1. Rate of decrease of the thermal performance

The overall heat transfer coefficient (U) as a function of time (t) was calculated for each run showed in Figure 2. The value of U decreased more rapidly in the first two hours rather on the clean plates, which can be called a fouling period. 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 in their study was fouling by whey protein 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.

The plot between the fouling resistance (R_f) and time (t) is shown in Figure 3. Trend of the graphs confirms the relationship of the U and t in

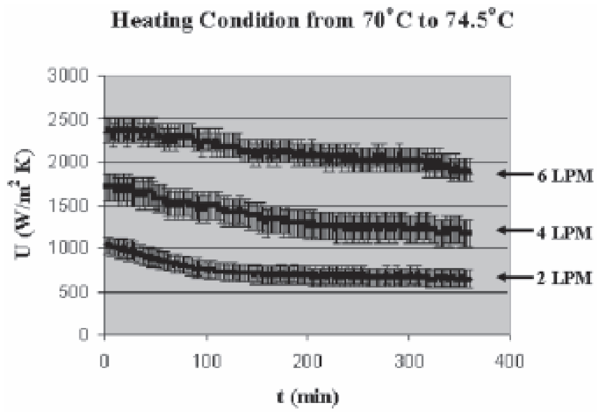

Figure 2. Evolution of the overall heat transfer coefficients with time

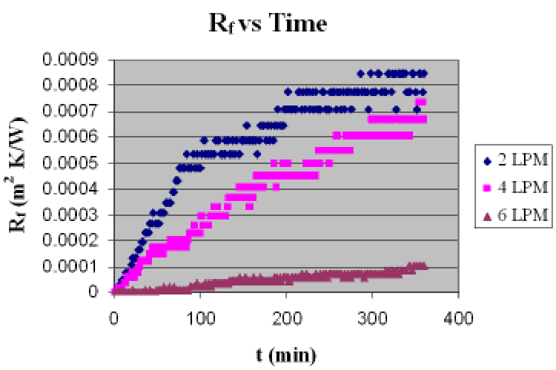

Figure 3. Evolution of the fouling resistance with time

Figure 2. The highest value of the R_f (0.00059 m^2 K/W) was found at the sixth hour of the experimental run with coconut milk flowrate of 2 LPM. To represent the rate of fouling, the increasing rate of the fouling resistance (dR_f/dt) was calculated as the initial rate (t = 0-2 hrs) and the final rate (t = 4-6 hrs), (Table 4). The results show that the rate of increase of the fouling resistance decreased when the coconut milk flowrate increased. 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. In other words, increasing of fluid Reynolds number resulted in a higher 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 and caused a slow deposition rate.

2. Comparison between the experimental data and fouling model from the literature

The experimental values of the overall heat transfer coefficient (U) were plotted and compared with the calculated values obtained from the empirical model presented by Lund and Bixby (1975) (equation (1)) as seen in Figures 4-6. Trend of the U with t obtained from the model has presented both fouling period and 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. The effective area per unit volume of plate heat exchangers are usually more than that of conventional heat exchangers, therefore the design contact time is less (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), in the non-linear regression polynomial form with the R-Square value of 96%, can be represented by equation (5). The model plots, with the experimental data, are shown in Figures 4-6.

$$\frac{U_0}{U} = -3.43\times10^{-6}t^2 + 4.46\times10^{-4}t \cdot Re - 4.34\times10^{-4}t \cdot U_0 + 3.32\times10^{-3}t - 9.64\times10^{-2}\,Re + 9.36\times10^{-2}\,U_0 + 3.32 \quad (5)$$

The initial rates of increase of the fouling resistance (dR_f/dt) obtained from the experimental works at 0-2 hours are plotted in comparison with the rates obtained from the empirical model presented by Fryer (1986) (equation (2)) in Figure 7. From the figure, the initial rate of increase of the fouling resistance decreases when the Reynolds number (flowrate) increases. Both the experimental data and the data predicted by the model agree

Table 4. Experimental data for the thermal performance analysis

Run number (LPM)	Coconut milk flowrate (ºC)	Coconut milk temp.	$U_{t = 0\ min}$ (W/m^2 K)	$U_{t = 6\ hr}$ (W/m_2 K)	$R_{f,\ t = 6\ hr}$ (m^2 K/W)	dR_f/dt (t = 0-2 hr) (m^2 K/Wmin)	dR_f/dt (t = 4-6 hr) (m^2 K/Wmin)
1	2	70-74.6	1035.3	643.8	0.00059	36.564×10^{-7}	6.0451×10^{-7}
2	4	70-74.6	1700.9	1173.6	0.00026	9.7055×10^{-7}	3.6326×10^{-7}
3	6	70-74.6	2367.7	1908.9	0.00010	2.8122×10^{-7}	2.7541×10^{-7}

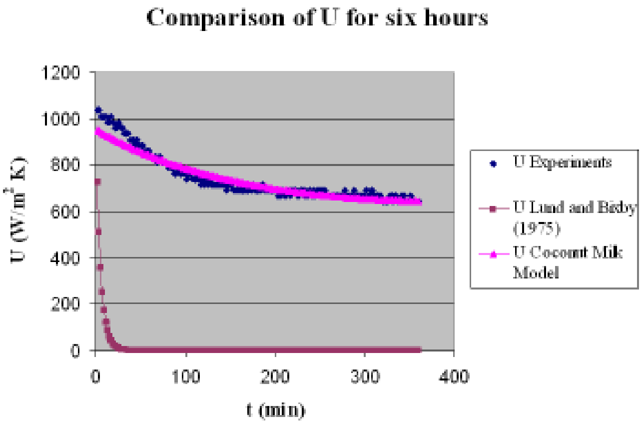

Figure 4. Comparison of the overall heat transfer coefficients obtained from the experiments and the models at flowrate 2 LPM

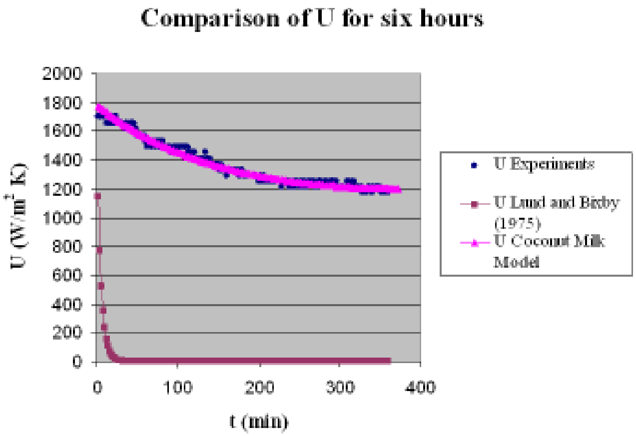

Figure 5. Comparison of the overall heat transfer coefficients obtained from the experiments and the models at flowrate 4 LPM

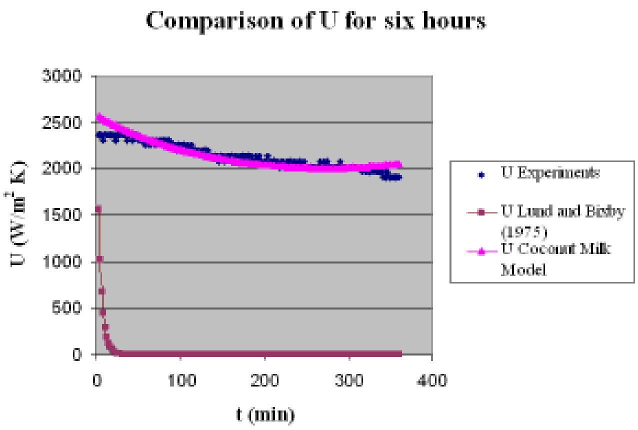

Figure 6. Comparison of the overall heat transfer coefficients obtained from the experiments and the models at flowrate 6 LPM

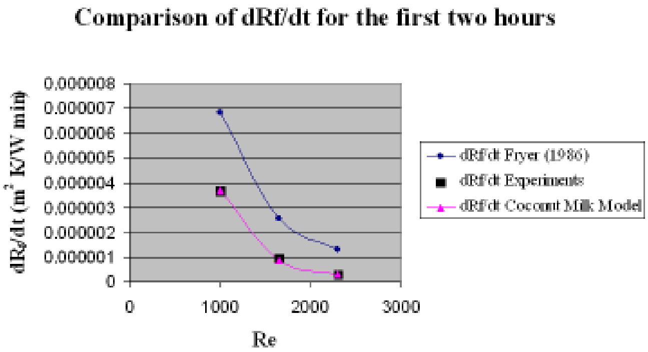

Figure 7. Comparison of the initial rate of increase of fouling resistance from the experiments and the models

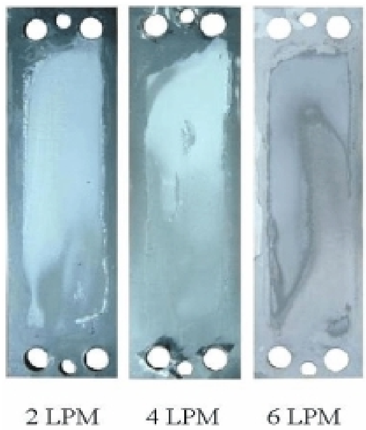

Figure 8. Photograph of the deposit on stainless steel plates at flowrate of 2, 4, and 6 LPM

with this phenomenon. This actually confirms that decreasing in the thickness of the laminar sub-layer by using higher 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 for this effect by recording the evolution of the U as seen in the previous section.

However, the skimmed milk model gave the higher rate of increase of fouling resistance than that obtained from the experiments. The difference in flow configuration and the difference in composition of fouling fluid are the main reasons for this. In the next section, with characterization of the deposit, differences in the deposit composition (cow milk and coconut milk) will confirm that a unique model to explain the coconut milk fouling is necessary. Here, to present the experimental data, the coconut milk model is formulated in the non-linear regression polynomial form with the R-Square value of 99%, represented by equation (6). The model plots, with the experimental data, are shown in Figure 7.

$$\frac{dR_f}{dt} = 1.95\times10^{-6}\,\mathrm{Re} + 1.89\times10^{-6}U_0 + 6.28\times10^{-6} \qquad (6)$$

3. Characterization of coconut milk fouling deposit

At the end of each experiment, the test section was dismantled. A photograph of the fouled plate for the operations with coconut milk flowrate of 2, 4, and 6 LPM was taken as in Figure 8. From the figure, fouling of the experimental

Table 5. Composition analysis of the deposit formation (% w/w)

Component(s)	Coconut milk solution	Coconut milk fouling 70-74.5 (ºC)
Protein	2.990	7.963
Fat	17.000	21.877
Minerals		
Calcium	0.0078	1.5603
Iron	0.0006	0.0258
Magnesium	0.0121	4.2883
Phosphorus	0.0410	0.8918
Potassium	0.0920	0.0393
Sodium	0.0415	7.0370

plates was observed by the naked eye as a white spongy deposit covering some part of the stainless steel plate. The operation with the lowest flowrate (2 LPM) shows the most contacting area covered by the foulant. This agrees with the results from the thermal performance calculations as this condition having the largest effect of fouling. Microanalysis results for protein, fat, and mineral of the dried coconut milk deposit are shown in Table 5. The coconut milk deposit contains protein (8%), minerals (14%) and fat (22%). At the same operating temperature, the cow milk deposit (type A) is made up of protein (50-60%), minerals (30-35%) and fat (4-8%) (Burton, 1968). The protein has been found to play an important role of cow milk fouling since the specific protein called β-lactoglobulin can denature and lose its stability in the liquid phase. However, for food fluid containing high percentage of fat such as coconut milk, a different phenomenon should be explained. This can begin with the literature about native chemistry of the coconut 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 and Goh (1994) described that the range of temperature 50-130ºC can reflect the complex protein structure. Two peaks or denaturation temperatures of coconut milk protein were found at about 92 and 110ºC respectively. Seow and Gwee (1997) stated that heating coconut milk at high sterilizing temperature can destroy heat labile proteins. This is followed by fat globules tending to aggregate and the liquid tending to contain 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 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. With this information, the coconut milk protein also acted as an important factor for coconut milk fouling at pasteurization temperatures. The structure of protein is altered by the processes of denaturation and aggregation to form deposit. Without undissolved protein as an emulsifying agent for the fat globules, small fat globules tend to aggregate. Attachment of aggregated fat particles onto the metal surface can then occur in significant amounts at this temperature.

The percentage of mineral content of the coconut milk deposit is also different from that of cow milk deposit. This is due to the difference in the native composition of the two fluids. Scanning electron microscopy (SEM) analysis was carried out on deposit sample obtained from the run with coconut milk flowrate of 2 LPM (Figure 9). The

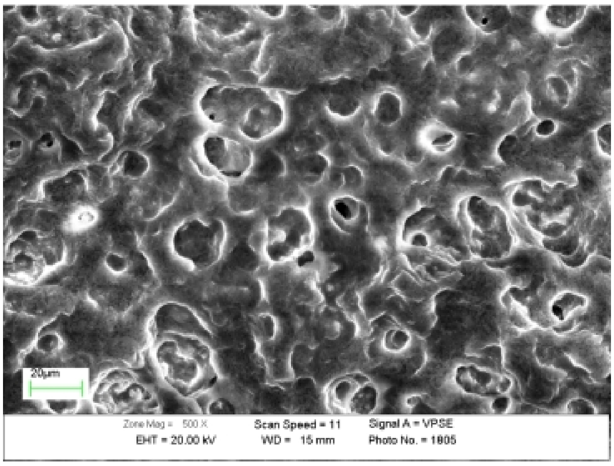

Figure 9. Foulant picture by SEM at 500X at flowrate of 2 LPM

mineral particles were embedded in the protein and fat layers. Further study is needed to verify for initial and subsequent layers of the deposit, which can lead to an understanding of the interaction between protein, fat, and mineral adsorption onto metal surface.

Conclusions

This study used engineering methods to investigate the effects of fluid flowrate on coconut milk fouling at pasteurization temperature (70-74.5ºC). The results have shown that the lower flowrate operation resulted in a higher rate of fouling by looking at the evolution of the overall heat transfer coefficient with time and the rate of increase of fouling resistance. An attempt had been made to predict the coconut milk fouling by using the model fouling from the literature. The results were not so good, and the coconut milk models were then provided. A possible mechanism of coconut milk fouling was proposed by exploiting the information obtained from chemical micro-analysis of the deposit and chemistry data of the coconut milk from previous research.

Nomenclature

A	overall heat transfer area (m^2)
LMTD	mean logarithm temperature difference (K)
Q	heat transfer rate (W)
R	universal gas constant (J/mol K)
Re	Reynolds number
Rf	fouling resistance (m^2 K/W)
T	temperature (ºC)
t	time (min)
U	overall heat transfer coefficient (W/m^2 K)

Subscripts

milk	coconut milk
t	time
o	clean condition
fi	fluid interface

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