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Dynamic Simulation of Plate and Frame Heat Exchanger Undergoing Rapid Fouling

Panya Triratana, Phavanee Narataruksa*, and Karn Pana-Suppamassadu

Department of Chemical Engineering, King Mongkut's Institute of Technology North Bangkok ,
1518 Pibulsongkram Rd., Bangsue, Bangkok, Thailand

Abstract

Mathematical model and dynamic simulation technique of plate heat exchangers (PHEs) with rapid fouling effects were presented. Crank Nicolson's method and the ghost node technique were used to solve the thermal model. Effects of fouling were added to model through the overall heat transfer coefficient correlation. Rung Kutta 4^{th} was used to receive the integral value of the fouling model. An experimental study of coconut milk pasteurization section by Pichitvitayakarn (2006) was used as a case study. The flow configuration was 1 pass 2 channels of hot water countercurrent with 1 pass 1 channel of coconut milk. Evolution of the coconut milk outlet temperature and the overall heat transfer coefficient with time from the simulation agreed well with those obtained from the experiments. The algorithm presented in this research work can be used to provide a result of step change of selected input variable(s), i.e. fluid flow rate and temperature. The feature allows control strategy to be specified in order to bring back an outlet temperature of one process stream when the process is undergoing fouling. The algorithm was also used to simulate the case of 1 pass 25 channels of hot water countercurrent with 1 pass 25 channels of coconut milk. The results of this case study indicated that adjustment of inlet temperature of hot water was appropriate in term of energy consumption.

Keywords: dynamic simulation, plate heat exchanger, rapid fouling

1. Introduction

Plate heat exchangers (PHEs) have been widely utilized in diary and food processing plants, chemical industries, power plant, and cooling system (Gut 2004) due to the ease of maintenance and cleaning, their compact designs and their excellent heat transfer coefficient characteristic (Shah and al., 1988). The PHEs consist of a pack of gaskets and corrugated metal plates pressing together with a frame. Gasket that seals around the plate prevents fluid mixing and forms PHE flow configuration such as series, parallel, and multi-pass arrangement by closing and opening ports where place at the four plate corners. Heat duty is easy to be adjusted by increasing or decreasing the number of metal plates.

To obtain the optimum flow configuration for a given duty, the steady state thermal model of PHEs has been used. A number of authors have presented steady state design methodologies for PHEs. Ngao-aram(1996) reported that ε-NTU method was useful for the design of PHEs for parallel or looped flow configuration which associated pressure drop across unit. Narataruksa (2000) developed general thermal model of PHEs for the uses of PHEs as two stream heat exchangers and multi-stream heat exchangers. Ribeiro(2002) showed the thermal performance which was the result of the simulation of co- and counter- current for series, parallel and multi pass arrangement herewith linear combination of exponential function. The results of the analysis clearly indicated the necessity of incorporating the dispersion and phase lag effect for prediction of transient behavior of multi-pass PHEs. Gut (2003) presented the thermal model and six parameter configurations that influence on exchanger performance. Next, Gut(2004) used this model and did the experiment to find heat transfer correlation, i.e. Nusselt Number. Heat transfer correlation corresponding with flow distribution pattern was a result of the research work. Gut(2004) optimized heat transfer area with the same thermal model and heat transfer correlation by screening method. The conclusion, screening method can be used to obtain the optimal configuration. Fernandes(2004) simulated the stirred yoketed in PHEs with computational fluid dynamics technique (CFD) to study velocity behavior in the flow channel. Numerical results concerning the difference between inlet and outlet yoghurt temperatures were compared with experimental data and a mean deviation of 6.9%and 7.3% for the simulations with variable and constant heat flux, were reported respectively.

However, to predict the change in PHE thermal performance where there are some disturbances, the steady state model has no longer useful. Especially, the PHEs used in food processes, a major problem is due to a kind of disturbance called food fouling. Fouling from food fluids has shown it significant effects on PHE performance resulting in significant increase in capital and operating costs of plants (Sandu & Lund, 1983). A number of authors have tried to simulate the effects of fouling. Prediction of fouling models for various food fluids was also presented such as the cow milk fouling models by Fryer (1985), Deplace (1994,1997) and Grispeerdt (2002), and coconut milk models by Pichitwitayakarn et. al.(2006). To reproduce the temperature profiles within the PHEs as a function of time, the fouling models have to be used with dynamic thermal models of PHEs as a dynamic simulation. Laksaman (1990) simulated thermal dynamic model of this kind of exchanger using cinematic model, and concluded that cinematic model can find not only the steady state temperature profiles but also dynamic temperature profiles. Shrafi (1997) predicted temperature profile of PHEs when the fluid viscosity was a function of temperature using explicit and Crank-Nicholson finite difference (FDM). Comparison of implicit and explicit methods was studied and can be concluded that explicit methods have the advantage of step change in hot fluid output temperature but it has a stability problem which can not be applied the time increment to small amounts. However, Crank-Nicolson FDM could be used which was an unconditionally stable method. Das (1995,2000) presented generalized models for thermal simulation of a single pass plate heat exchanger with flow distribution and end effects by using transfers function method, and concluded that flow maldistribution have a significant effect to thermal performance. Georgiadis (2000) simulated the effects of milk fouling by using thermal dynamic model coupled with kinetic milk fouling model. Three arrangements with 16 channels were used as case studies. The results of simulation were consistence with experiment data.

From literature survey, the dynamic thermal models were normally prepared to support a specific purpose of study of PHEs in the dynamic circumstances. For the operation of PHEs with food fouling, the model was found available for use with fouling models obtained from kinetic data of reaction fouling. In some cases, fouling models can be simply obtained from the experimental works which have shown the rate of decrease of thermal performance as function of operating parameters such as processing time, fluid temperature, and fluid flowrate. These empirical models are easy to obtain especially when the fouling mechanism is not dominated by reaction type. This work then presents fundamental dynamic models and simulations with respect to the fouling effects by the mentioned empirical fouling models. A system of PHE for pasteurization of coconut milk is used as a case study to compare the results of the simulated thermal performance with the experimental work.

2. A thermal dynamic model of PHEs

In PHEs hot fluid transfers heat to cold fluid through metal plates as shown in differential element (Figure 1). To obtain the thermal model for PHEs, following assumptions are utilized.

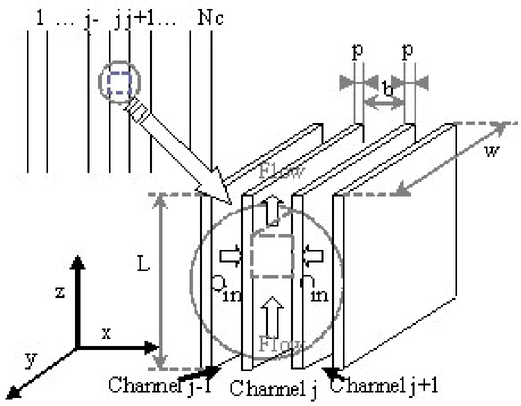


Figure 1 Channel Control Volume Element

- No diffusion of heat is considered in axial direction.
- Fluid flow rate and temperature profile are uniform across the channel and plate width.
- Each fluid is split equally between all related channels.
- Heat losses to environment are negligible.
- Header and follower parts of PHE are assumed to be insulated
- Fluid physical properties are not changed in a small range of temperature change.
- Complete mixing of liquid is obtained at outlet manifold.

- Heat convection between channels is calculated with respect to an overall heat transfer coefficient (U).
- Rate of fouling can be a function of processing time, fluid flowrate, and fluid temperature depending upon selected empirical fouling models.

The following equation describes the heat transfer between fluids over control volume which was derived via the fundamental energy conservation equation and simplified by above assumptions.

$$\frac{\partial T_{z,j}^{t}}{\partial t} = n_j v_j^t \frac{\partial T_{z,j}^{t}}{\partial z} + \frac{U_{j,j-1}^{t}\left(T_{z,j-1}^{t} - T_{z,j}^{t}\right)}{\rho_j^t C_{pj}^t b} + \frac{U_{j,j+1}^{t}\left(T_{z,j+1}^{t} - T_{z,j}^{t}\right)}{\rho_j^t C_{pj}^t b} \tag{1}$$

Where n is a direction of fluid, which value is +1 or -1 for downward and upward flow respectively. U is the overall heat transfer coefficient between hot and cold channel which can be estimated by a combination of thermal resistances as shown below.

$$\frac{1}{U_{j,x}^{t}} = \frac{1}{\alpha_x^t} + R_{fj}^{\ t} + \frac{p}{\lambda} + R_{fx}^{\ t} + \frac{1}{\alpha_j^t} \qquad \text{where } x \in \{j+1, j-1\} \tag{2}$$

α is a convective heat transfer coefficient of each fluid which can be evaluated via Nusselt Number (Nu), namely;

$$Nu = \frac{\alpha_j^t D_e}{\lambda} \tag{3}$$

Nu is a film coefficient which is a function of Reynolds Number (Re) and Prandtl Number (Pr). A general form of Nu for PHEs have been reported by Copper (1974).

$$Nu = 0.28\, Re^{0.65}\, Pr^{0.4} \tag{4}$$

$$Re = \frac{\rho_j^t v_j^t De}{\mu_j^t} \text{ and } Pr = \frac{Cp_j^t \mu_j^t}{\lambda} \tag{5}$$

And hydraulic diameter can be obtained by following relationship.

$$De = \frac{4 \times Ac}{Pc} \tag{6}$$

R_f is the fouling resistance on fouled plates. Fouling resistance can be obtained from fouling models (Fryer, 1985, Schreier,1993, Pichitvittayakarn, 2006) which some authors reported in the form of the rate of increase of Fouling Biot umber (dBi/dt). Bi can be calculated from the overall heat transfer coefficient within clean condition (U^0) and fouling resistance as show in the next equation.

$$Bi_j^t = R_{f\,j}^{\,t} U_j^0 \tag{7}$$

3. Numerical Simulation

Thermal Dynamic model which is a set of partial differential equations (PDE) was used to predict temperature profile by Finite Difference Method (FDM). Crank's Nicolson FDM is an implicit finite differential method with time dependence that gives stable solution for wide spatial direction and time (Smith,1985,Devid,1986), where a truncation error of time is of order 2. However, boundary conditions of PHEs are complex and depend strictly upon the internal flow configuration within the fluid channels. In this work, the ghost node technique (Narataruksa, 2000) is then used. The ghost need technique use three types of node, ghost node, real node and derived node. The real node is grid in flow direction. The ghost node is a node between adjacent two grids on the vertical direction or flow direction. The derived node is a combined node of the ghost node and real node. The distance between two adjacent derived nodes has a half value of the distance between two adjacent real nodes. Deriving the FDM model began with apply Centre Finite Difference with Crank's Nicolson method to general derived node. The FDM model in derived node index was changed to FDM model with real node and ghost node index. After that, the variables that have ghost node index were changed to real node index by applying an assumption in which the value of the ghost node properties is an average value of the value of two real nodes adjacent to the ghost node. Then, the FDM model retains only real node index as shown in equation 8. The FDM model is only used on the ghost nodes.

$$A_j^n T_{i,j}^{n+1} + B_j^n T_{i+1,j}^{n+1} = C_j^n T_{i,j}^n + D_j^n T_{i+1,j}^n + E_j^n (T_{i+1,j+1}^n + T_{i,j+1}^n) + F_j^n (T_{i+1,j-1}^n + T_{i,j-1}^n) \tag{8}$$

Where

$$A_j^n = 1 + \frac{n_j v_j^n \Delta t}{\Delta z} \qquad B_j^n = 1 - \frac{n_j v_j^n \Delta T_{i,j}^n}{\Delta z} \tag{9}$$

$$E_j^n = \frac{v_j^n U_{j,j+1}^n \Delta t}{\rho_j^n C_{pj}^n b} \qquad F_j^n = \frac{v_j^n U_{j-1}^n \Delta t}{\rho_j^n C_{pj}^n b} \tag{10}$$

$$C_j^n = B_j^n - E_j^n - F_j^n \qquad D_j^n = A_j^n - E_j^n - F_j^n \tag{11}$$

Fouling resistance as the rate of Bi change form (dBi/dt) is obtained by integration using Rung Kutta 4^{th} order. The calculation of R_f value can be done by substitution Bi value into equation (7). Then the U can be calculated by using R_f values on the left and right of the plate. Finally, all parameters of each channel, A-F, can be calculated.

When applying equations to all ghost nodes and boundary conditions, the equations were formed as a matrix equation, Ax = b. Inversing of matrix A was done and it has not changed with time. So the inverse matrix can be used for all time increasing. In PDE, initial conditions (I.C.) and boundary conditions (B.C.) were required. I.C. and B.C. of PHE systems were not the same and were set up corresponding to the internal flow arrangement.

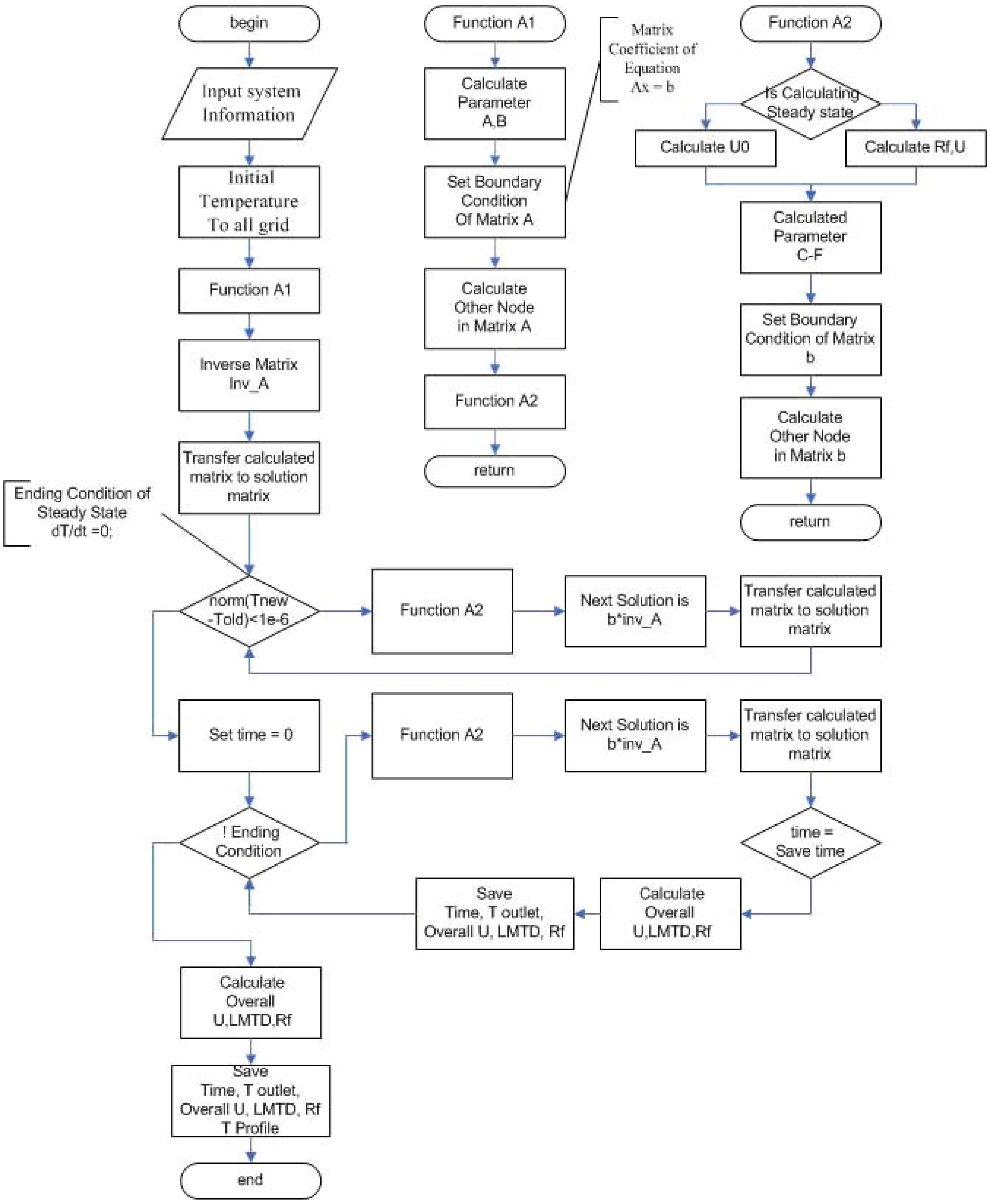


Figure 2 Algorithm

Simulation algorithm was shown in Figure 2. Firstly, with fluid flow-rate and temperature inlets, a steady state temperature profile with no heat loss was calculated for all channels. Next setting up time to zero, giving U at clean condition value of each plate (U^o_j) with U from the steady state was done. Now the calculation of PHE thermal performance with fouling effect was ready to begin. Starting with the calculation of fouling resistance, this can be done by solving a selected fouling model by using RK4 method. Further work was bringing its value to update in U model. Final step was the calculation of temperature profiles of the next time with the proposed thermal dynamic model. The calculating loop worked on until the time reaches a defining final time.

4. Case Study

PHE used for coconut milk pasteurization was referred as a case study in this work. The plate properties are showed in Table 1.

Table 1 : Plate configurations and properties (Pichitwitayakarn, 2006 and Narataruksa, 2000)

Plate Data	Case Study 1	Case Study 2
Thermal conductivity (W/m.K)	16.2	16.2
Width (m)	0.0085	0.205
Length (m)	0.3	0.785
Developed Area (m^2)	0.0255	0.168
Hot channel gab (m)	0.016	0.00366
Cold channel gab (m)	0.002	0.00366
Thickness (m)	0.0006	0.0009

Nusselt Number correlation used in this investigation was shown as below.

$$Nu = 0.036 Re^{0.8} Pr^{0.33} \tag{12}$$

The fouling resistance value was eliminated by the fouling model obtained from Pichitwitayakarn's (2006) experimental data as a function of time, namely;

$$\frac{dBi}{dt} = 3.187 \times 10^{-17} t^3 - 1.1257 \times 10^{-12} t^2 + 9.884 \times 10^{-9} t + 7.944 \times 10^{-6} \tag{13}$$

The case studies were separated into two cases. The first case was used to define a number of grids and the value of time difference for simulation. Then the simulation results were compared with experimental data of Pichitwitayakarn (2006). The second case was used to select condition for controlling PHEs undergoing rapid fouling.

4.1 Case Study 1

There were two objectives for solving this case study by the proposed algorithm. Firstly, a group of dynamic simulated results were needed to identify a minimum number of grids and a maximum number of time intervals in which the simulated results can be trustful. Secondly, to verify the thermal models and simulation technique, the simulated results were compared with the experimental results obtained by Pichitvittayakarn (2006) experiment.

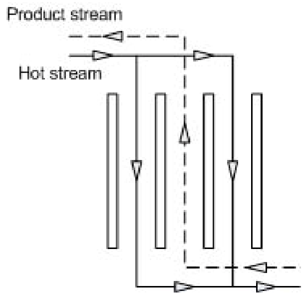


Figure 3 Three-channel flow arrangement which was used in Case Study 1

Table 2 : Fluid Properties

Properties	Case Study 1		Case Study 2	
	Water	Coconut milk	Water	Coconut milk
Volume flow (m^3/s)	$1.33x10^{-3}$	$6.67x10^{-5}$	0.00075	0.0025
Mass flow (kg/s)	1.2871	0.0792	0.0724	2.4610
T inlet (^{0}C)	90	70	90	70
μ (Pa.s)	0.0003	0.0012	0.0003	0.0012
k (W/m K)	0.673	0.675	0.673	0.675
Cp (J/kg K)	4205.1	3756.7	4205.1	3756.7
ρ (kg/m$^{3)}$	965.3	984.4	965.3	984.4

The simulation of 3 channels that was 1 pass 1 channel of coconut milk counter current with 1 pass 2 channels of hot water as shown in Figure 3 was investigated. The conditions of simulation were similar to Pichitwitayakan's (2006) experimental. The inlet properties of each fluid was shown in Table 2. Initial condition (IC) and boundary condition (BC) for this case study could be derived as following.

$$T_{i,a}^{0} = T_{h,in} \qquad i \in \{1 ... nGrid\} \text{ and } a \in \{1,3\} \tag{14}$$

$$T_{i,b}^{0} = T_{c,in} \qquad i \in \{1 ... nGrid\} \text{ and } b \in \{2\} \tag{15}$$

$$T^{n}_{nGrid,1} = T^{n}_{nGrid,3} \qquad n \in I^{+} \tag{16}$$

$$T^{n}_{0,2} = T_{cold\ in} \qquad n \in I^{+} \tag{17}$$

$$T^{n}_{nGrid,1} = T_{hot\ in} \qquad n \in I^{+} \tag{18}$$

$$T^{n}_{h,out} = \frac{T^{n}_{0,1} + T^{n}_{0,3}}{2} \qquad n \in I^{+} \tag{19}$$

4.2 Case Study 2

The objective of this case study was to use the algorithm in order to alter the conditions of the hot water, i.e. temperature and flow rate when the outlet coconut milk temperature was less than an acceptable temperature due to fouling effects. The flow diagram and flow configuration are shown as in Figures 4 and 5 respectively.

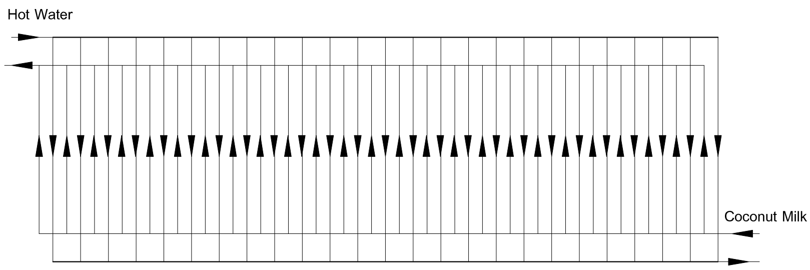


Figure 4 Fifty channel flow arrangement which was used in case study 2

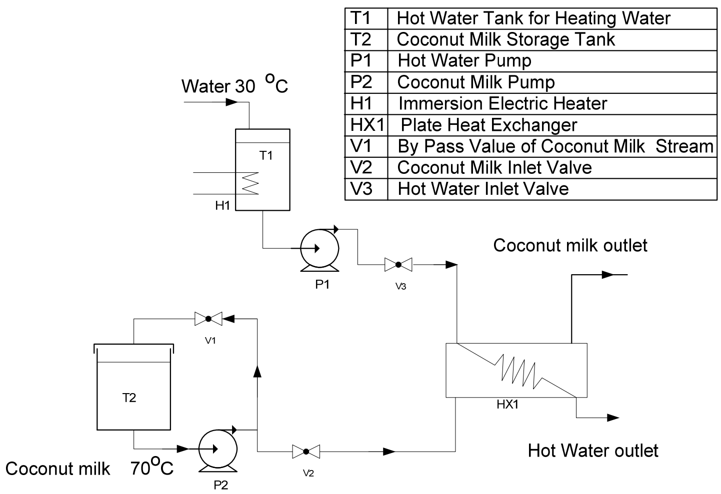


Figure 5 Flow diagram of case 2

The constrained and unconstrained situation of utility equipment that served temperature and flow rate of hot water was investigated in this case. The acceptable outlet coconut milk temperature of this case was 74 °C. The set point of the coconut milk temperature of this case was 74.5 °C.

Fluid properties at the inlet were shown in Table 1. IC and BC of this case was shown as following.

$$T_{i,a}^{0} = T_{hot\ in} \qquad i \in \{1...nGrid\} \text{ and } a \in \{1,3\} \tag{20}$$

$$T_{i,b}^{0} = T_{cold\ in} \qquad i \in \{1...nGrid\} \text{ and } b \in \{2\} \tag{21}$$

$$T_{nGrid,1}^{n} = T_{nGrid,x}^{n} \qquad n \in I^{+} \text{ and } x \in \{3,5,7...,49\} \tag{22}$$

$$T_{0,2}^{n} = T_{cold\ in} \qquad n \in I^{+} \tag{23}$$

$$T_{nGrid,1}^{n} = T_{hot\ in} \qquad n \in I^{+} \tag{24}$$

$$T_{h,out}^{n} = \frac{\sum_{x} T_{0,x}^{n}}{25} \qquad n \in I^{+} \text{ and } x \in \{1,3,5...,49\} \tag{25}$$

$$T_{c,out}^{n} = \frac{\sum_{x} T_{nGrid,x}^{n}}{25} \qquad n \in I^{+} \text{ and } x \in \{2,4,6...,50\} \tag{32}$$

The selected condition for parameter changing was the first condition that gave the outlet temperature of coconut milk being higher than the set point temperature. This case study separated into two sections.

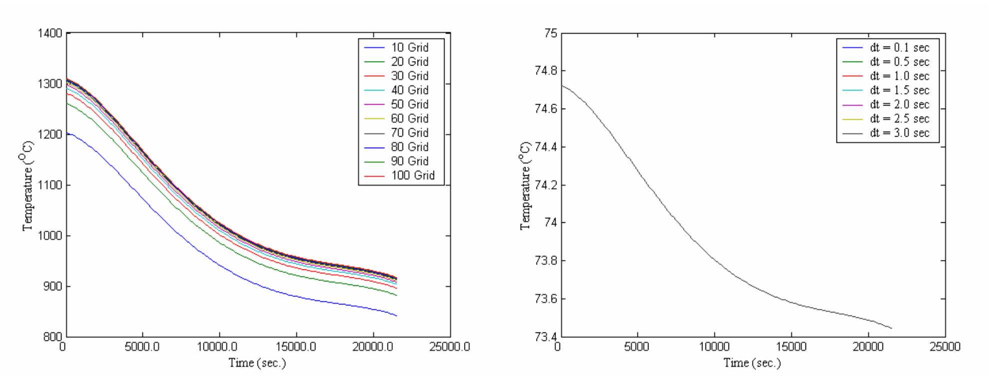
The first section investigated a case of unconstrained situation of utility equipment. In this section, only one parameter of inlet hot water, i.e. temperature or flow rate of hot water was freely adjusted. The change was done twice. The first change was done after PHEs was operated from clean condition until the outlet coconut milk temperature was less than the acceptable temperature. The second change was done when the outlet coconut milk temperature was less than the acceptable temperature for a second time.

The second section investigated a case of constrained situation of utility equipment. Limitation of temperature and flow rate changes of the hot water was up to 92 °C and 8 x10^{-4} m^3/s respectively. In this case, changing only one parameter could not retrieve the outlet coconut milk temperature back to the set point. Then, adjusting one parameter to maximum value was done first and another parameter was adjusted until the set point temperature was reached.

5. Result and Discussion

5.1 Case Study 1

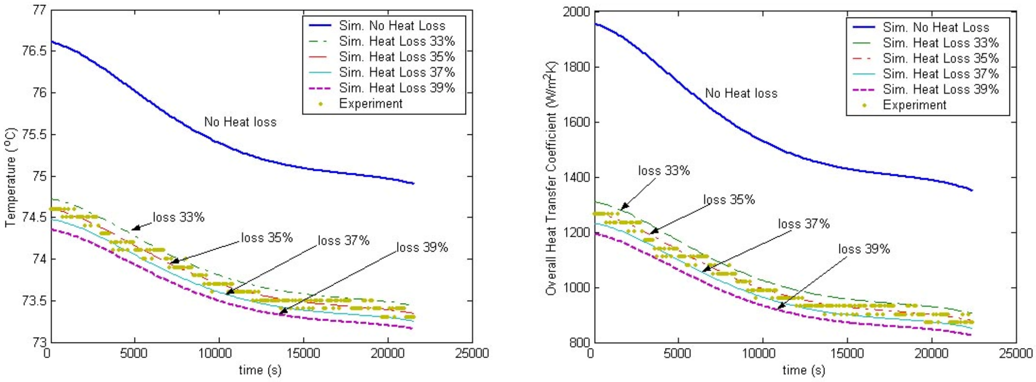
In the present investigation, the governing partial differential equation (PDE) was approximated by Finite Difference Scheme (FD scheme), which a convergence strongly depended on the number of applied grids. In general, the FD scheme tends to need a small grid size to assure the convergence, but also the smaller gird size implies more computational time. Therefore, the optimum number of grids was obtained by varying the number of grids, and the corresponding results were shown in Figure 6(a). The number of grids was varied from 10 to 100 grids with 10-grid increment. The simulated cold outlet fluid temperature vs. time profile changed dramatically within the range of small number of grids, and slowly changed when the number of grids was further increased to a higher value range. When the 100 grids were used, the temperature time profile was not different appreciably from those applied 80 and 90 grids. As a consequence, the present study adopted the 100 grids to implement for further study. In addition, the consistency of the FD scheme applied herein was not taken for granted, but after limiting both time-step and grid-size to zero, the representative FD equation returned to the original PDE.



(a) (b)

Figure 6 : Comparison of simulated cold outlet temperature vs time profiles obtained from (a) different number of grids. (b) different sizes of time interval

By applying a generalized Crank-Nicolson method, for a given set of equations and a set of grids, the sensitivity over time-step was complimented. Stability analysis demonstrated that this scheme was unconditionally stable for the dynamic model. Nevertheless, to reduce a computational time, the optimum time interval was searched, and the results were simulated with varied Δt between 0.1 to 3.0 second. As evidently seen from the Figure 6(b), the simulation results were not influenced by changes of time interval. The time interval of 1 second was chosen in order to preserve the variations of system's physical properties according to the temperature variation, however, i.e., the algorithm recalculated the most update physical properties after every 1 second.



(a) (b)

Figure 7: Comparison of the overall coefficient from simulation (100 Grid) and experiment

As displayed in Figure 6(a) a case with no heat loss (solid line), the simulated outlet temperature of the cold fluid was higher than that of the experiments conducted by Pichitvittayakarn (2006) about 1.1 °C. Since, the model did not incorporate for heat dissipations from the rig to environment. The pre-estimated amount of heat loss due to imperfect insulation was about 33%. This based on the experimental results of Pichitvittayakarn (2006). Therefore, once these heat losses were accounted for, the adjusted simulation results now exhibited well-agreed behavior with the experimental results. Similarly, the time profiles of the overall heat transfer coefficient both from the experiments (Pichitvittayakarn, 2006) and from the simulation illustrated a better agreement after the inclusion of heat losses, as seen in Figure 7(b).

5.2 Case Study 2

The first section incorporated the cases where only one parameter had been changed. Figure 8 illustrates the outlet temperature of coconut milk vs. time obtained by simulation. Table 3 concluded the conditions of this section.

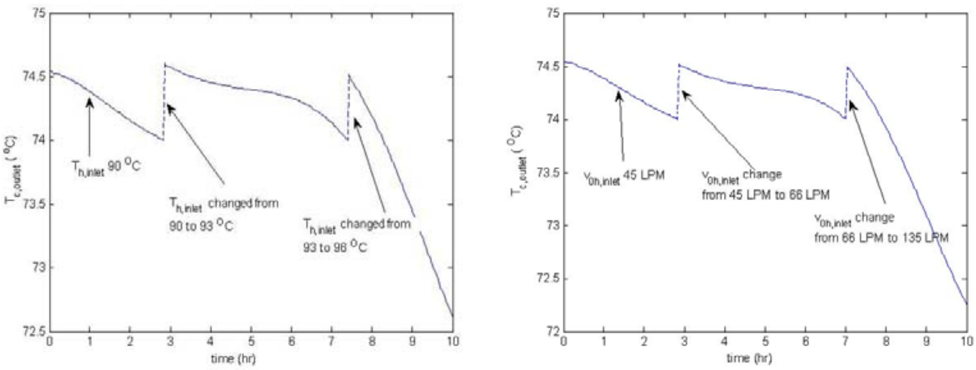


Figure 8: Outlet temperature of coconut milk vs. operating time

a) Changing hot water inlet temperature

b) Changing hot water flow rate

Table 3 : Simulation results of case 2 – first section

Energy cost per unit ($US/kW-hr)			0.0721	
Conditions	Temperature changes		Flow rate changes	
	1st	2nd	1st	2nd
Room temperature (°C)	30	30	30	30
Old temperature (°C)	90	93	90	90
New temperature (°C)	93	96	90	90
Old flow rate (m^3/s)	0.00075	0.00075	0.00075	0.0011
New flow rate (m^3/s)	0.00075	0.00075	0.0011	0.00225
Energy consumption (kW)	9.13	9.13	85.25	280.05
Extended operating time (hr)	4.6	0.84	4.2	0.84
Extended operating time for comparison (hr)	4.2	0.84	4.2	0.84
Cost of energy ($US)	2.765	0.553	25.814	16.964

When PHE which operated from clean condition gave the outlet coconut milk temperature being less than the acceptable temperature, adjusting of the inlet hot water temperature from 90 °C to 93 °C or adjusting of the hot water flow rate from 7.5 x10^{-4} m^3/s to 1.1 x10^{-3} m^3/s was done. After this, the inlet hot water temperature must be adjusted from 93 °C to 96 °C or the hot water flow rate must be adjusted from 1.1x10^{-3} m^3/s to 2.25 x10^{-3} m^3/s when the outlet coconut milk temperature was less than the acceptable temperature for the second loop. From this point, the energy consumption was important. Table 3 showed that the energy cost for the case of changing the hot water temperature was cheaper than that of changing the hot water flowrate case about 9.33 times and 30.7 time for the first and the second loop, respectively. Moreover, the time extension seemed to be longer than that of the flow rate adjustment. Therefore, the change of the inlet hot fluid temperature was appropriated in terms of energy consumption and extended operating time. This conclusion was based on assumption that the inlet hot water temperature change was not influence by time or step change.

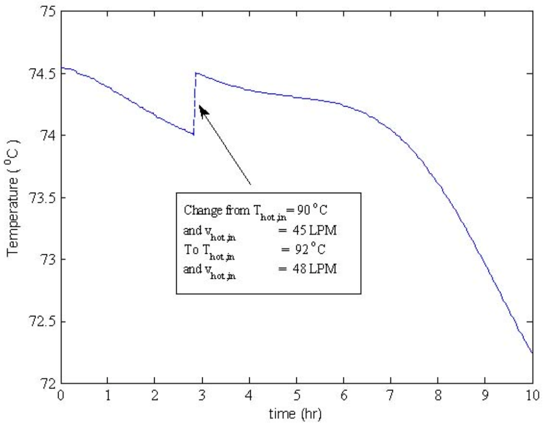


Figure 9: Coconut milk outlet temperature vs. time by simulation when inlet temperature and flow rate of hot water had been changed.

The second section was handled by multiple-parameter changing. If the inlet hot water temperature was adjusted to its maximum value of 92 ^{o}C, then the hot water flow rate was adjusted accordingly to $8x10^{-4}$ m^3/s. Alternatively, if the hot water flow rate was adjusted to its maximum value of $8.67x10^{-4}$ m^3/s, then the inlet hot water temperature was adjusted up to 92 ^{o}C. Figure 9 showed the simulated results of the outlet coconut milk temperature vs. time of the chosen condition. The results indicated that the strategy to control PHE when the single parameter adjustment did not work out, was an arrangement of the temperature adjustment coupled with the flow rate adjustment in which the changing values can be found roughly by the method proposed in the first section.

6. Conclusions

In this study, Crank-Nicolson Finite Difference scheme with central difference and ghost node technique were used to represent the PDE of dynamic thermal model of the plate heat exchangers. Rapid fouling effects were focused in this work as an internal disturbance. The empirical fouling model based on the work of Pichitvittayakarn (2006) was referred as an example of food fouling. The simulated results of the cold outlet temperature and the overall heat transfer coefficient vs time profiles agreed well with the experimental results from the work done by Pichitvittayakarn (2006). The proposed dynamic model and calculation algorithm is very promising in simulating the thermal performance of the PHE undergoes rapid fouling; however, the reliability of the simulation relies strongly on the accuracy of fouling models adopted therein. The algorithm presented in this work can also be used to identify the optimum control strategy for the PHE. Single or multiple parameter changing on the utility side can be delivered to extend PHE operating time. Magnitude of tuning can be investigated by simulation method already presented.

7. Nomenclature

Ac	Cross section area (m^2)
b	plate gab(m)
Bi	fouling Biot number
C_p	specific heat capacity (J/kg K)

D_e	Hydraulic diameter(m)
Nu	Nusselt Number
n	Sign of direction
Pc	Cross section Perimeter (m)
Pr	Pranlt Number
p	Plate thickness(m)
Re	Renold Number
R_f	Fouling Resistance (m^2 K/W)
t	Time(s)
T	Temperature(K)
U	Overall heat transfer coefficient (W/m^2 K)
v	Fluid velocity(m^2/s)
z	Distance in vertical direction (m)
nGrid	maximum number of grid, grids.

Symbol

ρ	Density (kg/m^3)
α	Convective heat transfer coefficient (W/m^2 K)
λ	Thermal conductivity(W/m K)
μ	Dynamic viscosity (Pa.s)

subscripts and superscripts

i	Number of grid; Spatial index
j	Number of channel
n	time index
t	time
c	cold fluid
h	hot fluid
in	inlet
nGrid	maximum number of grid

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