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ALGORITHM DEVELOPMENT FOR OPTIMAL CLEANING
OF HEAT EXCHANGER NETWORK
USING TIME DISCRETISATION APPROACH

Miss Slita Nusong

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Chemical Engineering
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สลิตา หนูสงค์ : การพัฒนาระเบียบวิธีสำหรับการทำความสะอาดที่เหมาะสมของข่ายงานเครื่องแลกเปลี่ยนความร้อนโดยวิธีการดีสครีไทเซชันของเวลา (ALGORITHM DEVEOPMENT FOR OPTIMAL CLEANING OF HEAT EXCHANGER NETWORK USING TIME DISCRETISATION APPROACH) อ. ที่ปรึกษา: อ. ดร. สุรเทพ เขียวหอม, 121 หน้า.

ในโรงงานอุตสาหกรรมเคมีซึ่งใช้งานเครื่องแลกเปลี่ยนความร้อน การเกิดตะกรันบนพื้นผิวแลกเปลี่ยนความร้อนเป็นปัญหาหลัก เนื่องจากการเกิดตะกรันทำให้ใช้พลังงานเพิ่มขึ้นส่งผลให้เกิดความสูญเสียทางเศรษฐศาสตร์ ดังนั้นจึงต้องมีการล้างทำความสะอาดเครื่องแลกเปลี่ยนความร้อนอย่างสม่ำเสมอเพื่อลดความสูญเสียที่เกิดขึ้นนี้ ในงานวิจัยนี้ได้ทำการเลียนแบบเครื่องแลกเปลี่ยนความร้อนทั้งในกรณีของเครื่องแลกเปลี่ยนความร้อนเครื่องเดียวและในกรณีของข่ายงานด้วย โดยใช้แบบจำลองการเกิดตะกรันแบบเชิงเส้นและเชิงเส้นกำกับ จากนั้นได้ศึกษาผลของตัวแปรในแบบจำลองต่อการเปลี่ยนแปลงตามเวลาของอุณหภูมิขาออกของกระแสร้อนและกระแสเย็น สัมประสิทธิ์การถ่ายเทความร้อนและอัตราการถ่ายเทความร้อน นอกจากนั้นได้สร้างปัญหาออฟติไมเซชันเพื่อหาตารางเวลาการล้างทำความสะอาดเครื่องแลกเปลี่ยนความร้อนที่ดีที่สุดโดยใช้วิธีการเวลาไม่ต่อเนื่อง ปัญหาออฟติไมเซชันที่สร้างขึ้นจะหาค่าผลรวมของต้นทุนการดำเนินการที่น้อยที่สุดภายใต้ข้อกำจัดเงื่อนไขสภาวะการดำเนินการ ตัวแปรออฟติไมซ์คือตัวแปรตรรกบ่งบอกถึงการตัดสินใจในการล้างทำความสะอาดเครื่องแลกเปลี่ยนความร้อนหรือไม่ในแต่ละช่วงเวลาที่กำหนดไว้ นอกจากนั้นได้พัฒนาวิธีการใหม่ในการจัดการกับตัวแปรตรรกจำนวนมากซึ่งพบในปัญหาที่สร้างขึ้น วิธีการที่พัฒนาขึ้นนี้สามารถแก้ปัญหาได้อย่างมีประสิทธิภาพและสามารถหาคำตอบที่ดีกว่าการแก้ปัญหาแบบเดิม

ภาควิชา........วิศวกรรมเคมี........	ลายมือชื่อนิสิต.....สลิตา หนูสงค์.....
สาขาวิชา......วิศวกรรมเคมี........	ลายมือชื่ออาจารย์ที่ปรึกษา.....สุรเทพ เขียวหอม.....
ปีการศึกษา.........2550…………	

4870509521 : MAJOR CHEMICAL EHGINEERINGR
KEY WORD : CLEANING SCHEDULE / FOULING / HEAT EXCHANGER NETWORK / OPTIMIZATION / MINLP

SLITA NUSONG : ALGORITHM DEVEOPMENT FOR OPTIMAL CLEANING OF HEAT EXCHANGER NETWORK USING TIME DISCRETISATION APPROACH. THESIS ADVISOR: SOORATHEP KHEAWHOM, PH. D., 121 pp.

In all chemical plants using heat exchangers, fouling of heat transfer surfaces is a major problem because it increase energy consumption resulting in economic losses. Thus, the regular cleaning of fouled units is implemented to reduce this losses. In this work, the simulations of heat exchanger in a case of single unit and also in network are performed based on linear and asymptotic fouling models. The effect of various model parameters on a variations with time of outlet temperature of hot and cold stream, heat transfer coefficient and heat transfer rate is investigated.

In addition, the problem of optimal cleaning schedule of heat exchangers based on time discretisation approach is formulated. The formulated optimization problem minimizes the summation of operating cost with subject to various operating conditions constraints. The optimized variables are logical variables decided whether a heat exchanger should be cleaned in each time period specified. Moreover, we also develop a new technique to handle a very large number of logical variables occurred in the problem formulated. Our technique can efficiently solve the problem while obtain a better solution compared with the traditional method.

Department……Chemical Engineering… Student's signature……Slita Nusong……

Field of study…Chemical Engineering… Advisor's signature……Soorathep Kheawhom……

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NOMENCLATURES

A_t	=	Total area available for heat transfer (ft^2)
R_t	=	Effective (overall) thermal resistance (h ft^2 °F/Btu)
U	=	Overall heat transfer coefficient (Btu/h ft^2 °F)
A_i	=	Total inner area available for heat transfer (ft^2)
A_o	=	Total outer area available for heat transfer (ft^2)
R_c	=	The conductive resistance for a cylindrical surface
r_i	=	Inner fouling factor (h ft^2 °F/Btu)
r_o	=	Outer fouling factor (h ft^2 °F/Btu)
h_i	=	The convection resistance (inner) (Btu/h ft^2 °F)
h_o	=	The convection resistance (outer) (Btu/h ft^2 °F)
L	=	Length of heat exchanger (ft^2)
k	=	Thermal conductivity of tube (Btu/h ft^2 °F)
F_o	=	The fouling factor for outer surface (h ft^2 °F/Btu)
F_i	=	The fouling factor for inner surface (h ft^2 °F/Btu)
R_f	=	The fouling factor (h ft^2 °F/Btu)
U_{dirt}	=	Overall heat transfer coefficient in dirty condition (Btu/h ft^2 °F)
U_c	=	Overall heat transfer coefficient in clean condition (Btu/h ft^2 °F)
Q	=	Heat transfer rate (Btu/h)

ΔT_{ln} = Log mean temperature difference (°F)

F_h = Mass flow rate of hot stream (lb/h)

F_c = Mass flow rate of cold stream (lb/h)

$T_{h,in}$ = Inner temperature of hot streams (°F)

$T_{h,out}$ = Outlet temperature of hot streams (°F)

$T_{c,in}$ = Inlet temperature of cold streams (°F)

$T_{c,out}$ = Outlet temperature of cold streams (°F)

F = Mass flow rate (lb/h)

$C_{p,h}$ = Specific heat capacity of hot stream (Btu/lb °F)

$C_{p,c}$ = Specific heat capacity of cold stream (Btu/lb °F)

r_f = Fouling rate (h ft^2 °F/Btu)

r_f^{∞} = Initial fouling rate (h ft^2 °F/Btu)

t = Time (month)

GREEK LETTERS

ε = Effectiveness

τ = Time constant of fouling decay

SUBSCRIPTS

i = Inner

o = Outer

t = Time

h = Hot stream

c = Cold stream

in = Inlet

out = Outlet

ACRONYM

max = Maximum

min = Minimum

LMTD = Log Mean Temperature Difference

LP = Linear Programming

MILP = Mixed Integer Linear Programming

NLP = Nonlinear Programming

MINLP = Mixed Integer Nonlinear Programming

MIP = Mixed Integer Programming

DE = Different Evolution

HEN = Heat exchanger network

CHAPTER I

INTRODUCTION

In all chemical industries, the energy required plays an important role in the operating costs. To intensify the energy consumption of the process, heat recovery is necessary. Therefore, heat exchanger networks are implemented in almost all chemical plants. However, there are many problems in heat exchanger network such as leaking or fouling. These problems lead to a reduction of heat exchanger network performance. Fouling of heat exchangers is a major industrial problem. It leads to the reduction of heat transfer efficiency and heat transfer rate. Therefore, it reduces the heat exchanger performance, resulting in an increasing of energy loss. It also reduces production rate, and increases cleaning and maintenance costs. Thus, the effective methods for mitigating fouling are important.

There are many effective mitigation fouling techniques (F. Smaili et al, 2001). Reducing the rate of fouling by interrupting the mechanisms causing fouling such as in crude oil systems by adding anti fouling chemicals. This method results in increasing the operation costs. Other methods are control of feedstock composition and operating conditions. Improve the performance of heat exchanger by using more efficient heat transfer equipment such as fluidized bed exchangers, or a more flexible network configuration including greater size or duplicate units for such duties. This technique increases the capital cost of the system. Remove fouling in heat exchanger by cleaning fouled units during operating, in order to restore thermal and hydraulic performance of the network. Cleaning method affects both the operating and capital costs. Generally, chemical processes use a combination of these techniques in order to minimize the overall operating costs.

The consideration of which and when heat exchanger to be cleaned is important. Normally, cleaning improves the heat exchanger performance results in reduction of energy costs. Whereas, during cleaning period the heat exchanger needs to be stopped, resulting in the requirement of external utility. Therefore, in cleaning period the external utilities cost actually increases. Thus, cleaning too often may not be economically favorable after all.

The problem of cleaning schedules is a mixed integer nonlinear programming (MINLP). It involves binary variables indicating which unit has to be cleaned and continuous variables indicating the network performance. The optimal cleaning problem requires a reliable model of the network, representative fouling models for predicting unit performance, and an efficient solution technique. The difficulties in this problem is the availability of reliable fouling models, owing to the variation in process fluid composition over extended operating periods and difficulties in extending laboratory results to complex (Smaili, F. *et al*., 2001). In previous research, Georgiadis and Pagageorgiou (2000) developed a mixed integer linear programming (MILP) model by using arithmetic-mean temperature differences instead of log-mean temperature differences. This model could be solved to give a global optimum. Smaili, F. *et al.* (2001) studied a mixed integer nonlinear programming model without approximate the nonlinear equations related to heat transfer or the fouling model. The mixed integer nonlinear programming problem was solved using outer approximation and extended relaxation algorithm. The approximation of the global optimal solution was provided by relaxed mixed integer nonlinear programming model. Thus, for small problems, the model is capable of rendering global optimality. However, because computational limitations for large models, a decomposition procedure is required.

In this work, we develop an algorithm based on mixed integer nonlinear programming problem. The main goal of this study is the development of algorithm using time discretisation. The optimal cleaning schedule of heat exchanger networks is obtained by solving the optimization problem formulated. We define a binary variable that identifies when and which each heat exchanger is cleaned. To handle logical variables, we propose a novel technique using decimal to binary transformation. The model does not approximate the nonlinear equations related to heat transfer or the fouling models.

1.1 Research Objective

The objective of this research is to develop algorithm based on time discretisation approach in order to find the optimal cleaning schedule of heat exchanger networks under fouling condition. The optimal results are obtained by using a newly technique to handle a logical variable. The objective function postulated to minimize value of the operating cost.

1.2 Scopes of research

1. Study the problem formulation using time discretisation approach.

2. Mathematic models of the heat transfer coefficient and the temperature relations in a heat exchanger are studied.

3. The cleaning schedule model applied to a crude oil preheat train, the exponential asymptotic fouling behavior and linear fouling behavior are considered.

4. The case studies of this research are divided to two cases; first case is focused on a single heat exchanger case for 24 months horizon. The second case deals with a heat exchanger network case of ten heat exchangers and the time horizon contains 18 months.

5. Two differential cleaning costs were used; 4,000 and 8,000 £/unit.

6. A differential evolution (DE) optimization method is implemented to optimize the cleaning schedule of heat exchanger network.

7. Programs written to optimize the cleaning schedule of heat exchanger network are based on C language.

1.3 Contributions of research

The contributions of this research are follows:

1. The new algorithm to optimize the cleaning schedule is developed using time discretization approach.

2. The newly technique to handle a logical variable is used.

1.4 Research procedures

1. Study the literature reviews related to optimization of cleaning schedule for heat exchanger network.
2. Study the differential evolution optimization method.
3. Formulate the synthesis problem using time discretization approach.
4. Optimize the cleaning schedule for heat exchanger network via minimizing operation cost.
5. Analyze the obtained solution.
6. Conclude and write the thesis.

1.5 Research Framework

This thesis is organized as follows: First, the literature reviews related to optimal cleaning schedule of heat exchanger network are presented in Chapter II. Second, the theories of the heat exchanger, fouling formation and nonlinear programming problem are explained in Chapter III. Third, the simulations of single heat exchanger results are presented in Chapter IV. Next, the results of optimal cleaning schedule for single heat exchanger and heat exchanger network are presented in Chapter V. Finally, the conclusions and the recommendations for future work are given in Chapter VI.

CHAPTER II

LITERATURE REVIEW

In recent years, the fouling is major problem in heat exchanger network. It reduces heat transfer rate causing in the reduction of heat exchanger performance. There are many effective fouling mitigations techniques such as using antifouling compound, increasing the heat transfer area and regular cleaning. The combination of these techniques applies in order to minimize the operating cost. In general, it is necessary to determine the optimal cleaning schedule of heat exchanger network for improved heat exchanger performance. This chapter provides a review of the optimization of cleaning schedule of heat exchanger network.

2.1 Mathematic model of fouling

The simulation of fouling in heat exchanger for predicting the variation of overall heat transfer coefficient and variations of outlet temperature of hot and cold streams is important. These variations have a significant effect on production rate and operating cost. The main goal is to find the variation of outlet temperature of hot and cold streams with time to plan the optimum cleaning schedule of heat exchanger network that provide the minimum operating cost. Thus, the accuracy of fouling model is necessary.

The mathematic model of fouling has been proposed by Steinhagen, H.M. (1998). Two highly complex fouling problems have been described, where the heat exchangers are part of a network of flash tanks, intermediate tanks and digesters. From this work, systematic collaborative investigations have been performed, involving a wide range of experimental and modeling studies at laboratory and plant level. As a result of these investigations, several potential fouling mitigation strategies could be identified.

Wang, L. *et al.* (2001) studied the simulation of heat exchanger network using flexibility consideration approach. It is clear that the two equations are linear with respect to temperatures but they are nonlinear with respect to heat capacity flow rates. From this work, they found that the different cleaning methods may be used after the fouling has become bigger than the value of fouling factor of original design setting. The time for the fouling accumulates from zero to the original design setting value can be called an operating period.

Moreover, Bohnet, M. *et al*. (2003) proposed the simulation of crystalline fouling. The simulation of real crystal growth requires a continuous variation of the geometric flow model. Results of the numerical simulation are prediction of fouling resistance as a function of time. The temperature distribution within the fouling layer is calculated.

Kaikko, J. *et al.* (2007) studied the effect of heat exchanger fouling on the performance of Stirling engine and determine the optimal cleaning. The optimal cleaning can be determined by adding the costs for one period that includes the time for the fouling and time for cleaning. The optimization is based on determining the fouling time that yields the minimum cost flow. Cleaning time is assumed independent of the fouling time. The cleaning is performed for both heat exchangers at the same time.

In addition, Steinhagen, H.M. *et al.* (2007) proposed the model for the prediction of fouling resistance of dehydrate process for the production of phosphoric acid. The results of the experiments are used to develop mechanistic model. For removal of deposits by dilute sulphuric acid solutions. The predictions of the suggested models for fouling and cleaning are compared with measured data. They found that at low velocities the deposition process is mainly controlled by the mass transfer of reactants to the heat transfer surface. The fouling rate is increased by increasing velocity. At higher fluid velocity the deposition is influenced mostly by chemical reaction on the surface.

2.2 Optimization of cleaning schedule

The optimization of cleaning schedule in heat exchanger network has been considered until recently. Casado *et al.* (1990) proposed a model based on the cost of cleaning the fouled exchangers. The asymptotic fouling model for counter current flow exchangers and thermal analysis of the hot and cold streams are implemented in this work. This work explained the costs of fouling and proposed a time dependent objective and cost function in the process operation. The cleaning plan based on minimization of the process operation cost.

Nilay, S. *et al.* (1995) proposed a mathematic model for simultaneously scheduling production and maintenance activities within a multipurpose plant, taking account of both production resourced and maintenance. The formulation results in large scale mixed integer linear programming models can be solved using standard MILP packages, as well as tailored branch and bound technique. In addition to the set of constraints which are needed to accurately model the problem, and additional redundant constraints are added in order to make the solution more efficient.

Wilson, D.I. *et al.* (1999) proposed the optimization of membrane scheduling in reverse osmosis of seawater desalination. The systematic method is required to calculate the optimal cleaning schedule of reverse osmosis network. The problem is analyzed using a discrete time interval approach, assuming an exponential decay in membrane permeability and perfect regeneration at cleaning. The scheduling problem is complicated by the lack of long term fouling or performance data. The problem is nonconvex (MINLP) and features a number of local optima, so that the solution is sensitive to the starting point. The results obtained are very sensitive to the cost and fouling model employed in the simulation. For the cleaning, the total numbers of cleaning increase with the complexity of the network. More cleaning actions are required as the number of units in each stage increase. Inspection of the cleaning schedule and operating parameters indicated that cleaning is frequently prompted by the operating parameter constrained. The cost function on the form of solutions generated and the reliable input data are important. The optimal cleaning schedule problem is used a multiperiod formulation. Thus, the problem of when a unit has to be cleaned is considered directly. This is resulting in only certain units may be selected to be cleaned. But, the formulation is proposed to answer the question of when to clean which exchanger.

Also, Smaili, F. *et al.* (1999) studied the optimization of scheduling of cleaning in heat exchanger networks subject to fouling for sugar industry. This work described the use of an NLP/MINLP formulation incorporating a new modeling formulation to obtain cleaning schedules for the thin juices preheat train in a sugar refinery. The MILP or MINLP must be combined with a reliable simulation of the network including models of the fouling behavior of the units in the network. Linear fouling models were obtained by reconciliation of data from the plant operating system. The accuracy of modern numerical techniques is usually greater than the certainty attached to fouling data and fouling models. The nonconvexity of the problem resulted in a number of suboptimal but adequate solutions. The global optimum was non-intuitive.

Moreover, Georgiadis, M.C. *et al.* (2000) considered the short term cleaning scheduling problem of complex heat exchanger networks under fouling, a special application in heat exchanger network under milk fouling. A mixed integer nonlinear programming model was developed, and linearized to a mixed integer linear programming model. The later model can be solved to global optimality yields a very tight formulation. It required a few nodes in the branch and bound tree. The mixed integer nonlinear programming model cannot be used for solution of problems with more than 10 – 12 exchangers over an operating horizon of 24 months. In addition, it was shown that the mixed integer nonlinear programming may lead to suboptimal solutions. On the other hand, the linearized mixed integer linear programming model was solved with modest computational effort. A number of examples with up to 15 exchangers have been solved to illustrate the capability and efficiency of the proposed model.

Next year, Georgiadis, M.C. *et al.* (2001) proposed a mathematical programming framework for introduction of fouling consideration during the heat integration of batch plant operation. A short-term scheduling problem is considered that seeks to determine the optimal utilization of the available plant resourced over a given time horizon. Due to fouling, the performance of heat integrated units decrease with time which therefore have to be shut down for cleaning after regular intervals. An iterative procedure for solving the resulting nonconvex mixed integer nonlinear programming has been proposed, involving the solution of a series of mixed integer linear programming and nonlinear programming subproblems. A series of mixed integer linear programming /nonlinear programming problems can be solved where during each iteration a decreasing upper bound in the objective function of the mixed integer linear programming problem and integer cuts excluding previous integer solutions can be imposed. Upon termination, the algorithm determines a range within which the optimal objective function is guaranteed to lie.

The nonlinear model was described by Smaili, F. *et al.* (2001). This work developed mixed integer nonlinear programming model scheduling problem of oil refinery crude preheat, based on a regular time discretisation heuristic. The mixed integer nonlinear programming model described the constraints of process including pressure drop and pump-around limitations. Solution of the model obtained using a commercial optimization solver that the equation representing the network and its constraints were written in the GAMS programming environment and solved using DICOPT++. In this research, there are two case studies: (I) an idealized network containing 14 exchangers over three years and (II) an operational plant is featuring 27 exchangers for a two-year horizon. The fouling models and parameters for study II were obtained by reconciliation of plant data. The formulation is nonconvex so that the solutions were selected from local optima generated by starting from a number of starting points. The results demonstrated several expected features, e.g. the regular cleaning of exchangers with significant impact on overall network performance, and nonintuitive ones, such as the ordering of cleaning actions were obtained in reasonable CPU times when the problem did converge. Comparisons of the mixed integer nonlinear programming model with a simple greedy algorithm showed the former to converge faster, while the latter returned a suboptimal result but proved to be robust.

In additional, a mixed integer nonlinear programming formulation of the cleaning schedule problem for continuously operating heat exchanger networks has been studied by Smaili, F. *et al.* (2002). The formulation is solved using the outer approximation/ extended relaxation algorithm. They have employed similar fouling models in each exchanger. The fouling model appropriate for a given exchanger based on existing plant data or worst case estimates. The approach has been demonstrated using three examples. The first case studied the cleaning schedule of single heat exchanger. An objective function postulated to energy and cleaning costs. Both linear and asymptotic fouling behaviors were considered. For case studied two, three heat exchanger networks containing stream splitting in the network was considered. This case is interesting because of symmetry in the network. The third case is more complicated interns of number of units and representations of crude preheat train.

Moreover, the formation used regular time discretization. Even a globally optimal solution to the mixed integer nonlinear programming formulation may not be the best schedule if the time discretization is too coarse. The results are very dependent on the accuracy of the process simulation and the fouling model data, which involve considerable uncertainty. The uncertainty of fouling data was more significant for problems with long time horizons. The desire for globally optimal solutions must be considered alongside the reliability of the input data. They found that the problem size can be reduced and faster convergence obtained.

Moreover, Smaili,F. *et al.* (2002) proposed the long-term scheduling of cleaning of heat exchanger networks. The comparison of outer approximation based solution with a backtracking threshold accepting algorithm (BTA) is studied. The scheduled obtained for this work highlight the importance of the form of the objective function. The objective function used here did not consider the state of the network beyond the immediate horizon, resulting in noticeable boundary effects for shorter horizon scenarios. And both techniques are able to generate optimal cleaning schedules. The performance of the BTA algorithm appears stable and applicable to realistic size case study sizes without complications.

Rodera, H. *et al.* (2003) presented different heat exchanger network problem formulations that consider several of the heat exchanger network modeling and optimizations. In order to find the optimal cleaning schedule, the governing equations are mass balances, heat balances, heat transfer rate and heat transfer coefficient calculation. The variable specified or optimized are heat exchanger areas and binary variables, stream flows and inlet temperatures and time periods. The simplifying assumptions used in this problem are discretisation of the time span.

Miller, D.C. *et al.* (2004) studied the optimization of heat exchanger networks using Tabu search. The objective is to minimize the utility costs, fixed charges for each heat exchanger and an area-based cost for each heat exchanger. This work proposed that the area of a heat exchanger is highly nonlinear function of the temperature difference and heat load. The solution of heat exchanger networks provides both the superstructure and operating parameters. Thus, the solution includes a set of binary and continuous variable. For all case studied, the global optimal solution can be found with a probability higher than 90%.

In additional, Bagajewicz, M.J. *et al.* (2004) illustrated a mixed integer linear programming cleaning schedule optimizer model applied to typical preheat train configuration. This model based on assumptions similar to those made by Smaili et al (2002). The model does not approximate the nonlinear equations related to heat transfer or the fouling models. Instead, it takes a special rearrangement to obtain linear expressions. So, for small problems, the model is capable of rendering global optimality. They have found better solutions than those proposed by the mixed integer nonlinear programming model proposed by Smaili,F. *et al* (2002). The result shows that moving-horizon strategies are not effective in solving this kind of problem, that cyclic schedules imposed to the models are clearly not applicable either, and that heuristic strategies can derive into really bad solution.

Consequently, Markowski, M. *et al.* (2005) illustrated the optimization of cleaning schedule for heat exchanger network. Heat exchanger cleaning is postulated to maximize the avoid loss understood as the value of energy recovered of cleaning the heat exchanger network, minus the value of energy recovered without heat exchanger network cleaning, minus the cost of heat exchanger network cleaning. The result shown that the value of energy recovered is affected by the specific cost of energy. The cost of heat exchanger network cleaning depends on the cost of cleaning intervention on a specific heat exchanger. The formulation is both integer and continuous decision variables and the function is mixed integer nonlinear programming problem. For a large heat exchanger network may require a prohibitively large computational effort. But an approximation solution can be obtained by maximizing a nonlinear function in many integer variables.

Montagna, J. M. *et al.* (2007) proposed the model of multiperiod optimization for the planning of multiproduct batch plants. Multiperiod MILP formulation involves discrete decisions for structure selection and continuous decision for operation at each period at the plant. In multiperiod problems where the binary variables increase with each additional time periods the MILP solution time increases nearly exponentially. The model performance is also affected by the number of available discrete sizes for each stage. Therefore, the increasing in discrete size is causing in the increasing in continuous variables, discrete variables and computation time.

Sanaye, S. *et al.* (2007) studied simulation of the heat exchanger network based on the actual input data obtained for a specified petrochemical plant. The optimal cleaning schedule of the heat exchanger network was obtained. The software designed for the mentioned purposes is introduced, and the variations of outer temperatures, overall heat transfer coefficients and heat transfer rates with time for a typical cooler in the urea unit are shown as a case study. It should be mentioned that the simulation and optimization software program and their outputs work correctly just for their case studies and are not generally applicable to other heat exchanger networks and fluid flow conditions. The results of finding the optimal cleaning schedules for time horizon is 12 and 24 months, the dependency of the cleaning schedules of the exchangers on the time duration of operation is obvious. It was found that different optimum cleaning schedules provided the same amount of saving.

CHAPTER III

THEORY

3.1 Fouling in Heat Exchanger

Fouling is a general term that includes any kind of deposit of extraneous material. It appears upon the heat transfer surface during the lifetime of the heat exchanger. Because of the deposit, an additional resistance to heat transfer is introduced and the operational capability of the heat exchanger is reduced. In many cases, the deposit is heavy enough to significantly interfere with fluid flow and increase the pressure drop required to maintain the flow rate through the exchanger.

The designer must consider the effect of fouling upon heat exchanger performance during the desired operational lifetime and make provision in his design for sufficient extra capacity to insure that the exchanger will meet process specifications up to shutdown for cleaning. The designer must also consider what mechanical arrangements are necessary to permit easy cleaning.

3.1.1 Mechanism of Fouling

There are several different basic mechanisms by which fouling deposits may be created and each of them in general depends upon several variables. In addition, two or more fouling mechanisms can occur in conjunction in a given service.

Sedimentation fouling

Many streams and particularly cooling water contain suspended solids which can settle out upon the heat transfer surface. Usually the deposits thus formed do not adhere strongly to the surface and are self limiting. Sedimentation fouling is strongly affected by velocity and less so by wall temperature. However, a deposit can bake on to a hot wall and become very difficult to remove.

Inverse solubility fouling

Certain salts commonly found in natural waters are less soluble in warm water than in cold. If such a stream encounters a wall at a temperature above that corresponding to saturation for the dissolved salt, the salt will crystallize on the surface. Crystallization will begin at especially active points-nucleation sites-such as scratches and pits, often after a considerable induction period, and then spread to cover surface. The buildup will strong and adherent and usually requires vigorous mechanical or chemical treatment to remove it.

Chemical reaction fouling

Common sources of fouling on the process stream side are chemical reactions that result in producing a solid phase at or near the surface. For example, a hot heat transfer surface may cause thermal degradation of one of the components of a process stream, resulting in coke deposits on the surface. These deposits are often extremely tenacious and may require such extreme measures as burning off the deposit in order to return the exchanger to satisfactory operation.

Corrosion product fouling

If a stream corrodes the metal of the heat transfer surface, the corrosion products may be essential to protect the remaining metal against further corrosion, in which case any attempt to clean the surface may only result in accelerated corrosion and failure of the exchanger.

Most of the above fouling processes can occur in combination such as sedimentation fouling and inverse solubility fouling.

3.1.2 Effect of Fouling on Heat Exchanger

The effect of fouling is to form an essentially solid deposit upon the surface, through which heat must be transfer red by conduction. If we knew both the thickness and the thermal conductivity of the fouling, we could treat the heat transfer problem simply as another conduction resistance in series with the wall. In general, we know neither of these quantities and the only possible technique is to introduce the additional resistance as fouling factors in computing the overall heat transfer coefficient.

Fouling effects inside the tube usually cause no particular problem if allowance has been made for the reduction in heat transfer and the small increase in flow resistance. However, fouling on the outside of finned tubes can be a more complicated matter, because in extreme situations there is a possibility that the finite thickness of the fouling layer can effectively close off the flow through the fins. On the other hand, finned surfaces are sometimes found to be more resistant to fouling than plain surfaces. The reasons of this are not well-established, though it may be that the expansion and contraction of the surface during normal operational cycles tends to break off brittle fouling films.

3.2 Basic knowledge of Heat Exchanger

Heat exchangers are devices that facilitate hate transfer between two fluids at different temperatures without allowing them to mix. There are called indirect contact exchangers. However, if the fluids do not tend to mix naturally, a direct contact heat exchanger may be used, e.g. a water chiller.

3.2.1 Overall Heat Transfer Coefficient

Heat is being transferred from the fluid inside, through dirt or fouling film, through the tube wall, through another fouling film to the outside fluid at a local bulk temperature. The general form of this coefficient is written

$$U = \frac{1}{A_t R_t} \tag{3.1}$$

where A_t is the total area available for heat transfer and R_t is the effective (overall) thermal resistance. Calculating U is clearly a matter of first determining R_t. For a simple shell and tube heat exchanger, thermal resistance is the sum of three basic resistive components in series:

- convection resistance on the tube side
- conduction resistance of the wall between the two flow streams
- convection resistance on the shell side

So the overall resistance as

$$R_t = \frac{1}{A_i h_i} + R_c + \frac{1}{A_o h_o} \tag{3.2}$$

where subscripts i and o designate inner and outer, respectively, and R_c is the conductive resistance for a cylindrical surface derived as

$$R_c = \frac{\ln(r_o / r_i)}{2\pi L k} \tag{3.3}$$

Notice that can use either A_i or A_o as the total area available for heat transfer A_t in equation (3.2). It makes no difference which one is used, as long as the specified. Using $A_o = 2\pi r_o L$ as the basis, it is obtained

$$U_o = \frac{1}{A_o R_t} = \frac{1}{A_o\left(\frac{1}{A_i h_i} + \frac{\ln(r_o / r_i)}{2\pi L k} + \frac{1}{A_o h_o}\right)} \tag{3.4}$$

which, after simplifying yields

$$U_o = \frac{1}{\left(\frac{r_o}{r_i h_i} + \frac{r_o \ln(r_o / r_i)}{k} + \frac{1}{h_o}\right)} \tag{3.5}$$

Similarly, for $A_i = 2\pi r_i L$

$$U_i = \frac{1}{\left(\frac{1}{h_i} + \frac{r_i \ln(r_o / r_i)}{k} + \frac{r_i}{r_o h_o}\right)} \tag{3.6}$$

Because of normal operation, inner surface of a heat exchanger can become coated with deposits that leach out of the working fluids and corrode due to reaction with the fluid. These factors present additional resistance to heat transfer that can be modeled via a fouling factor equation (3.3) can be modified as

$$R_t = \frac{F_i}{A_i} + \frac{1}{A_i h_i} + R_c + \frac{1}{A_o h_o} + \frac{F_o}{A_o} \tag{3.7}$$

to consider fouling, where F_o and F_i are the fouling factors for outer and inner surfaces, respectively. Generally, performance is gradually degraded over time and costs are increased because of maintenance requirements and down time. The fouling factor is generally a known quantity based on the working fluid.

3.2.2 Fouling Factor

After period of the operation the heat transfer surfaces for a heat exchanger may become coated with various deposits present in the flow systems, or the surfaces may become corroded as a result of the interaction between the fluids and the material used for construction of the heat exchanger. In either even, this coating represents an additional resistance to the heat flow, and thus results in decreased performance. The overall effect is usually represented by a fouling factor, or fouling resistance, R_f, which must be included along with the other thermal resistances making up the overall heat transfer coefficient.

Fouling factor must be obtained experimentally by determining the values of U for both clean and dirty conditions in the heat exchanger. The fouling factor is thus defined as

$$R_f = \frac{1}{U_{dirt}} - \frac{1}{U_c} \tag{3.8}$$

3.2.3 The Log Mean Temperature Different

The physical flow of heat exchanger units is simply too complex to obtain analytical solution, e.g. because turbulence, developing flow, separation, etc. Moreover, diverse geometry and architecture preclude generalizing results into a few relevant correlations. Instead, an approximate integral approach in which the analysis is only dependent upon temperatures at the inlets and outlets and the overall convection coefficient.

The form of Newton's Law of Cooling

$$Q = UA\Delta T_{\ln} \tag{3.9}$$

where A_t and U_m are the total area available for heat transfer and the overall convection coefficient. Respectively, and ΔT_{ln} is a temperature difference between the hot and cold fluids is not a constant.

The method of the "Log Mean Temperature Difference "(LMTD) introduce to solving heat exchanger problems. This procedure allows calculating ΔT_{ln}, which can be thought of as an appropriately averaged temperature difference between the two flow streams. It is probably no surprise that ΔT_{ln} depends upon the heat exchanger configuration, flow arrangement, etc. There are a number of additional assumptions we must make to implement this method

- The unit is insulated such that no heat is exchanged with its surroundings; heat transfer only takes place between the hot and cold streams within the unit
- specific heats of both fluids are constant
- overall heat transfer coefficient is constant
- potential and kinetic energy changes can be neglected

So the form of LMTD for co current flow are defined as

$$\Delta T_{\ln} = \frac{(T_{h,out} - T_{c,out}) - (T_{h,in} - T_{c,in})}{\ln[(T_{h,out} - T_{c,out})/(T_{h,in} - T_{c,in})]} \tag{3.10a}$$

the form of LMTD for counter current flow are defined as

$$\Delta T_{\ln} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln[(T_{h,in} - T_{c,out})/(T_{h,out} - T_{c,in})]} \tag{3.10b}$$

where the subscripts *h* and *c* designate the hot and cold fluids, respectively.

Stated verbally, it is the temperature difference at one end of the heat exchanger less the temperature difference at the other end of the exchanger divided by the natural logarithm of the ratio of these two temperature differences.

3.2.4 Effectiveness-NTU

The LMTD approach to heat exchanger analysis is useful when the inlet and outlet temperatures are known or are easily determined. The LMTD is then easily calculated, and the heat flow, surface area, or overall heat transfer coefficient may be determined. When the inlet or exit temperatures are to be evaluated for a given heat exchanger, the analysis frequently involves an iterative procedure because of the logarithmic function in the LMTD. In these cases the analysis is performed more easily by utilizing a method based in the effectiveness of the heat exchanger in transferring a given amount of heat. The effectiveness method also offers many advantages for analysis of problems in which a comparison between various types of heat exchangers must be made for purposes of selecting the type best suited to accomplish a particular heat transfer objective.

The heat exchanger effectiveness can be defined as

$$Effectiveness = \varepsilon = \frac{actual \quad heat \quad transfer}{\max imum \quad possibility \quad heat \quad transfer}$$

The actual heat transfer may be computed by calculating either the energy lost by the hot fluid or the energy gained by the cold fluid. Consider the counter current flow exchanger

$$Q = F_h C_{p,h}(T_{h,in} - T_{h,out}) = F_c C_{p,c}(T_{c,out} - T_{c,in}) \tag{3.11}$$

To determine the maximum possible heat transfer for the exchanger, the first recognize that this maximum value could be attained if one of the fluids were to undergo a temperature change equal to the maximum temperature difference present in the exchanger, which is the difference in the entering temperatures for the hot and cold fluids. The fluid which might undergo this maximum temperature difference is the one having the minimum value of FC_p since the energy balance requires that the energy received by one fluid be equal to that given up by the other fluid; if the fluid with the larger value of FC_p go through the maximum temperature difference, this would required that the other fluid undergo a temperature difference greater than the maximum, and this is impossible. So, maximum possible heat transfer is expressed as

$$Q_{\max} = (FC_p)_{\min}(T_{h,in} - T_{c,in}) \tag{3.12}$$

The maximum fluid may be either the hot or cold fluid, depending on the mass flow rates and specific heats. For the counter current flow

$$\varepsilon_h = \frac{F_h C_{p,h}(T_{h,in} - T_{h,out})}{F_h C_{p,h}(T_{h,in} - T_{c,out})} = \frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,out}} \tag{3.13}$$

$$\varepsilon_c = \frac{F_c C_{p,c}(T_{c,in} - T_{c,out})}{F_c C_{p,c}(T_{h,in} - T_{c,out})} = \frac{T_{c,in} - T_{c,out}}{T_{h,in} - T_{c,out}} \tag{3.14}$$

3.3 Mathematical Programming

3.3.1 Basic concepts of Mathematical Programming

Mathematical programming is a class of methods for solving constrained optimization problems. Since both continuous and binary variables can be used in the corresponding mathematical programming models, these methods are perfectly suited for typical design tasks encountered in process synthesis and process integration.

Generally, a mathematical programming model consists of an objective function (typically some economic criteria) and a set of equality constraints as well as inequality constraints. The general form is indicated below

$$Min\ f(x,y)$$

Subject to

$$g(x,y) \leq 0$$

$$h(x,y) = 0$$

where

$$x \in R^n$$

$$y \in [0,1]^m$$

It should be noticed that the variables x and y in general are vectors of variables, and that the constraints g and h similarly are vectors of function. The objective function is assumed to be a scalar.

The mathematical modeling of the systems lead to different types of formulations, such as Linear Programming (LP), Mixed Integer Linear Programming (MILP), Non-Linear Programming(NLP), and Mixed integer Non-Linear Programming (MINLP) models.

If there are no binary variables, and all functions f, g and h are linear, we have the simplest class of problems, the Linear Programming models. Using the simplex algorithm, for example, LP models with hundreds of thousands variables and constraints can be solved in reasonable times today’s computer resources. If there are no binary variables, and at least one of the functions f, g and h are non- linear, we have a Non-Linear Programming problem. There are generally much harder to solve, especially if the nonlinearities are nonconvex, because a local optimum may be found.

If there are binary variables in the model, and all function f, g and h are linear, we have a Mixed Integer Linear Programming (MILP) problem. These can be solved to global optimality provided the number of binary variables dose not cause a combinatorial explosion. Finally, if there are binary variables in the model, and at least one of the function f, g and h are non-linear, we have the hardest class of problems, Mixed Integer Non-Linear Programming (MINLP) models. Unfortunately, most real design problems are of the MINLP type with significant problems related to computer time and local optima.

3.3.2 Integer and Mixed Integer Programming

Many problems in plane operation, design, location, and scheduling involve variables that are not continuous but instead have integer values. Decision variables for which the levels are a dichotomy, for example are termed [0 1] variables. Other integer variables might be real numbers 0, 1, 2, 3, etc. Sometimes we can treat integer variables as if they were continuous, especially when they assume large values, and round the optimal solution to the nearest integer value. This step leads to a suboptimal solution, yet one that is quite acceptable from a practical viewpoint. Most of the integer programming problems are inherently combinatorial in nature, that is, the integer variables in the objective function correspond to combinations of n element taken m at a time so that the number of possible combinations to consider is (n m), or correspond to permutations of n elements so that the number of possibilities is n!.

First let us classify the types of problems that are encountered in optimization with discrete variables. The most general case is a mixed-integer programming (MIP) problem in which the objective function depends on two set of variables, x and y; x is the vector of integer variables and y denotes the continuous variables. If only integer variables are involved ($y_j = 0$), we have an integer programming problem. Finally, a special case of IP is binary integer programming, where all variables xi are either 0 or 1. Many MIP problems are linear programming. These problems are calling MILP problems.

Problems involving discrete variables in which some of the functions are nonlinear are called mixed-integer nonlinear programming (MINLP) problems. Most of techniques that have been proposed for nonlinear discrete optimization are centered around one or more of the following five basic concept:

(1) Rounding-off the continuous optimum
(2) Adaptation of nonlinear optimization techniques
(3) Linear approximation
(3) Binary representation of variables
(4) Direct search

The relative effectiveness of any technique is quite problem-dependent and no single procedure can claim a uniform advantage over all others for all problems, or even claim to be generally effective.

The most common approach to solving nonlinear discrete-value problems in practice has been to treat the variables as continuous ones. Once the continuous optimum has been determined by select a feasible set of values of the discrete variables near the optimal point for the continuous variables. The selected point may not represent the discrete optimum and be misleading but frequently represents a quite suitable solution for practical purpose.

In the second approach, nonlinear discrete-valued problems are treated as nonlinear programming problems in which the discreteness of the variables is one of the restrictions. In the third approach, linear programming is used in conjunction with integer programming with any nonlinear functions begin liberalized. The fourth approach involves the transformation of a nonlinear function into a polynomial function into a linear function of binary variables. As to the last approach, discrete search techniques have not been demonstrated to be particularly reliable. The method most commonly referred to as sectioning search is known to be in efficient and may not find even a local optimum if it encounters a sharp ridge or valley in the objective function surface.

In conclusion, a number of types of integer programming problems can be solved by specialized computer codes. Small dimensional problems can be solved by enumerative techniques such as branch and bound. But often problems that are superficially amenable to integer programming cannot be solved in a reasonable amount of time. And, perhaps more importantly, one mathematical formulation may lead to very quick solutions while another formulation of the same physical problem may result in very slow execution, or be even virtually unsolvable. To know when and how to avoid incorrect problem formulation those are intractable requires considerable integer programming skill.

3.3.3 Differential Evolution

In the optimization process of a different task the method of first choice will usually be a problem specific heuristic. Different Evolution (DE) algorithm is a stochastic optimization method minimizing an objective function that can model the problem's objective while incorporation constraints. The algorithm mainly has three advantages: finding the true global minimum regardless of the initial parameter values, fast convergence, and using a few control parameters.

3.3.3.1. Differential evolutionary algorithm

DE was first introduced by Storn & Price. As it is typical for EAs, DE does not require any prior knowledge of the search space, nor of the derivative information. It is a very simple population based, stochastic optimization algorithm which is very powerful and robust at the same time. Figure 1 shows the flowchart of DE. The algorithm starts by generating a randomly distributed initial population of N vectors. Mutation and recombination is then performed on each vector X_i of the generated population in order to create a trial vector U_i.

The basic *DE/rand/1/bin* and trigonometric schemes are used in this algorithm.

DE/rand/1/bin scheme starts by randomly selecting three vectors in the populations. The perturbed vector V_i is then generated based on the three previously selected vectors
as follows:

$$V_i = X_{r3} + F(X_{r2} - X_{r1}) \tag{3.15}$$

where, $X_{r1};X_{r2}$ and X_{r3} are randomly selected vectors, and $r1 \neq r2 \neq r3 \neq i$ are satisfied. $F \in [0; 1+]$ is a control parameter of the algorithm. The trigonometric mutation scheme also starts by randomly selecting three vectors in the populations as in the *DE/rand/1/bin* scheme. But, the perturbed variable is calculated using the center point of the hypergeometric triangle of three previously selected vectors. The perturbed vector V_i is then generated by perturbing the center point a sum of three weighted vector differentials, as described by the following formulation:

$$V_i = \frac{(X_{r1} + X_{r2} + X_{r3})}{3} + (p_2 - p_1)(X_{r1} - X_{r2})$$
$$+ (p_3 - p_2)(X_{r2} - X_{r3}) + (p_1 - p_3)(X_{r3} - X_{r1}) \tag{3.16}$$

where,

$$p_1 = \frac{|f(X_{r1})|}{|f(X_{r1})| + |f(X_{r2})| + |f(X_{r3})|}$$

$$p_2 = \frac{|f(X_{r2})|}{|f(X_{r1})| + |f(X_{r2})| + |f(X_{r3})|}$$

$$p_3 = \frac{|f(X_{r3})|}{|f(X_{r1})| + |f(X_{r2})| + |f(X_{r3})|}$$

:

Where, X_{r1}, X_{r2} and X_{r3} are randomly selected vectors, and $r1 \neq r2 \neq r3 \neq i$ are satisfied.

The perturbed vector $V_i(v_{i,1}, v_{i,2}, ..., v_{i,n})$ and its parent vector $X_i(x_{i,1}, x_{i,2}, ..., x_{i,n})$ are subjected to the crossover operation, which finally generates the trial vector $U_i(u_{i,1}, u_{i,2}, ..., u_{i,n})$ as follows:

$$u_{i,j} = \begin{cases} v_{i,j}, & if \quad random[0,1) \leq CR \vee j = random[1,n); \\ x_{i,j}, & otherwise \end{cases} \tag{3.17}$$

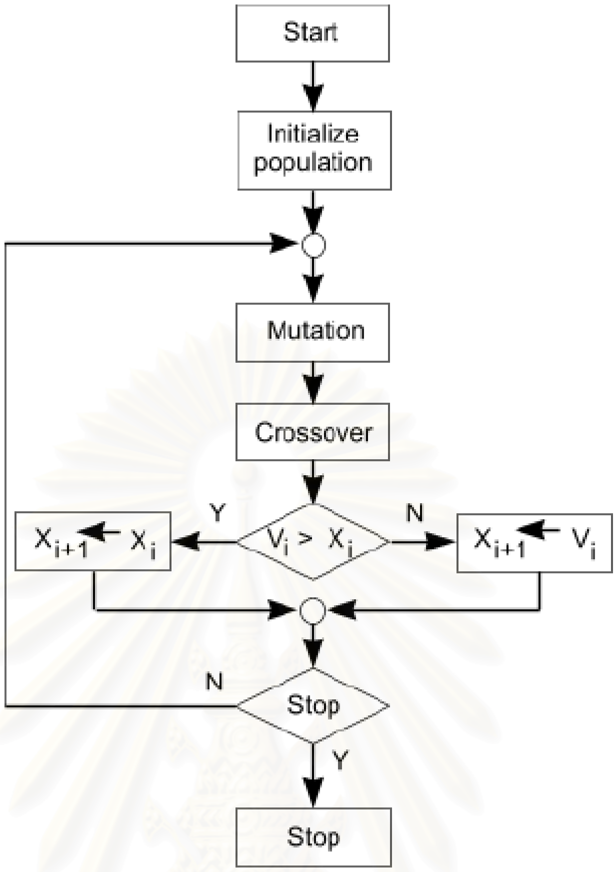

Figure 3.1: The flowchart of the differential evolutionary algorithm.

Where $CR \in [0, 1]$ is crossover factor. The created trial vector U_i is then compared with its parent vector X_i. If the trial vector is better than the parent vector, the trial vector replaces its parent vector in the population, as expressed in the following formulation:

$$X_{i+1} = \begin{cases} U_{i,} & if \quad f(U_i) \le f(X_i); \\ X_i, & otherwise \end{cases} \tag{3.18}$$

The evolutionary process repeats until the stopping criteria is satisfied.

3.3.3.2. The constrain handling scheme

1. Handling integer and discrete variables

The original DE is incapable of handling discrete variables. However, it is very easy to modify the algorithm to deal with integer and/or discrete variables. First, continuous variables are converted to integer variables by truncation. Then, the truncated variables are used to evaluate the objective function. It can be expressed using the following expression:

$$x' = (\text{int})x; \tag{3.19}$$

Discrete variables can also be easily handled. Instead of directly using discrete variables as the optimized variables, the index of all discrete variables are assigned first. The index of each discrete variable is then used as the optimized variables. But, to evaluate the objective function, the original discrete variables are used.

2. Handling boundary constraints

It is important that the optimize variables must lie inside their allowed ranges. We replace each variable that violates boundary constraints by the upper or lower limits, according to the following rule:

$$x' \begin{cases} x_i^{(L)}, & if \quad x < x_i^{(L)}; \\ x, & if \quad x_i^{(L)} \le x \le x_i^{(U)}; \\ x_i^{(U)}, & if \quad x > x_i^{(U)}; \end{cases} \tag{3.20}$$

Where, $x_i^{(L)}$ and $x_i^{(U)}$ are the upper and lower bounds of each variable, respectively.

3. Dominance-based selection scheme

A dominance-based selection scheme is used to incorporate constraints into the fitness function. When comparing trial vector U_i with its parent vector X_i, we can have three possible situations. In the first case, both U_i and X_i are feasible. The vector with a better objective function survives to the next generation. In the second case, one is feasible, but the other one is infeasible. The feasible vector survives to the next generation. In the last case, where both vectors are infeasible. The vector with lower degree of constraints violation survives to the next generation. The rule for the selection is defined as follows:

$$X_{i+1} = \begin{cases} X_{i,} & X_i \prec U_i; \\ U_i, & otherwise; \end{cases} \qquad (3.21)$$

Where, $X_i \prec U_i$ denotes that X_i dominates U_i. That is X_i has better objective function than U_i and/or lower degree of constraints violation.

4. Handling equality constraints

Generally, the equality constraints can be used to reduce the number of dimensions for the optimization problem without distorting the results. However, identifying the reduced variables is still a hard task. Moreover, some equality constraints are irreducible, and cannot be used to transform the problem to the lower dimension problem. Consider the case of n-dimensional optimization problem with *m* equality constraint *(H(X) = 0),* the degree of freedom for this problem is actually *n - m*. That is only *n-m* variables are independent, while *m* variables are defined by the equality constraints. Therefore, any infeasible vector *X* containing *n* variables can be repaired by solving the system of m equations. Newton's method herein is applied to solve the system of equality constraint equations. In the first step, *m* variables from totally *n* variables are randomly selected to be repaired. The degree of constraints violation are checked whether it is greater than a specified tolerance *e*. Infeasible vectors with small degree of violation are allowed to survive. This helps to maintain diversity in the population. On the other hand, infeasible vectors with large degree of violation are then repaired by solving the system of m equations. The corrected vector X that is computed by equation 3.22 moves each equality constraint closer to the allowable range.

$$X_{i+1} = X_i - J^{-1}(X_i)H(X_i) \qquad (3.22)$$

Where, $J(X_i)$ is the Jacobian matrix, and $H(X_i)$ is the vector of equality constraints violation. Iteration stops if either the sum of the degree of constraints violation is less than a given tolerance e, or the maximum iteration number has been reached.

CHAPTER IV

SIMULATION OF HEAT EXCHANGER

This chapter describes the simulation of single heat exchanger in heat exchanger network for preheating crude oil in refinery process. The simulation of heat exchanger for predicting the variation of overall heat transfer coefficient, the variation of heat transfer and variations of outlet temperature of hot and cold streams is important. These variations have a significant effect on production rate and operating cost. The main goal is to find the variation of outlet temperature of hot and cold streams with time to plan the optimum cleaning schedule of heat exchanger network that provide the minimum operating cost.

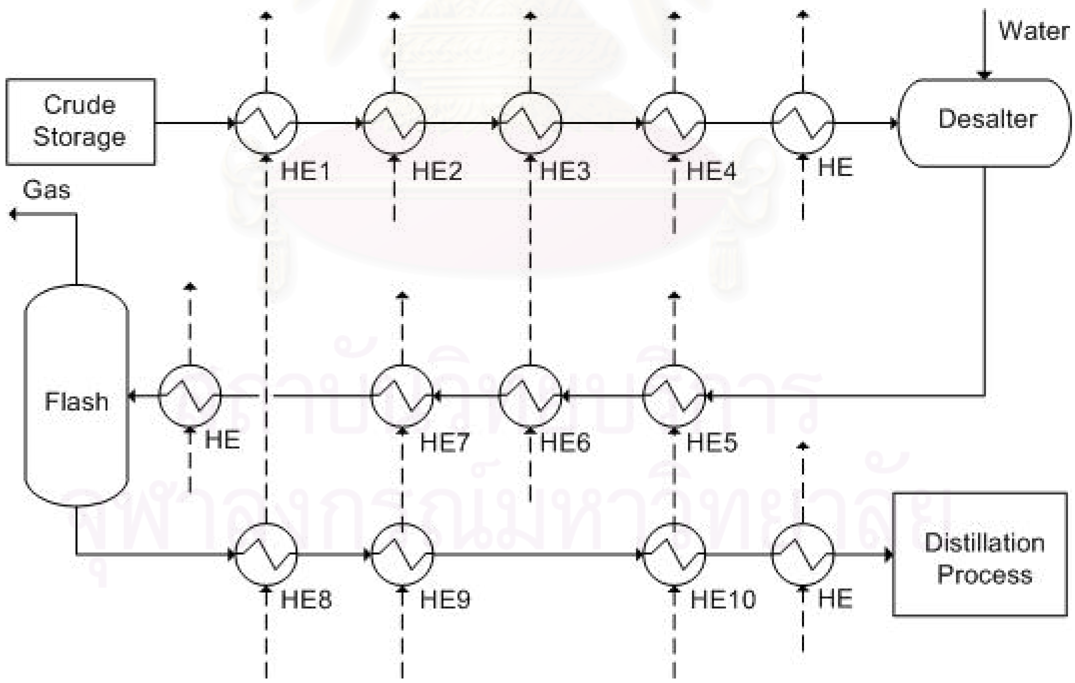

Figure 4.1 The schematic diagram of crude unit heat exchanger network. Solid line: Cold stream and Dot line: Hot stream.

The heat exchanger network (HEN) consists of a number of hot and cold input streams that pass through a set of heat transfer units in a fixed configuration as shown in Figure 4.1. There are 13 heat exchangers in this HEN, which features 3 cold streams and 9 hot streams. The cold streams correspond to the crude stream from storage. Detail of the models is discussed below.

4.1 Heat exchanger model description

The formulation presented here is based on the assumptions below.

- Constant flow inputs. Input mass flow rates are fixed. We thus consider here the situation where the heat exchanger is operating under fixed input flow condition, i.e., maximum throughput. Only changes due to cleaning actions are considered. The input flow rates may change from period to period in order to reflect seasonal variations or shifts in operation.

- Constant physical parameters. The variation in fluid heat capacity with temperature is neglected.

- Film heat transfer coefficients are assumed to remain constant despite changes in Prandtl and Reynold numbers caused by different temperatures and fouling.

- No energy losses.

- The heat exchanger is bypassed for isolation during cleaning. And, the fouling in bypassed heat exchanger is neglected.

- Fouling models used. Individual heat exchangers are model using a lumped parameter. Formulates using the fouling resistance approach, where the change in overall heat transfer coefficient is related to the fouling as presented in equation 4.1

$$r_f(t) = \frac{1}{U(t)} - \frac{1}{U_c} \tag{4.1}$$

where $U(t)$ is overall heat transfer coefficient (Btu/h ft^2 °F), U_c is overall heat transfer coefficient when the unit is clean and $r_f(t)$ is fouling resistance (Btu/h ft^2 °F).

4.1.1 Fouling model formulations

The rate of fouling varies with fluid composition, flow rate and temperature. The variation of temperature is a strong effect on fouling deposition. In this work, the asymptotic fouling formulation model is used for estimating the changes in r_f, based on equation 4.2, and linear fouling formation model is shown in equation 4.3.

Asymptotic fouling model

$$\dot{r}_f(t) = r_f^{\infty}(1 - \exp(-t/\tau)) \tag{4.2}$$

Linear fouling model

$$\dot{r}_f = c \tag{4.3}$$

where r_f^{∞} is asymptotic fouling resistance (h ft^2 °F/Btu), t is time interval since the last cleaning (month) , τ is a fouling time constant (month) and c is constant fouling rate (ft^2 °F/Btu).

4.1.2 Hot and cold streams outlet temperature

Each heat exchanger unit is formulated as a single pass counter current unit. Assuming no energy loss, an energy balance for the cold and hot streams of a heat exchanger gives

Heat transfer rate of cold stream

$$Q_c = F_c C_{p,c}(T_{c,out} - T_{c,in}) \tag{4.4}$$

Heat transfer rate of hot stream

$$Q_h = F_h C_{p,h} (T_{h,in} - T_{h,out}) \tag{4.5}$$

where F is mass flow rate (lb/h)and C_p is specific heat ((Btu/lb °F)

The heat transfer rate in a heat exchanger is explained as

$$Q = UA\Delta T_{\ln} \tag{4.6}$$

where Q is heat transfer rate (Btu/h), U is overall heat transfer coefficient (Btu/h ft^2 °F), A is heat transfer surface area (ft^2) and ΔT_{ln} is logarithmic mean temperature (°F)difference (LMTD)

The log mean temperature difference, ΔT_{ln} is given by

$$\Delta T_{\ln} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln(T_{h,in} - T_{c,out})/(T_{h,out} - T_{c,in})} \tag{4.7}$$

The performance of individual heat exchangers is calculated using the NTU-effectiveness method. Heat exchangers are modeled here as simple counter current units. Here the parameters α and R are defined as

$$\alpha = \frac{UA}{F_c C_{p,c}} \tag{4.8}$$

$$R = \frac{T_{c,out} - T_{C,in}}{T_{h,in} - T_{h,out}} = \frac{F_h C_{p,h}}{F_c C_{p,c}} \tag{4.9}$$

Using the above equations, the hot and cold stream outlet temperature can be computed from

$$T_{h,out} = \frac{(1-R)}{\exp(\alpha(1-R))-R}T_{h,in} + \frac{1-\exp(\alpha(1-R))}{\exp(\alpha(1-R))-R}T_{c,in} \qquad (4.10)$$

$$T_{h,out} = K_h T_{h,in} + K_c T_{c,in} \qquad (4.11)$$

$$T_{c,out} = R(T_{h,in} - T_{h,out}) + T_{c,in} \qquad (4.12)$$

where

$$K_h = \frac{(1-R)}{\exp(\alpha(1-R))-R} \qquad (4.13)$$

$$K_c = \frac{1-\exp(\alpha(1-R))}{\exp(\alpha(1-R))-R} \qquad (4.13)$$

From above equations, The inlet and outlet temperatures of the hot stream and cold stream ($T_{c,in}$ and $T_{h,in}$) , the mass flow rate of hot stream and cold stream (F_c and F_h), the heat transfer area (A), the overall heat transfer coefficient (U_c) and the specific heat capacity of hot stream and cold stream ($C_{p,c}$ and $C_{p,h}$) for the single heat exchanger are known. The values of α , R, K_h and K_c were calculated. Thus, the value of outlet temperature of cold stream and hot stream, the overall heat transfer coefficient and the heat transfer rate are obtained.

4.2 Preliminary study of single heat exchanger

In the case of single heat exchanger, we considered at a single counter current shell and tube heat exchanger. The configuration of single heat exchanger is shown in Figure 4.2.

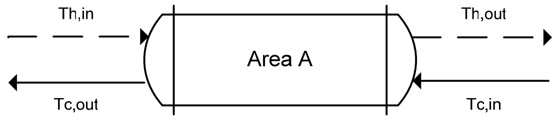

Figure 4.2 The schematic diagram of single heat exchanger. Solid line: Cold stream and Dot line: Hot stream.

4.2.1 The influence of fouling model on performance of heat exchanger

Fouling decrease the overall heat transfer coefficient and heat transfer rate. This is resulting in the reduction of heat exchanger performance. Different fouling models can be obtained from experimental laboratory, online monitoring and data reconciliation. In additional, each heat exchanger of a network has different rates of fouling, depending on film temperatures and stream compositions. Thus, the effect of fouling behavior on heat exchanger is important. This studied considers a linear fouling model and asymptotic fouling model behavior. The results of fouling formation and the variation of overall heat transfer coefficient with time are shown in Figure 4.3 and Figure 4.4.

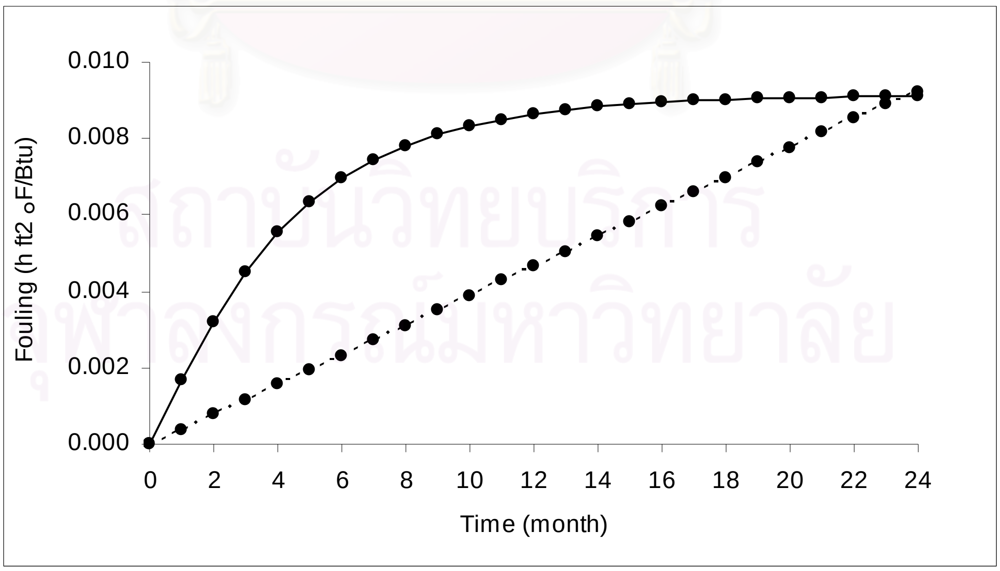

Figure 4.3 The variation of fouling formation with time. Solid line: asymptotic fouling Dot line: linear fouling

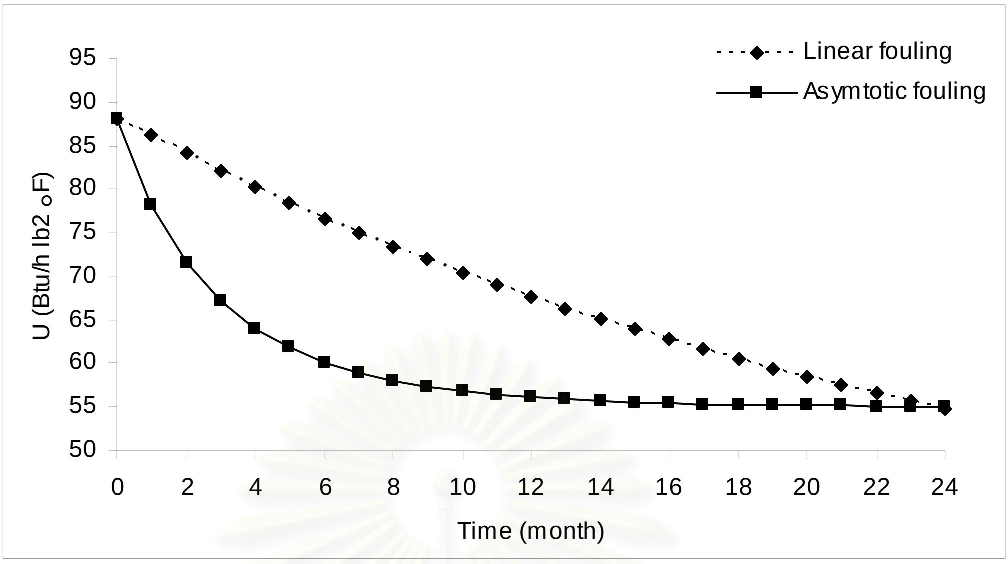

Figure 4.4 The variation of overall heat transfer coefficient with time. Solid line: asymptotic fouling Dot line: linear fouling

Figure 4.3 present the fouling formation of linear model and asymptotic model in 24 months without cleaning. It is observed that the initial rate of fouling in the asymptotic fouling case is lager than linear fouling. The variation of asymptotic fouling changes rapidly at the initial stages of operation and then stabilizes to the initial stages at asymptote. This is due to the exponential term in equation 4.2. The asymptotic fouling model is the first order model. This is approach is justified on the basis of accuracy of data available. At the same time, the variation of linear fouling change in linear form. This is due to the fact that linear fouling model is simple model. It models with constant parameters, based on approximation temperature ranges of individual units.

The variation of overall heat transfer coefficient after 24 months without cleaning is presented in Figure 4.4. The overall heat transfer coefficient is decreasing with time. It is noted that from equation 4.1, the fouling and overall heat transfer coefficient are reverse variation. Thus, the increasing of fouling is causing in the decreasing of overall heat transfer coefficient. It is observed that initially, the overall heat transfer coefficient changes rapidly for the case of asymptotic fouling model. So that the reduction of overall heat transfer coefficient in asymptotic fouling is faster than linear fouling.

4.2.2 The performance of heat exchanger under fouling condition

From previous section, we observed that asymptotic fouling model is more sensitive to overall heat transfer coefficient than linear fouling model. Thus, the asymptotic fouling model in equation 4.2 is considered in this section. The simulation output are fouling formation, the outlet of cold and hot streams of heat exchanger, the variation of fouling with time, the variation of overall heat transfer coefficient with time and the variation of heat transfer rate with time. The operating time of this simulation is 24 months. The parameters of this heat exchanger network are shown in Table 4.1. The simulations results for the single heat exchanger are presented in Figure 4.5 – 4.8.

Table 4.1 Model parameter for single heat exchanger case

Parameter	Value
$T_{c,in}$(°F)	347
$T_{h,in}$(°F)	631.4
F_h(lb/h)	207,940
F_c(lb/h)	649,217
$C_{p,h}$(Btu/lb °F)	0.67
$C_{p,c}$(Btu/lb °F)	0.57
U_o(Btu/h ft^2 °F)	88.1
U_c(Btu/h ft^2 °F)	88.1
r (linear fouling) (ft^2 °F/Btu)	2.9x10^{-4}
r (asymptotic fouling) (h ft^2 °F/Btu)	6.73x10^{-3}
A(ft^2)	1,257.2

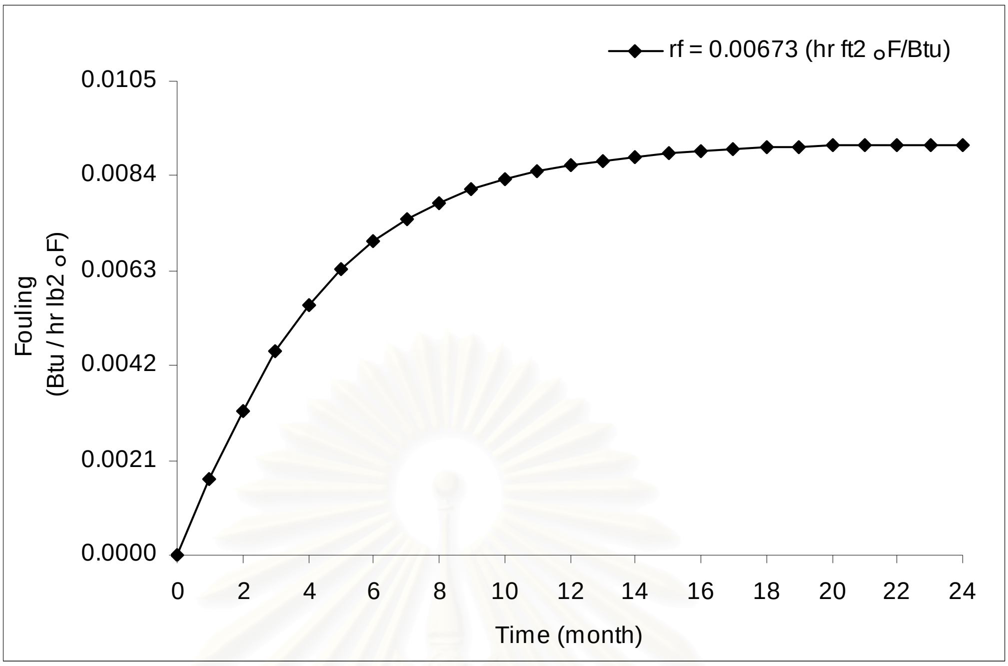

Figure 4.5 The schematic diagram of the variations of the fouling in single heat exchanger with time (r_f = 0.00673 h ft^2 °F/Btu).

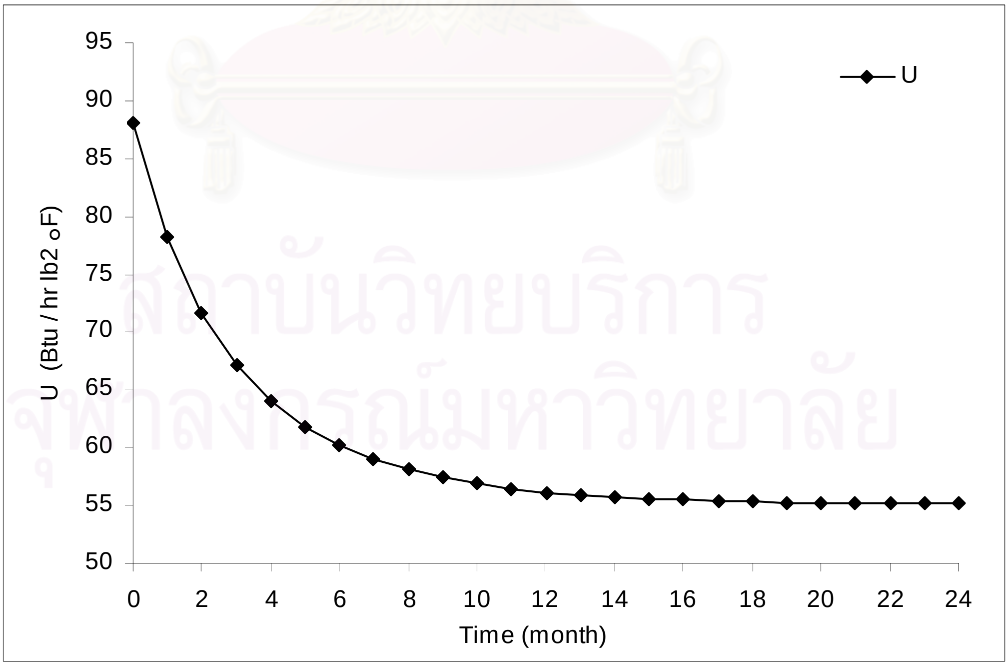

Figure 4.6 The schematic diagram of the variations of the overall heat transfer coefficient (U) of single heat exchanger with time.

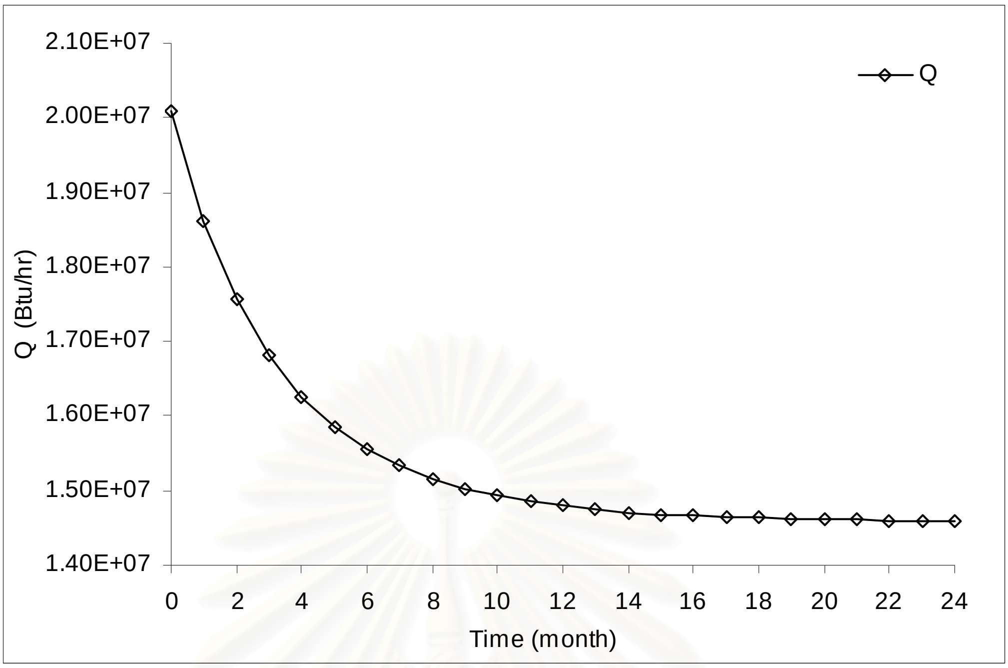

Figure 4.7 The schematic diagram of the variations of the heat transfer rate (Q) of single heat exchanger with time.

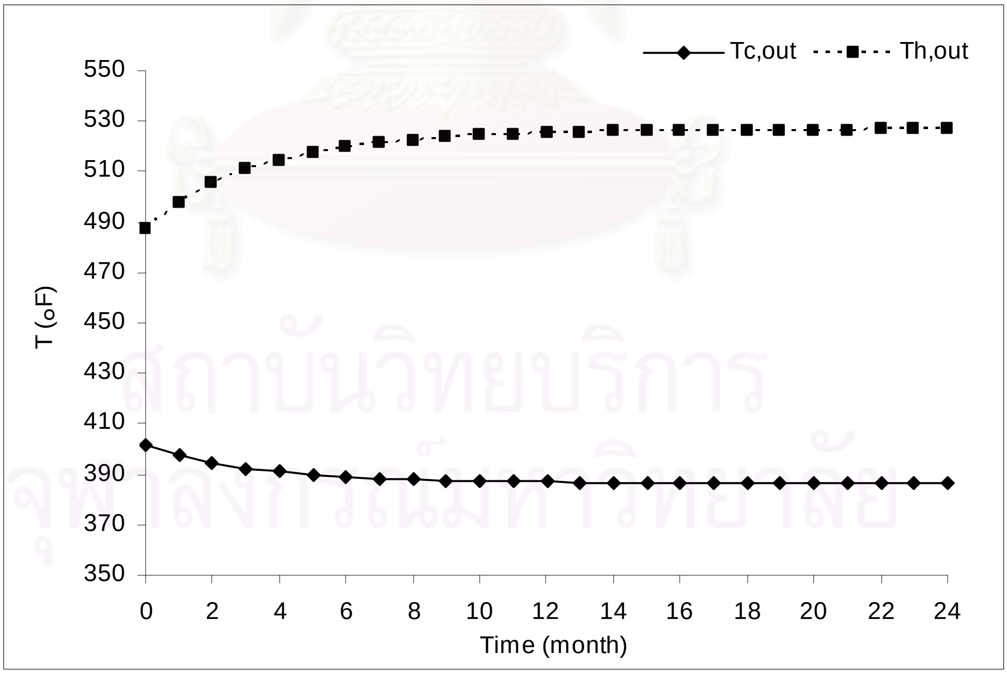

Figure 4.8 The schematic diagram of the variations of the outlet temperatures of hot stream ($T_{h,out}$) and cold stream ($T_{c,out}$)of single heat exchanger with time. Solid line: Cold stream and Dot line: Hot stream.

The output results show that the variation of these parameters change rapidly at the initial stages of operation and then stabilize to the initial stages at asymptote. This is due to the nature of asymptotic fouling model, as see in Fig. 4.5. It is noted that from equation 4.2 the asymptotic fouling model is exponential function. So, at initial state the fouling formation changes rapidly and then stabilizes to the initial stages at asymptote.

Fouling decreases the overall heat transfer coefficient about 37.43% (Fig. 4.6) from initial stages. It is noted that from equation 4.1, the overall heat transfer coefficient varies inverse ratio to the fouling. Due to the fouling, an additional resistance to heat transfer is introduced, and the heat transfer of the heat exchanger is reduced. Thus, the increasing of fouling is resulting in the reduction of overall heat transfer coefficient.

From figure 4.7, fouling reduces the heat transfer rate about 27.38% from initial stages. Considering equation 4.6, the heat transfer rate depends on the overall heat transfer coefficient. Therefore, the decreasing of overall heat transfer coefficient is causing in the reduction of heat transfer rate.

The outlet temperature of hot stream increases with time, and cold stream reduces with time (Fig 4.8). This is due to the fact that fouling reduced the efficiency of heat transfer in the heat exchanger. Therefore, the reduction of heat transfer rate reduces outlet temperature of cold stream ($T_{c,out}$) about 3.70% and increase outlet temperature of hot stream ($T_{h,out}$) about 7.50%. We observed that the distribution of fouling is very sensitive to the temperature distribution.

4.2.3 The influence of fouling parameters on performance of heat exchanger

In this section, the fouling parameters such as time decay of fouling formation, initial rate of fouling formation and heat transfer surface area are considered.

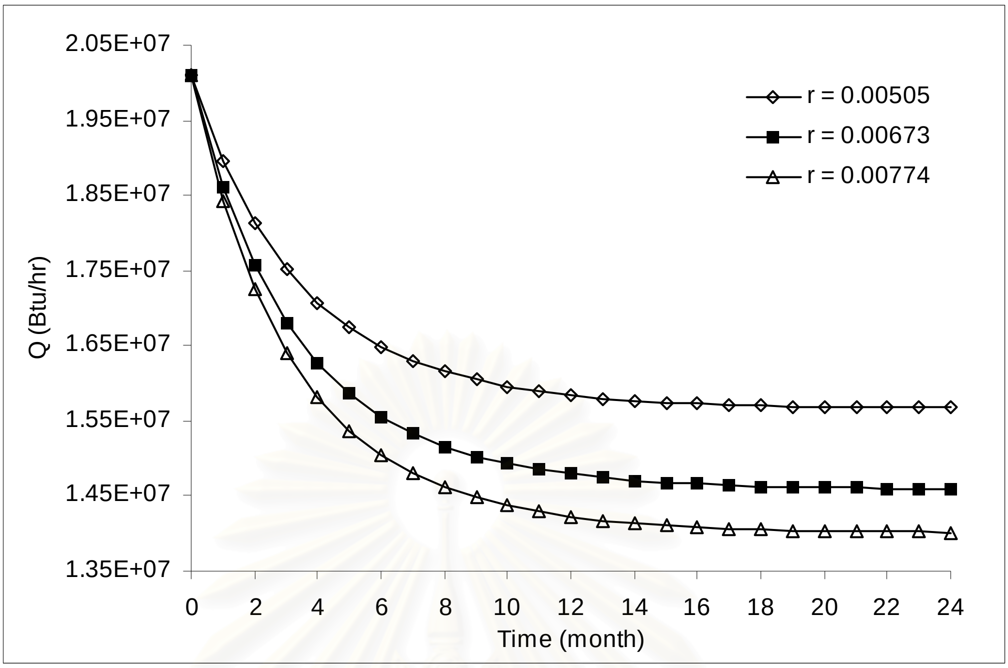

Figure 4.9 The schematic diagram of the variations of the heat transfer rate (Q) of single heat exchanger with different initial fouling rate

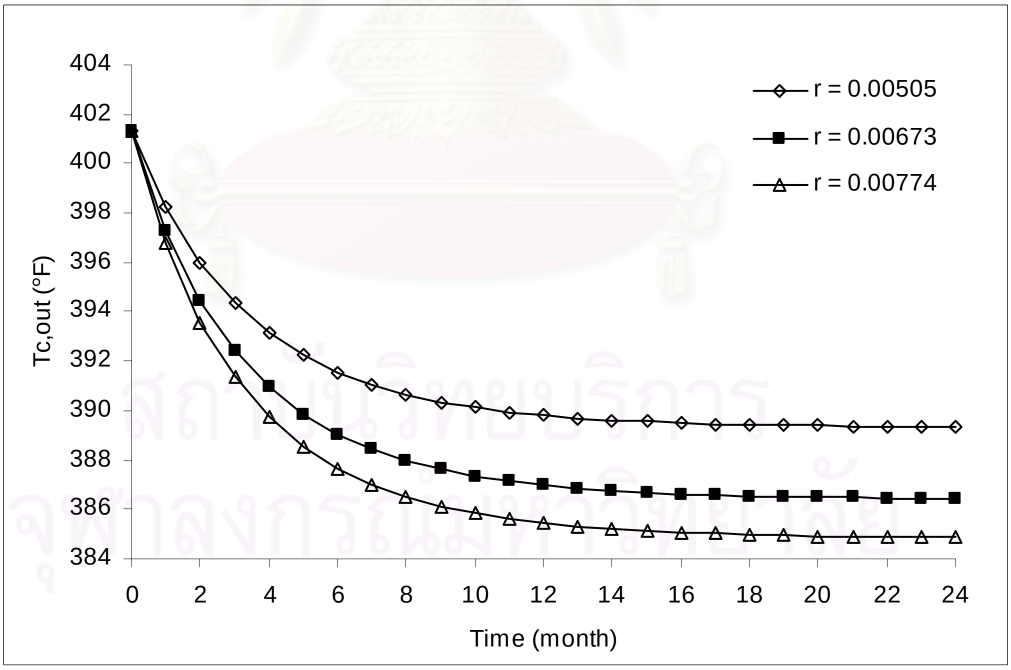

Figure 4.10 The schematic diagram of the variations of the outlet temperature of cold stream in single heat exchanger with different initial fouling rate

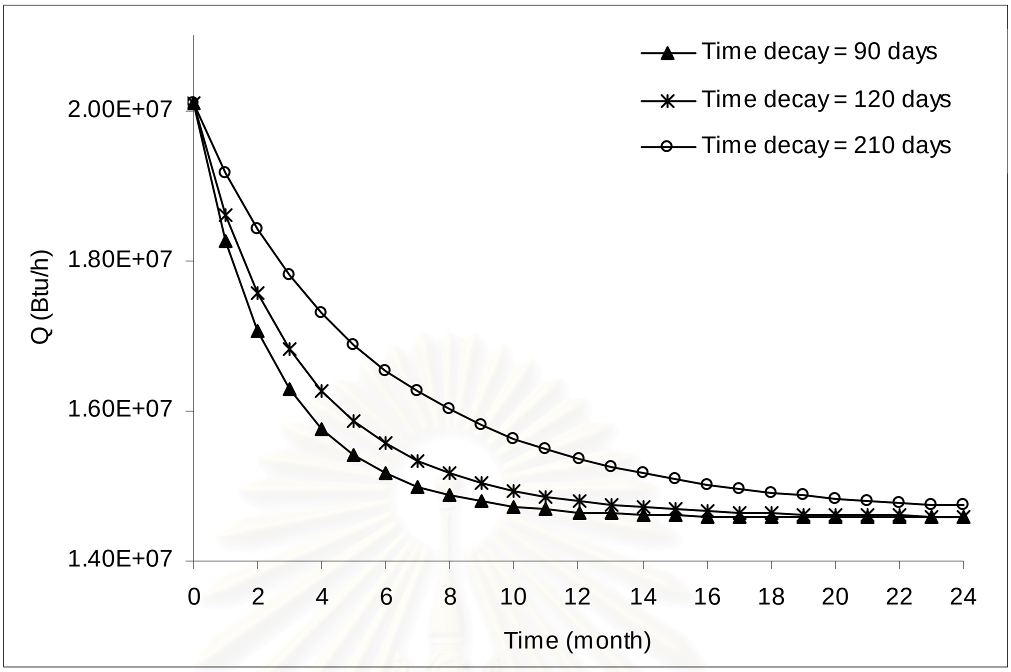

Figure 4.11 The schematic diagram of the variations of the heat transfer rate (Q) of single heat exchanger with different time decay of fouling formation

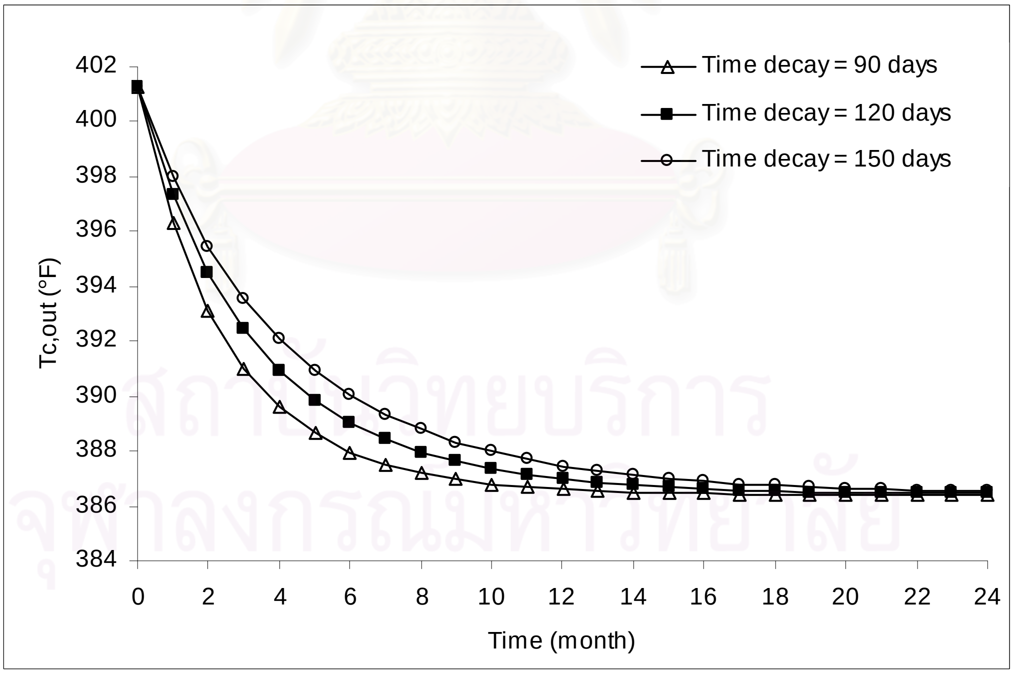

Figure 4.12 The schematic diagram of the variations of the outlet temperature of cold stream in single heat exchanger with different time decay of fouling formation

The variation of heat transfer rate versus time for different values of initial fouling rate (0.00505-0.00774 hr ft^2°F/Btu) are presented in Figure 4.9 and Figure 4.10. It is observed that the different in initial rates is very sensitive to the value of the heat transfer rate as seen in equation 4.2. The larger initial fouling rate for asymptotic fouling cases result in a rapid decay in heat transfer rate. In addition, the heat transfer rate is reduced to the lowest value in the case of largest initial fouling rate. This result also is causing in the rapid reduction of outlet temperature of cold stream as shown in Figure 4.10.

Figure 4.11 and Figure 4.12 are represented the variation of heat transfer rate with time for different values of time decay of fouling formation (90, 120 and 210 days). From equation 4.2, the increasing of time decay of fouling formation (τ) lead to the increasing of the value of exp($-t/\tau$). It is observed that the large value of time decay of fouling formation (τ) provide the small value of fouling (r_f). Thus, the increasing of time decay fouling formation (τ) result in the reduction of fouling formation and increasing of heat transfer rate at a given time. The effectiveness of heat exchanger increases by increasing in the time decay of fouling formation (τ). Due to the reduction of fouling formation, the outlet temperature of cold stream change slowly as shown in Figure 4.11. This result indicates the important of initial fouling rate and time decay of fouling formation. It has a considerable effect on the fouling formation and performance of heat exchanger. Therefore, the accuracy data of parameters in fouling model is required for predicting of performance of heat exchanger. The optimization cleaning schedule problems require a reliable fouling model for predicting unit perform.

CHAPTER V

OPTIMIZATION OF CLEANING SCHEDULE OF HEAT EXCHANGER NETWORK

In this chapter, the optimizations of cleaning schedule of single heat exchanger and heat exchanger network are studied. The optimization problems are using the time discretization approach. The detail of the simulation of the performance of heat exchanger can be seen in Chapter IV. This section considers cleaning schedule of crude oil preheating heat exchanger network as shown in Figure 5.1. This heat exchanger network consists of 13 heat exchangers. In this heat exchanger network, there are 3 cold streams and 9 hot streams. The first cold stream is crude oil form storage tank to desalter. The outlet temperature of cold stream after the desalter is decreased 50 °F. The second stream is crude oil from desalter to flash. The third ones is the crude oil after flash that sent to furnace. The phase change and temperature change across the flash are negligible. The linked of hot streams are the heat recovery from this units. The studied are divided into two cases: the first one focuses on the cleaning schedule of single heat exchanger (a heat exchanger number 10 in heat exchanger network as shown in Figure 5.1) whereas the second one deals with the cleaning schedule of heat exchanger network in Figure5.1. The objective function for this problem is the minimization of total operating cost in a fixed operation time.

5.1 Problem formulation in discrete forms

The basic idea in the discrete formulation is to divide the length of time horizon (t_F) to be considered into a number of periods (NP), the length Δt = t_F/NP. Time periods are divided into two subperiods (Smaili et al, 2002). The first period is a *cleaning subperiod* (Δt^{cl}). In this period, heat exchangers are cleaned. And the second one is an *operating subperiod* (Δt^{op}). In this period, the heat exchangers are operated and the formulations of fouling are occurred. The discretisation of the total time horizon is shown in Figure 5.2. The length of each subperiod can be adjusted as necessary. This results due to the fact that the numbers of continuous variables increase with the time periods (Moreno, M.S. *et al.*, 2007).

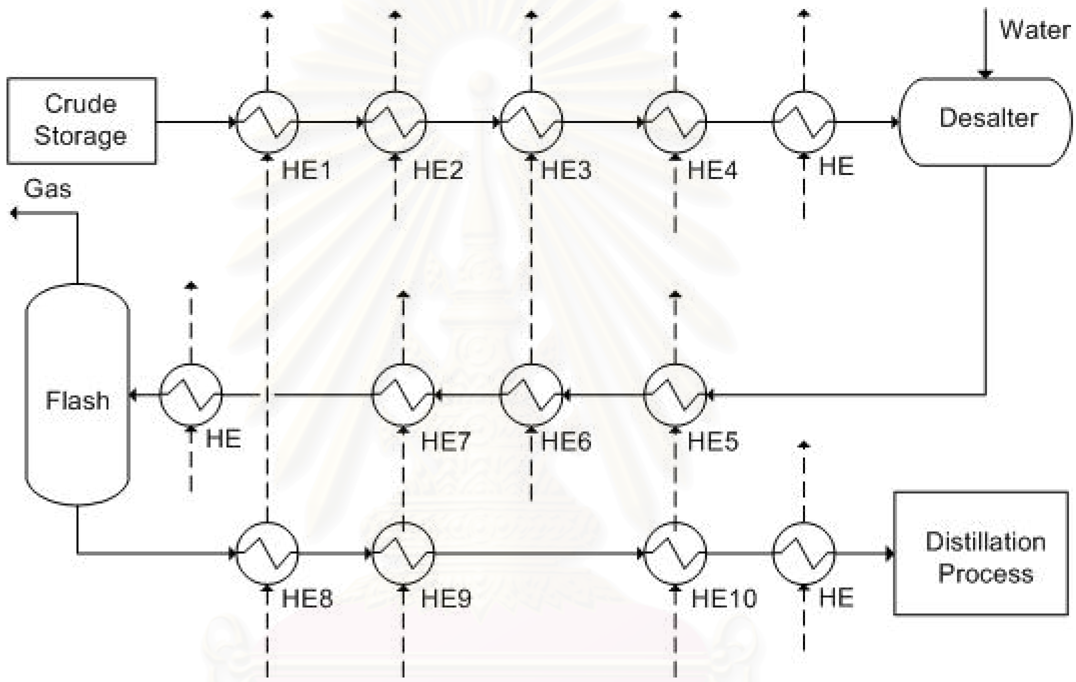

Figure 5.1 The schematic diagram of crude unit heat exchanger network. Solid line: Cold stream and Dot line: Hot stream.

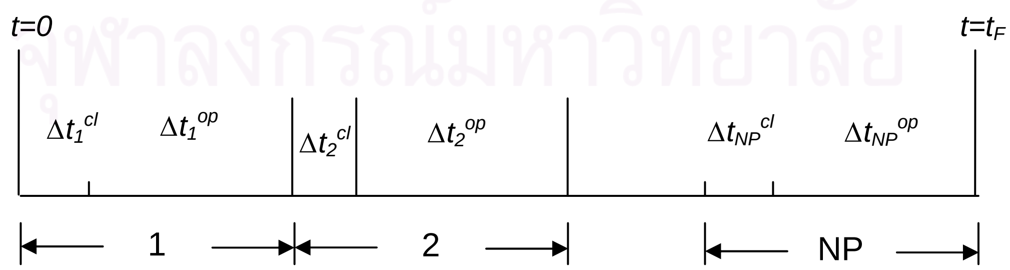

Figure 5.2 Time horizon discretisation with the operating period and cleaning period (Smaili et al, 2002).

The cleaning status of each exchanger *(n)* in each cleaning subperiod *p* is described by a binary variable, $y_{n,p}$, where

$$y_{n,p} = \begin{cases} 1 & if \quad unit \quad n \quad is \quad working \quad in \quad period \quad p \\ 0 & otherwise \end{cases} \tag{5.1}$$

The formulation involves the following indices:

n = 1,…, NE where NE is the number of heat exchangers to be considered for cleaning.

p = 1,…, NP where NP is the number of periods to be considered for cleaning.

Using equation (4.10) and (4.11) in chapter IV, the outlet temperatures of the hot and cold streams in discrete form are

$$T_{n,p}^{h,out} = K_c T_{n,p}^{c,in} + K_h T_{n,p}^{h,in} \tag{5.2}$$

$$T_{n,p}^{c,out} = R(T_{n,p}^{h,in} - T_{n,p}^{h,out}) + T_{n,p}^{c,in} \tag{5.3}$$

where R is constant value as defined in previous Chapter, K_h and K_c were calculated, as see in Chapter IV.

For the case of series heat exchanger network, if the heat exchanger is clean in period p, the outlet temperature of hot stream is equal to the inlet temperature. If it is not cleaned, it is equal to the temperature at the end of previous period (p-1).

For unit n within period p, the heat transfer coefficients in each subperiod are calculated at the beginning of the cleaning subperiod and are related to the values in the previous subperiod, as given:

- Cleaning subperiod:

$$U_{n,p\neq1}^{cl} = \frac{U_{p-1}^{op}}{1+U_{p-1}^{op}\dot{r}_{fn,p}^{op}\Delta t_p^{op}} \tag{5.4a}$$

$$U_{n,1}^{cl} = U_n^{initial} \tag{5.4b}$$

Equation 5.4b allows the problem to start from a "dirty" condition.

- Operating subperiod:

$$U_{n,p}^{op} = \frac{U_{n,p}^{cl}}{1+U_{n,p}^{cl}\dot{r}_{fn,p}^{cl}\Delta t_p^{cl}} y_{n,p} + (1-y_{n,p})U_{clean,n} \tag{5.5}$$

where $U_{clean,n}$ is the overall heat transfer coefficient after cleaning ($U_{clean,n} = \eta_c\ U_{n,1}^{cl}$ where η_c represents the fraction of the clean value to which the heat transfer coefficient is restored after cleaning, Δt_p^{op} and Δt_p^{cl} are fixed.

Fouling formations in discrete form, $\dot{r}_{fn}$ is the fouling rate of each unit in each period, given by

Asymptotic fouling (calculated at the beginning of each subperiod)

(a) Cleaning subperiod

$$\dot{r}_{fn,p}^{cl} = \dot{r}_{fn,p-1}^{op} \exp(-\Delta t_p^{op} / \tau_n) \tag{5.6a}$$

(b) Operating subperiod

$$\dot{r}_{fn,p}^{op} = \dot{r}_{fn,p}^{cl} \exp(-\Delta t_p^{cl} / \tau_n) y_{n,p} + \frac{r_{fn}^{\infty}}{\tau_n}(1-y_{n,p}) \tag{5.6b}$$

Equation 5.6a and 5.6b represent approximation to equation 4.2. The derivation of fouling model is given in Appendix A. The dynamic nature of asymptotic fouling suggests that the length of each time period should be chosen to be a reasonable fraction of the fouling decay constant τ_n.

For the case of simple fouling model, Linear fouling

$$\dot{r}_f = c \tag{5.7}$$

where c is constant for a particular exchanger.

The objective function of finding the optimum heat exchanger network cleaning schedule is to be minimizing the operating costs in specific duration. Therefore, the objective function was computed for various time intervals between consecutive cleaning. The model refers to the tradeoff between furnace extra fuel costs due to fouling and heat exchanger cleaning costs (Smaili et. al, 2001).

$$Obj_{\cos t} = \sum_{p=1}^{NP}\sum_{n=1}^{NE} C_E (Q_{n,clean} - Q_{n,p})\Delta t + \sum_{p=1}^{NP}\sum_{n=1}^{NE} C_{cl}(1 - y_{n,p}) \tag{5.8}$$

where

NE	the number of heat exchangers in the heat exchanger network (unit)
NP	the number of cleaning period (month)
C_E	the cost of furnace extra fuel (£/(Btu/h))
$Q_{n,clean}$	the heat transfer rate between hot and cold fluids in unit n in clean condition (Btu/h)
$Q_{n,p}$	the heat transfer rate between hot and cold fluids in unit n at period p with fouling (Btu/h)
Δt	time length of period (for this study, Δt=30 days)

C_{cl} the cost of heat exchanger cleaning (£/unit)

The optimal cleaning schedule is obtained by minimizing equation (5.8) (minimizing the operation costs)

Applying the constraint in order to reduces the solution space as well as the amount of computations for finding the optimal cleaning schedule by minimizing equation (5.8), the constraint on the operating cost is as follow,

The outlet cold temperature of each heat exchanger must be greater than the inlet cold one and the outlet hot temperature of each heat exchanger must be lower than the inlet hot one:

Cold temperature:

$$T_{c,out} - T_{c,in} \geq 0 \tag{5.9}$$

Hot temperature:

$$T_{h,in} - T_{h,out} \geq 0 \tag{5.10}$$

There are also restrictions in minimum values that certain temperatures can reach:

$$T_{c,out} - T_{c,out}^{\min} \geq 0 \tag{5.11}$$

The optimization cleaning schedule problem is using a multiperiod formulation. This problem is mixed integer nonlinear programming problem (MINLP). This is due to the constraint, as these involve binary variables ($y_{n,p}$) indicating which unit has to be cleaned and continuous variables indicating the heat exchanger network performance. In addition, the log means temperature different introduced nonlinearlity into the heat exchanger unit, heat exchanger network and performance. Because of the multiperiod formulation, the problem of when a unit has to be cleaned can be considered directly. The certain units may be selected to be cleaned because the problem can be constrained. In this study, the input mass flow rates are fixed, and any variation in fluid heat capacity with temperature is neglected. The continuous variable used in formulating the model of the network, $y_{n,p}$ is allowed to vary from 0 to 1. In this research, we propose newly technique that transforms decimal number to binary number.

5.2 Logical variable

From previous studies as shown in Chapter2, there are many problems in large optimal cleaning schedule problems such as binary variables, constraints and approximations. To handle logical variables, we propose a novel technique using binary to decimal transformation. This is resulting in no approximation and the reduction of logical variables and constraints.

5.2.1 Decimal to binary transformation

In order to convert from a base-10 integer (decimal) numeral to its base-2 (binary) equivalent, the number is divided by two. The (integer) result is again divided by two, its remainder is the next most significant bit. This process repeats until the result of further division becomes zero.

For example, 118_{10}, in binary, is:

Operation	118 ÷ 2= 59	59 ÷ 2= 29	29 ÷ 2= 14	14 ÷ 2= 7	7 ÷ 2= 3	3 ÷ 2= 1	1 ÷ 2= 0
Remainder	0	1	1	0	1	1	1

Reading the sequence of remainders from the bottom up gives the binary numeral 1110110_2

5.2.2 Binary to decimal transformation

In the representation of a binary integer, each 1 indicates the occurrence of the corresponding power of 2. To convert from base-2 (binary) to base-10 (decimal) is the reverse algorithm. Starting from the left, double the result and add the next digit until there are no more.

For example to convert 10101101_2 to decimal:

Binary	1	0	1	0	1	1	0	1	
Decimal	$(2^7$x1)	+$(2^6$x0)	+$(2^5$x1)	+$(2^4$x0)	+$(2^3$x1)	+$(2^2$x1)	+$(2^1$x0)	+$(2^0$x1)	= 173

In this work, the problem has 1 logical variable and 72 constaints in the case of single heat exchanger with 24 time horizon. The boundary, $y_{n,p}$, is varied from 1 to 16777215 for first case study. $y_{n,p}$ = 1 means heat exchanger was cleaned every month and $y_{n,p}$ = 16777215 is no cleaning actions. For the case of heat exchanger network and 18 time horison, the problem has 10 logical variables and 540 constraints. The logical variable, $y_{n,p}$ is varied from 1 to 524287 (18 month horizon). $y_{n,p}$ = 1 means heat exchanger is cleaned every month and $y_{n,p}$ = 524287 is no cleaning.

5.3 Optimization of cleaning schedule for single heat exchanger

In this section, we consider the cleaning schedule of single heat exchanger. The operating time is 24 months. The single heat exchanger is counter current shell and tube heat exchanger. This studied divided three cases: first one focuses on the influence of linear fouling model and asymptotic fouling model on optimal cleaning schedule and operating cost. The second case focuses on the influence of initial fouling rate and time decay of fouling formation whereas the third one deals with the influence of cleaning costs on optimal cleaning schedule and operating cost. The parameters for optimization of single heat exchanger case are shown in Table 5.1.

5.3.1 The influence of fouling model on optimal cleaning schedule

Fouling decrease the overall heat transfer coefficient and heat transfer rate. This is resulting in the reduction of heat exchanger performance. Thus, the effect of fouling behavior on heat exchanger is important. This studied considers the linear and asymptotic fouling behavior. The simulations of fouling formation, the variation of overall heat transfer coefficient and the variation of heat transfer rate are shown in previous chapter. The results of the outlet temperature profile of cold stream for linear and asymptotic fouling are presented in Figure 5.3 – 5.4. The optimal cleaning schedule of single heat exchanger is shown in Table 5.2.

Table 5.1 Model parameter for single heat exchanger case

Parameter	Value
Tc,in(°F)	347
Th,in(°F)	631.4
Fh(lb/h)	207,940
Fc(lb/h)	649,217
Ch(Btu/lb °F)	0.67
Cc(Btu/lb °F)	0.57
Uo(Btu/h ft^2 °F)	88.1
Uc(Btu/h ft^2 °F)	88.1
r (linear fouling) (ft^2 °F/Btu)	$2.9x10^{-4}$
r (asymptotic fouling) (h ft^2 °F/Btu)	$6.73x10^{-3}$
A(ft^2)	1,257.2

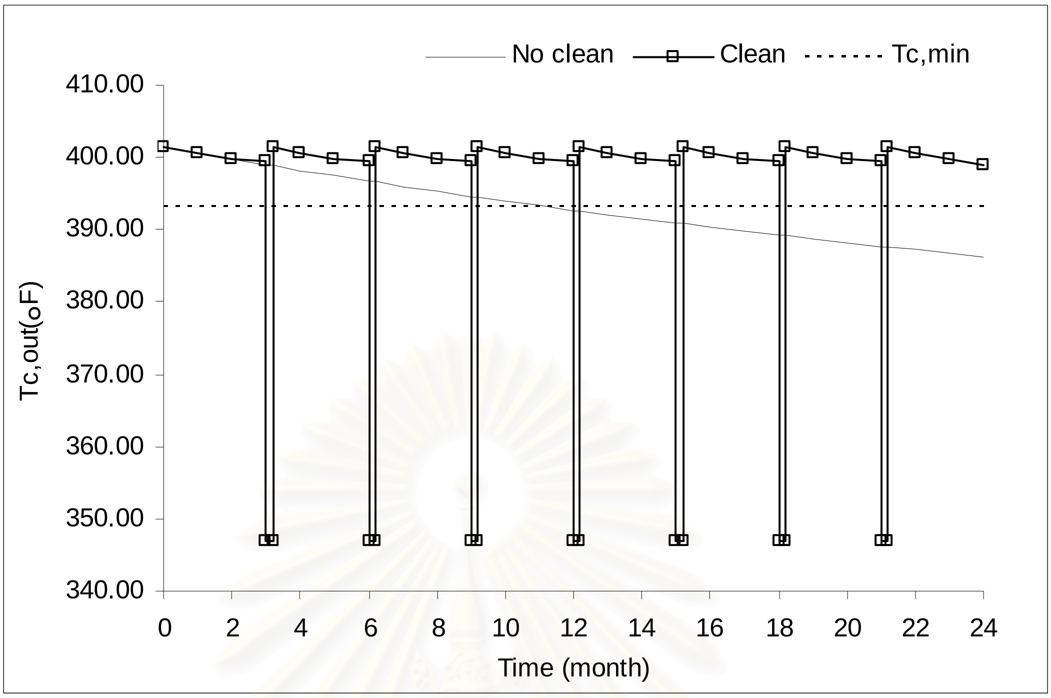

Figure 5.3 The variation of outlet temperature of cold stream for linear fouling with time.

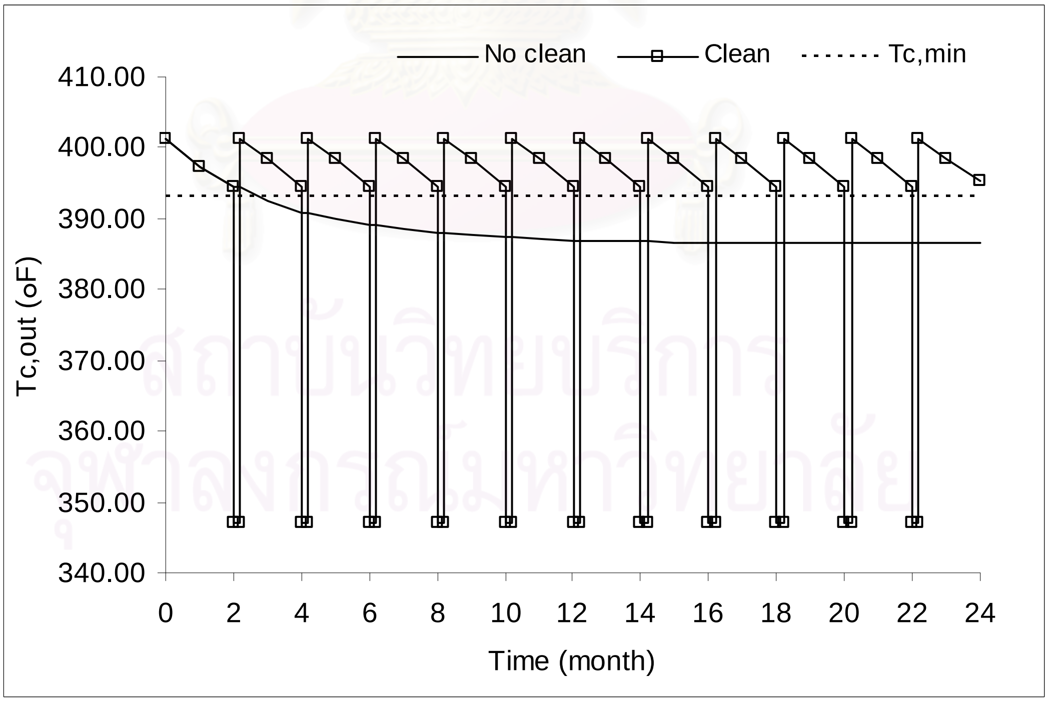

Figure 5.4 The variation of outlet temperature of cold stream for asymptotic fouling with time.

Table 5.2: Optimal cleaning schedule for linear and asymptotic fouling

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	No. of cleaning
Linear fouling			/			/			/			/			/			/			/				7
Asymptotic fouling		/		/		/		/		/		/		/		/		/		/		/			11

Figure 5.3 and Figure 5.4 present the outlet temperature of cold stream profiles for linear fouling model and asymptotic fouling model. It can be seen from Figure 5.3 and Figure 5.4 that no cleaning occurs in the initial period and the end of period. This is due to the fact that the fouling is starting accumulate in initial periods, and the outlet temperatures of cold stream are higher than the minimum temperature ($T_{c,min}$) in later periods.

Table5.2 presents optimal cleaning schedule of single heat exchanger in 24 months for linear fouling model and asymptotic fouling model. It can be seen from Table 5.2 that the number of cleaning in asymptotic fouling are more than linear fouling. The linear fouling case shows seven cleaning at regular intervals, where as the asymptotic fouling case shows eleven cleaning actions. In this case, the optimal period is 3 months for linear fouling case and 2 months for asymptotic fouling case. This result is due to the overall heat transfer coefficient that changes rapidly in asymptotic fouling model. Similarly, the reduction of outlet temperature of cold stream in asymptotic fouling is faster than the linear fouling. Thus, the outlet temperatures of cold stream in asymptotic fouling is reduced to the minimum temperature ($T_{c,min}$) before linear model. This result is causing in the first cleaning of asymptotic fouling model occurred in second period ($t = 2$). From this study, we ensure that the fouling models have the considerable affects on the optimal cleaning schedule and operating cost. Thus, the optimization of cleaning schedule requires a reliable fouling model for predicting unit performance.

5.3.2 The influence of fouling parameter on optimal cleaning schedule

In asymptotic fouling model, initial fouling and time decay in fouling formation could be studied. The simulation of the variation of outlet temperature of cold stream under these parameters is presented in previous section (Chapter V). This section is considered the effect of fouling parameter on the optimal cleaning schedule and operating cost. This section is divided to two cases, first case focus on the effect of initial fouling rate (0.00505 hr ft^2°F/Btu, 0.00673 hr ft^2°F/Btu and 0.00774 hr ft^2°F/Btu). The second case deals with the effect of time decay of fouling formation (90 days, 120 days and 210 days) on cleaning schedule and operating cost.

5.3.2.1 The influence of initial fouling formation on optimal cleaning schedule

From previous Chapter, It is observed that the different in initial rates is very sensitive to the value of the heat transfer rate. The larger initial fouling rate for asymptotic fouling cases result in a rapid decay in heat transfer rate. The result of the effect is proposed in Table 5.3. And, the comparison between the number of cleaning and operating cost with different time decay of fouling formation is presented in Figure 5.5.

Table 5.3: Optimal cleaning schedule with different of initial fouling rate in single heat exchanger

Month / r (hr ft2°F/Btu)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	No of cleaning	Cost (£)
0.00505		/		/		/		/		/		/		/		/		/		/		/			11	147,364
0.00673		/		/		/		/		/		/		/		/		/		/		/			11	176,912
0.00774	/		/		/		/		/		/		/		/		/		/		/		/		12	194,756

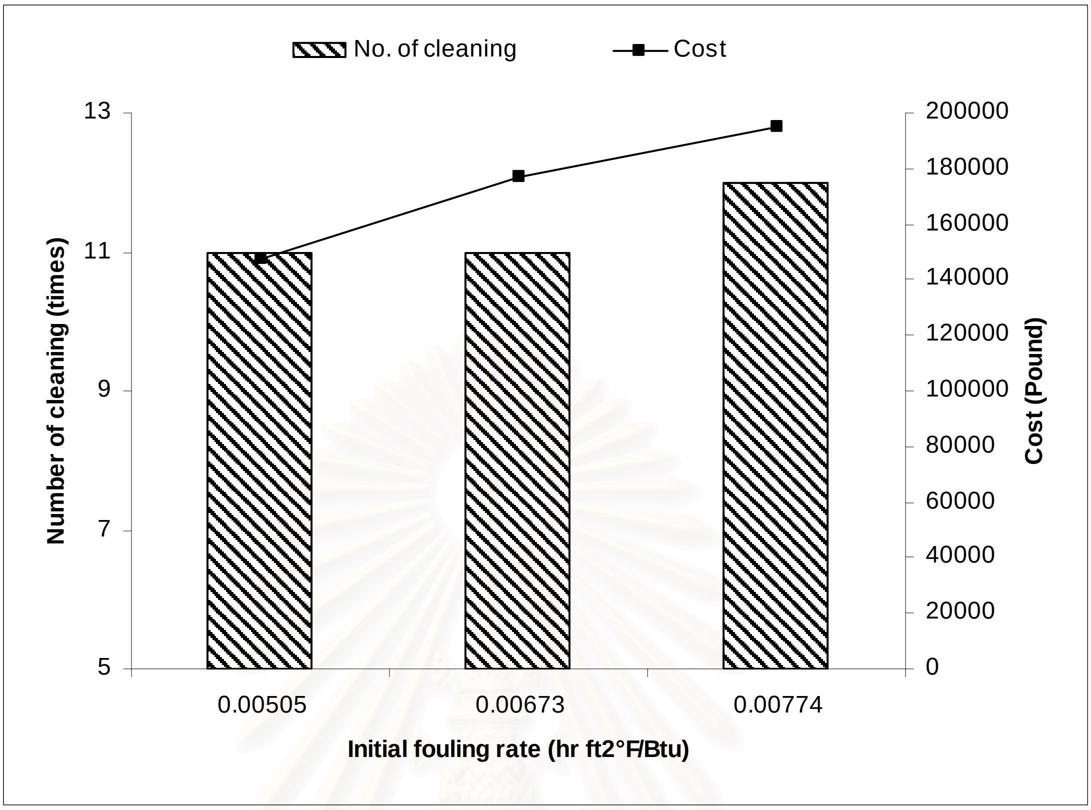

Figure 5.5: The comparison of number of cleaning and operating cost in different initial fouling rate.

From Table 5.3, it is observed that the number of cleaning and operating cost are 11 times and 147,364£ in 0.00505 hr ft^2°F/Btu of initial fouling rate. In the case of initial fouling rate is 0.00673 hr ft^2°F/Btu, the number of cleaning is 11 times and the 176,912£ for the operating cost. Finally in the case of initial fouling rate is 0.00774 ft^2°F/Btu, the number of cleaning and operating cost are 12 time and 194,756£, respectively. This result is due to the increasing in initial fouling rate that is resulting in the decreasing in heat transfer rate. Thus, the rapid change in heat transfer rate is occurred in the case of large value of initial fouling rate. Similarly, the variation of outlet temperature of cold stream in large initial fouling rate is faster than the case of small initial fouling rate. The rapid reduction of outlet temperature of cold stream to the minimum temperature is causing in more number of cleaning.

The operating cost increased when the initial fouling rate is increased. This is due to more cleaning actions in the case of large initial fouling rate. Moreover, the different of heat transfer rate (ΔQ) from initial value of the large initial fouling rate is more than the case of small initial fouling rate. It is leading to the large value of fuel cost. This value is the main factor in objective function. Thus, the operating cost is increased when the initial fouling rate is increased.

5.3.2.2 The influence of time decay of fouling formation on optimal cleaning schedule

The results of the influence of time decay of fouling formation on optimal cleaning schedule for single heat exchanger are presented in Table 5.4 and Figure 5.6.

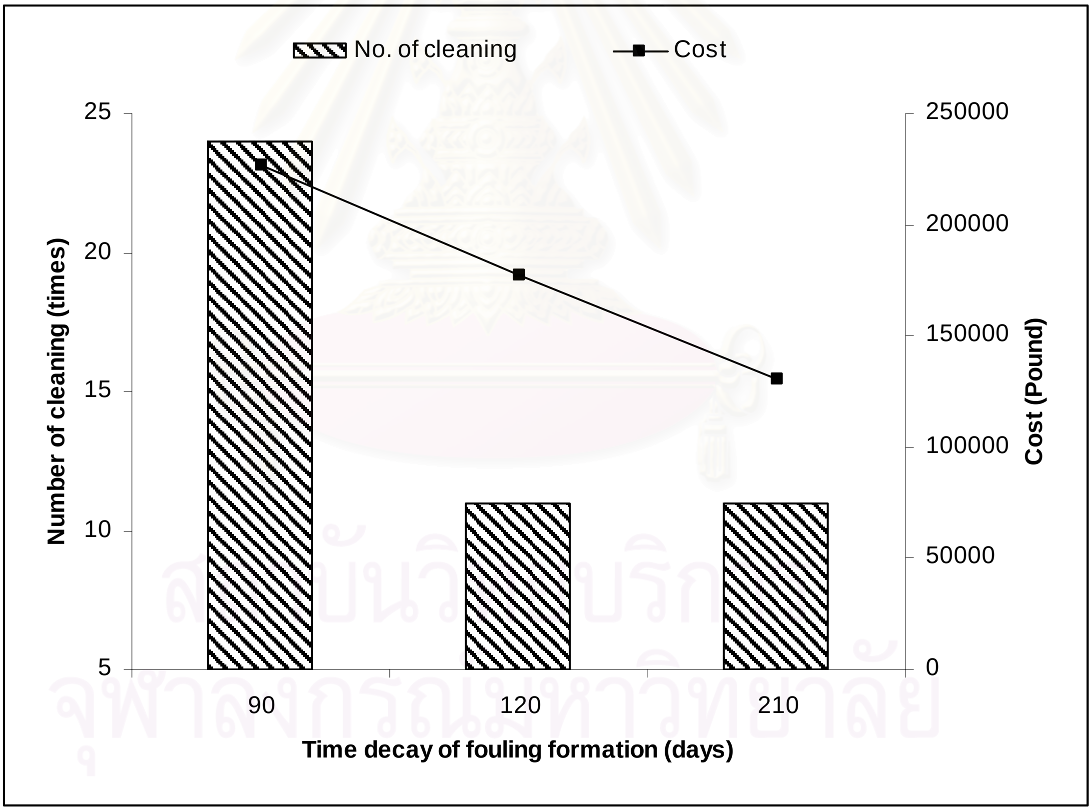

Figure 5.6: The comparison of number of cleaning and operating cost in different time decay of fouling formation

Table 5.4: Optimal cleaning schedule with different of time decay of fouling formation in single heat exchanger

Month τ (days)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	No of cleaning	Cost (£)
90	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	24	226,524
120		/		/		/		/		/		/		/		/		/		/		/			11	176,912
210		/		/		/		/	/		/		/		/		/		/		/		/		11	130,029

From Table 5.4, it can be seen. For the case of time decay of fouling formation is 90 days, the number of cleanings is 24 times, and the operating cost is 226,524£. In the case of 120 days, the number of cleanings and the operating cost are 11 times and 176,912£, respectively. Finally, the case of time decay of fouling formation equals to 210 days, the number of cleanings is 11 times and 130,029£ for operating cost. From table 5.3, the number of cleaning is decreased when the time decay of fouling formation is increased. This result is due to the fact that the large value of time decays of fouling formation (τ) provide the small value of fouling. Thus, the increasing in the decay of fouling formation is resulting in the slow deposition of fouling. In the case of small value of time decay of fouling formation, the outlet temperature of cold is rapidly decreased. Thus, the outlet temperature of cold stream in this case is reduced to the minimum temperature early the case of large value of time decay of fouling formation. This result is causing in more cleaning action. Considering in the operating cost, it is decreased when the time decay of fouling formation is increased. This is due to less cleaning actions in the case of large time decay of fouling formation. In addition, the reduction of time decay of fouling formation is resulting in the increasing in the difference of heat transfer rate (ΔQ) from initial value. It is note in equation 5.8 that the heat loss (ΔQ) is the main affect on objective function that is corresponding to the fuel cost. Therefore, the rapid decreasing in heat transfer rate is causing in the decreasing in heat loss. Thus, the decreasing heat loss with time decay of fouling formation is resulting in the decreasing in operating cost.

This result indicates the important of initial fouling rate and time decay of fouling formation. These parameters are sensitive to the fouling formation and performance of heat exchanger. Thus, the reliable of fouling data and the accuracy of fouling model should be considered.

5.3.3 The influence of cleaning cost on optimal cleaning schedule

The cleaning cost represents a major factor in cost of cleaning as shown equation. 5.8. The cleaning cost could be considered to the type and size of heat exchanger and process consideration. In this work, the values of fuel cost (Cef) are constant, and two different cleaning costs (4000 and 8000) were used. The results are present in term of cost of saving, given by

$$Saving = \frac{Cost(Uncleaned) - Cost(cleaned)}{Cost(Uncleaned)} x100$$

The results of operating cost are shown in comparison with no cleaning case. The optimal cleaning schedules of this studied are represented in Table 5.5 and the cost saving are presented in Table 5.6(a) and 5.6(b).

Table 5.5: Optimal cleaning schedule with different of cleaning cost in single heat exchanger

(a) Linear fouling

Month / Cleaning cost (£/unit)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Cost
4000			/			/			/			/			/			/			/				59,834
8000				/				/				/				/				/					82,863

(b) Asymptotic fouling

Month / Cleaning cost (£/unit)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Cost
4000		/		/		/		/		/		/		/		/		/		/		/			176,912
8000		/		/			/			/		/			/			/			/				217,286

Table 5.6: Summary result for single heat exchanger with 24 months

(a) Linear fouling

	Linear fouling			
	Smaili' s work		This work	
Cleaning cost (£)	£	% saving	£	% saving
Unclean	206,000	-	206,000	-
4,000	81,547	59.0	59,834	70.9
8,000	No reported	-	82,863	59.77

(b) Asymptotic fouling

	Asymptotic fouling			
	Smaili' s work		This work	
Cleaning cost (£)	£	% saving	£	% saving
Unclean	322,000	-	322,000	-
4,000	178,066	44.7	176,912	45.06
8,000	No reported	-	217,286	2.51

From Table 5.5(a), the minimum costs are 59,834£ for 4,000£ cleaning cost and 82,863£ for 8,000£ cleaning cost in linear fouling case. And from Table 5.5(b), the minimum costs are 176,912£ for 4,000£ cleaning cost and 217,286£ for 8,000£ cleaning cost in asymptotic fouling case. From this table, the numbers of cleaning actions in case of cleaning cost 8,000£ is lower than 4,000 £. The results obtained that fewer cleaning actions are performed as the increasing of cleaning cost (Ccl), as expected. It is observed form table 5.6 that the % saving of linear fouling model is higher than asymptotic fouling model. This is due to the fact that the fouling formation in asymptotic fouling is faster than the linear fouling. The outlet temperatures of cold stream in asymptotic fouling reduced to the target temperature ($T_{c,min}$) before linear model. Thus, the numbers of cleaning in asymptotic fouling model are more than linear fouling. Similarly, the % saving of 4,000 £ is higher than 8,000 £ in all fouling models. It is observed from table 5.5 (a) and 5.5 (b), the number of cleaning in the case of cleaning cost equal to 4,000 £ is higher than the case of cleaning cost equal to 8,000. It is note that from equation 5.5, the cleaning cost is major factor in objective function. In order to minimize the operating cost, cleaning actions are decreased when the cleaning cost is increased. It is observed that all of solutions for single heat exchanger are cyclic. This means that the heat exchanger is cleaned every time when fouling reaches a certain value.

5.4 Optimization of cleaning schedule for heat exchanger network

In this section, we considered the optimal cleaning schedule of heat exchanger network under fouling condition. This studied divided into two cases. The first case focuses on the optimization of cleaning schedule of heat exchanger network for linear fouling and asymptotic fouling model. The second one deals with the optimization of cleaning schedule of heat exchanger network for no minimum constraint case (no $T_{c,min}$). The operating time horizons are 18 months. The parameters of this heat exchanger network are shown in Table 5.15.

5.4.1 Optimization of cleaning schedule of heat exchanger network for linear fouling and asymptotic fouling

In this studied, we considered the effects of fouling model and cleaning cost on optimal cleaning schedule. Table 5.7(a) and 5.7(b) are presented the optimal cleaning schedule of this heat exchanger network for linear fouling model. In addition, the temperature profiles of cold streams are presented in figure 5.7 – 5.16. Table 5.8(a) and 5.8(b) are presented the optimal cleaning schedule of this heat exchanger network for asymptotic fouling model, and the temperature profiles of cold streams are presented in figure 5.17 – 5.26. The results are summarized in Table 5.9 and Table 5.10.

Table 5.7: Optimal cleaning schedule with different of cleaning cost in heat exchanger network: Linear fouling.

(a) Ccl = 4000 £

No. \ Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1				/					/					/					3
2					/					/				/					3
3					/					/				/					3
4			/				/				/				/				4
5					/								/						2
6					/								/						2
7					/					/				/					3
8				/					/					/					3
9			/				/			/				/					4
10			/			/			/			/			/				5
No. cleans / period	0	0	3	2	5	1	2	0	3	4	1	1	2	6	2	0	0	0	32

COST = 234,755 £

(b) Ccl = 8000 £

No. \ Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1				/					/				/						3
2					/						/					/			3
3					/					/					/				3
4				/			/				/				/				4
5									/										1
6						/						/							2
7							/							/					2
8								/						/					2
9					/					/				/					3
10				/					/					/					3
No. cleans / period	0	0	0	3	3	1	2	1	3	2	2	1	1	4	2	1	0	0	26

COST = 340,186 £

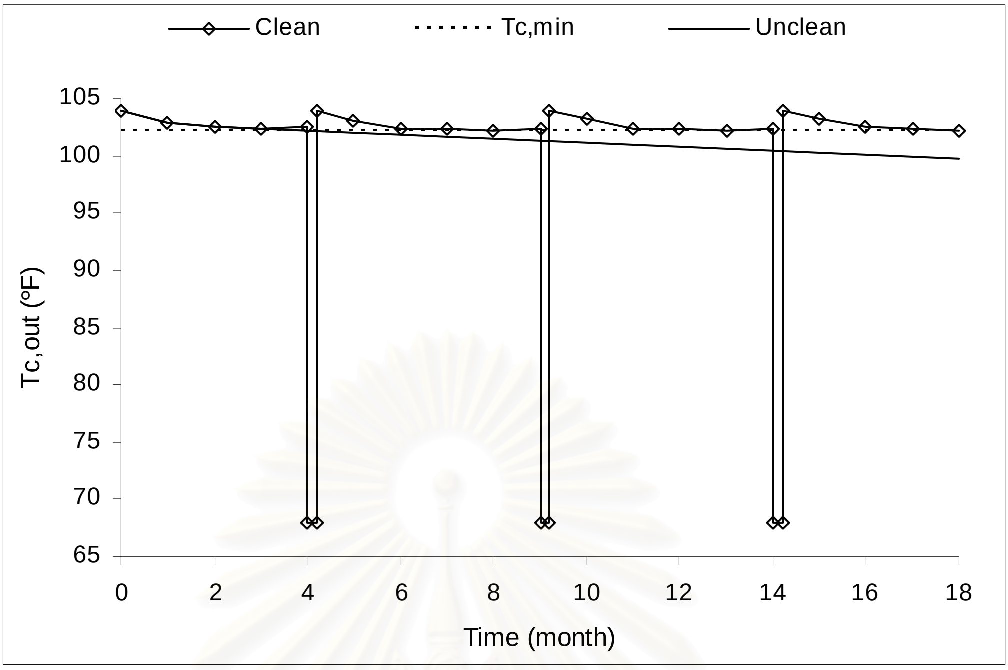

Figure 5.7: The schematic diagram of the variations of the outlet temperatures heat exchanger number 1 for linear fouling with cleaning cost = 4,000£

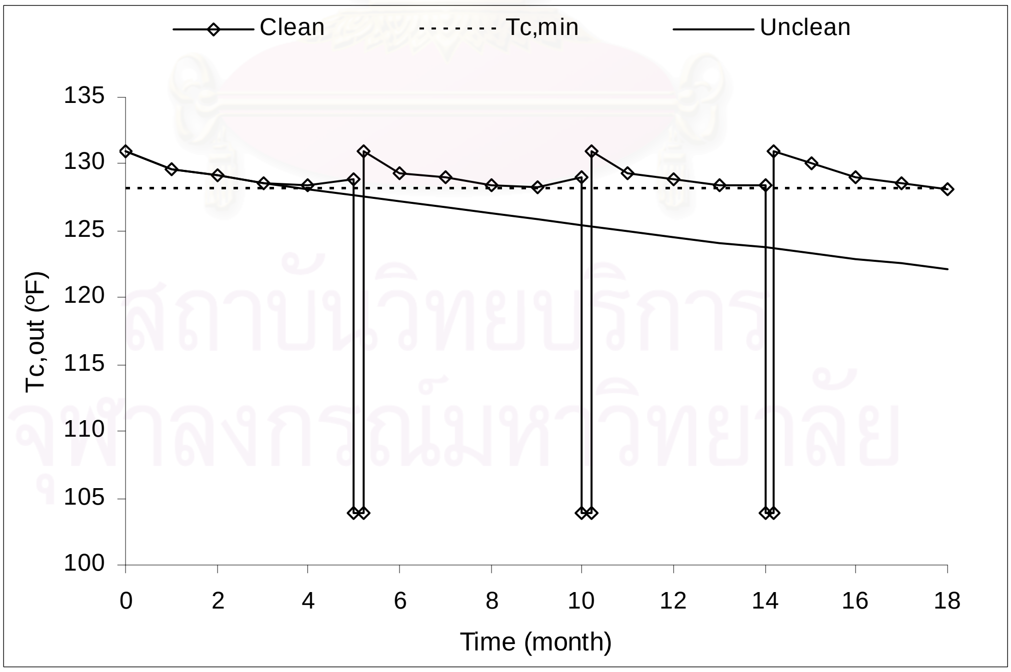

Figure 5.8: The schematic diagram of the variations of the outlet temperatures heat exchanger number 2 for linear fouling with cleaning cost = 4,000£

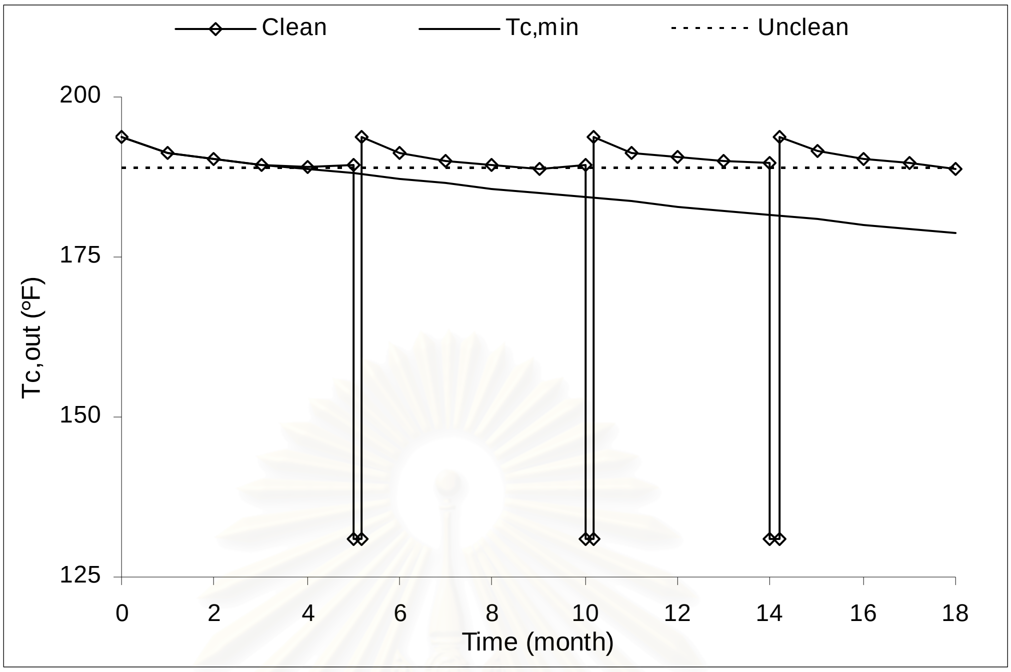

Figure 5.9: The schematic diagram of the variations of the outlet temperatures heat exchanger number 3 for linear fouling with cleaning cost = 4,000£

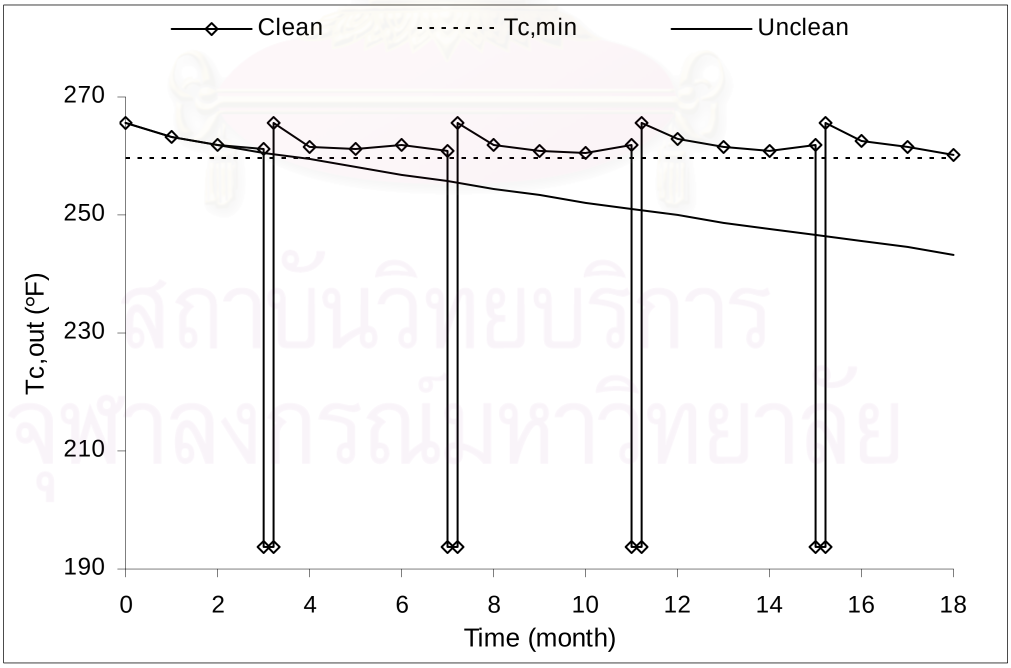

Figure 5.10: The schematic diagram of the variations of the outlet temperatures heat exchanger number 4 for linear fouling with cleaning cost = 4,000£

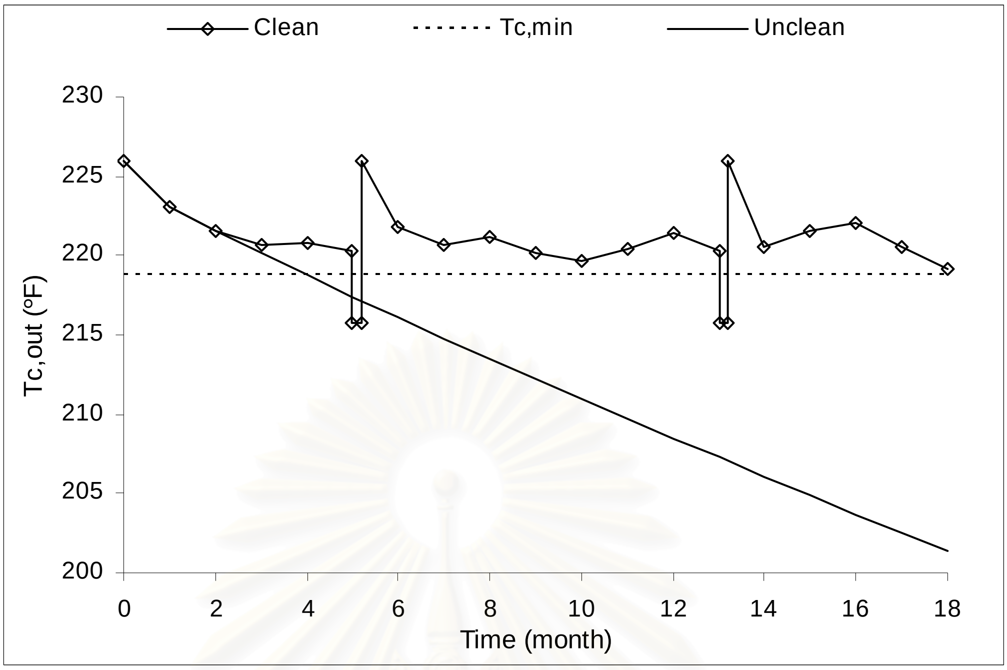

Figure 5.11: The schematic diagram of the variations of the outlet temperatures heat exchanger number 5 for linear fouling with cleaning cost = 4,000£

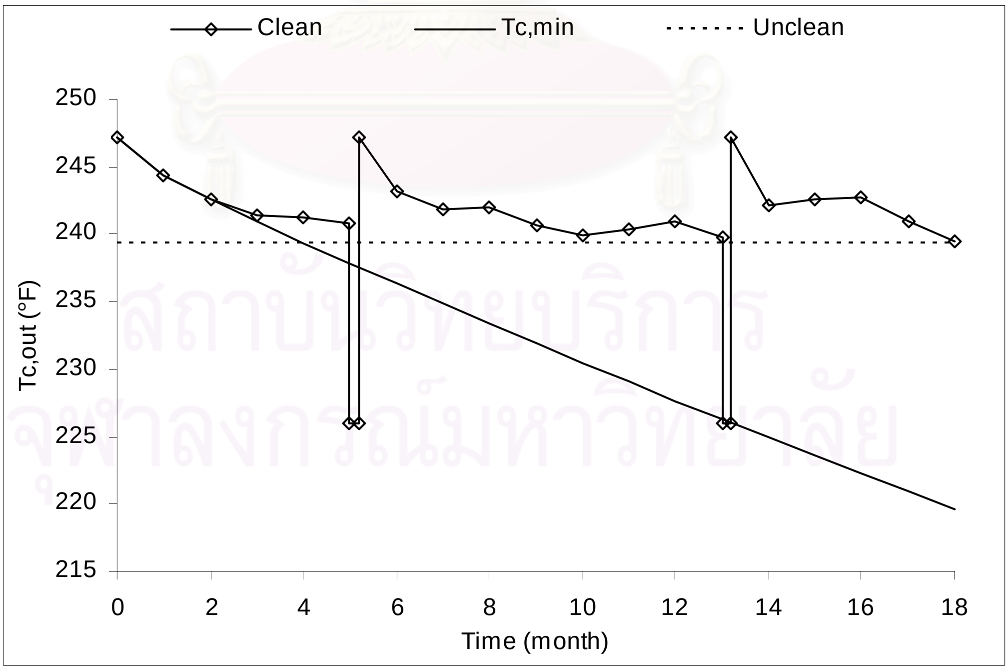

Figure 5.12: The schematic diagram of the variations of the outlet temperatures heat exchanger number 6 for linear fouling with cleaning cost = 4,000£

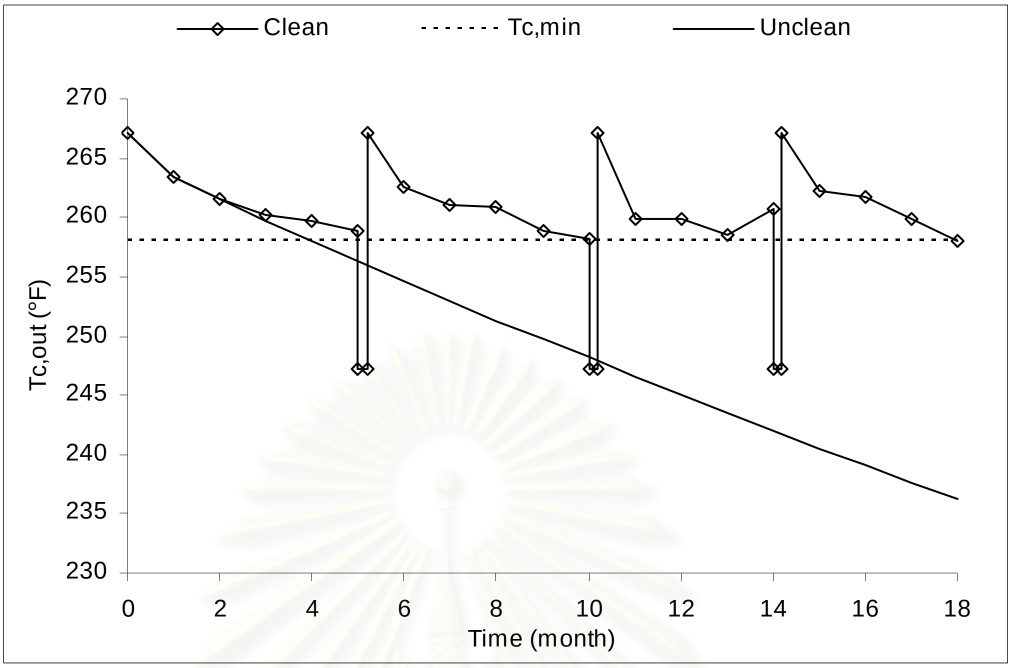

Figure 5.13: The schematic diagram of the variations of the outlet temperatures heat exchanger number 7 for linear fouling with cleaning cost = 4,000£

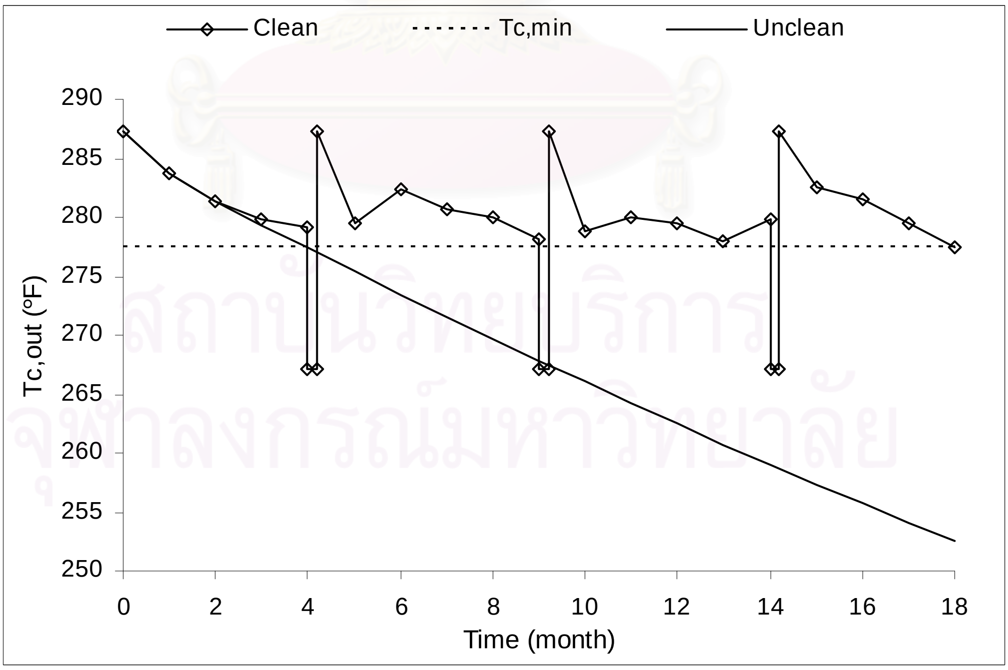

Figure 5.14: The schematic diagram of the variations of the outlet temperatures heat exchanger number 8 for linear fouling with cleaning cost = 4,000£

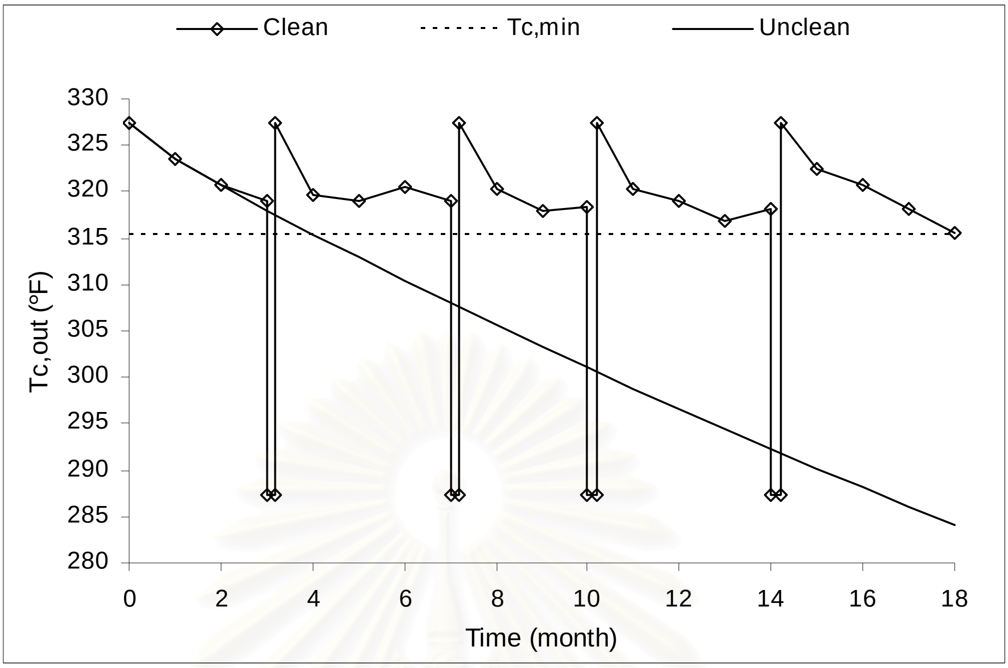

Figure 5.15: The schematic diagram of the variations of the outlet temperatures heat exchanger number 9 for linear fouling with cleaning cost = 4,000£

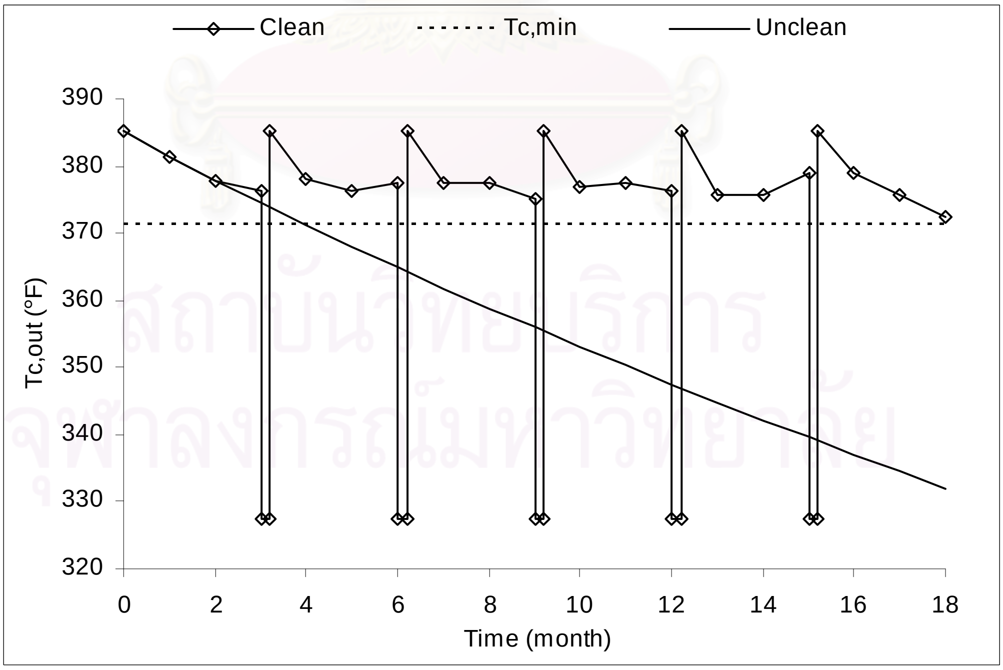

Figure 5.16: The schematic diagram of the variations of the outlet temperatures heat exchanger number 10 for linear fouling with cleaning cost = 4,000£

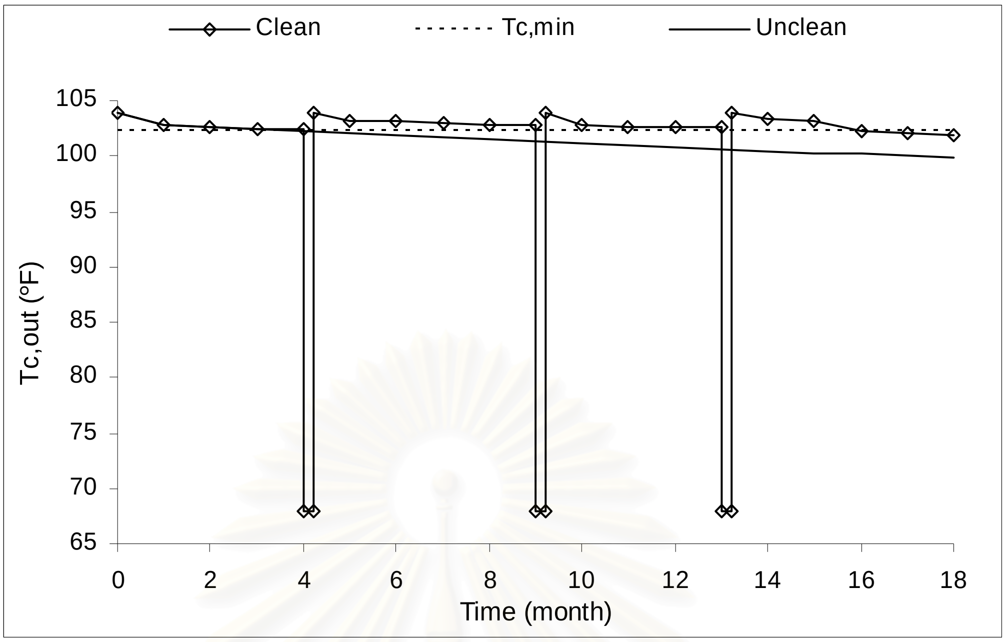

Figure 5.17: The schematic diagram of the variations of the outlet temperatures heat exchanger number 1 for linear fouling with cleaning cost = 8,000£

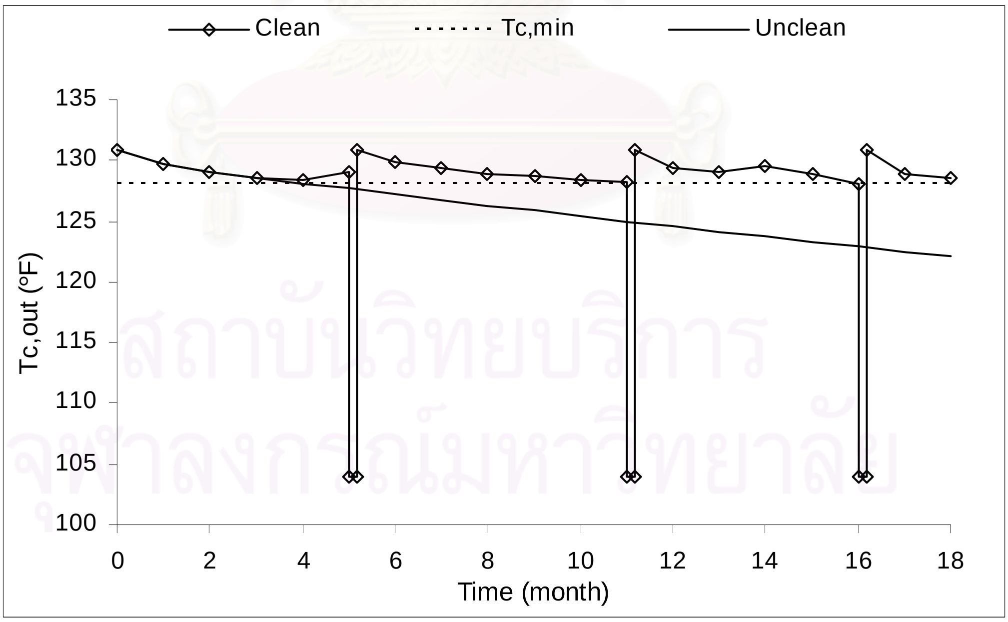

Figure 5.18: The schematic diagram of the variations of the outlet temperatures heat exchanger number 2 for linear fouling with cleaning cost = 8,000£

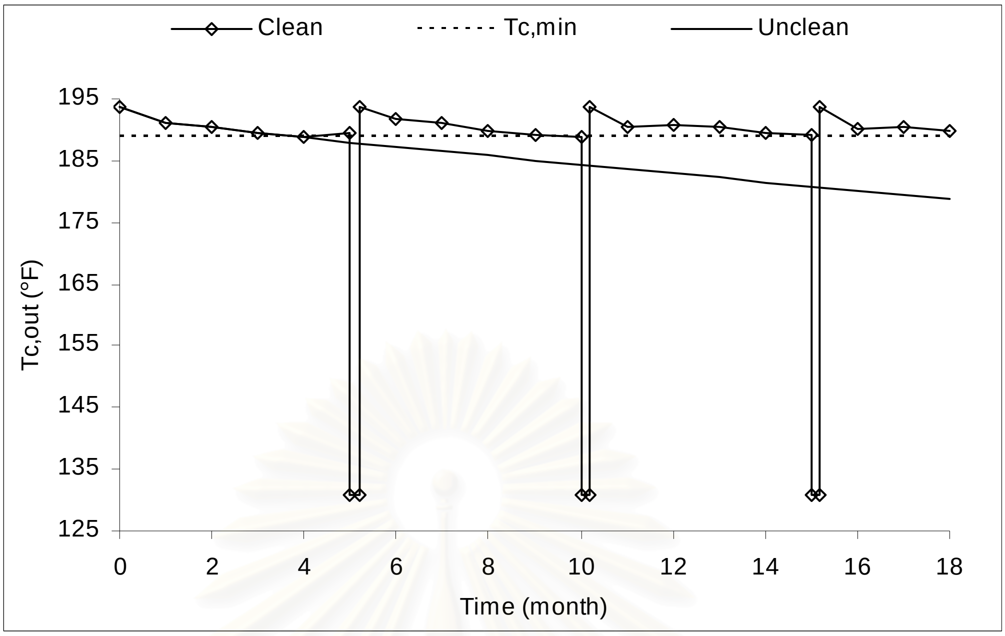

Figure 5.19: The schematic diagram of the variations of the outlet temperatures heat exchanger number 3 for linear fouling with cleaning cost = 8,000£

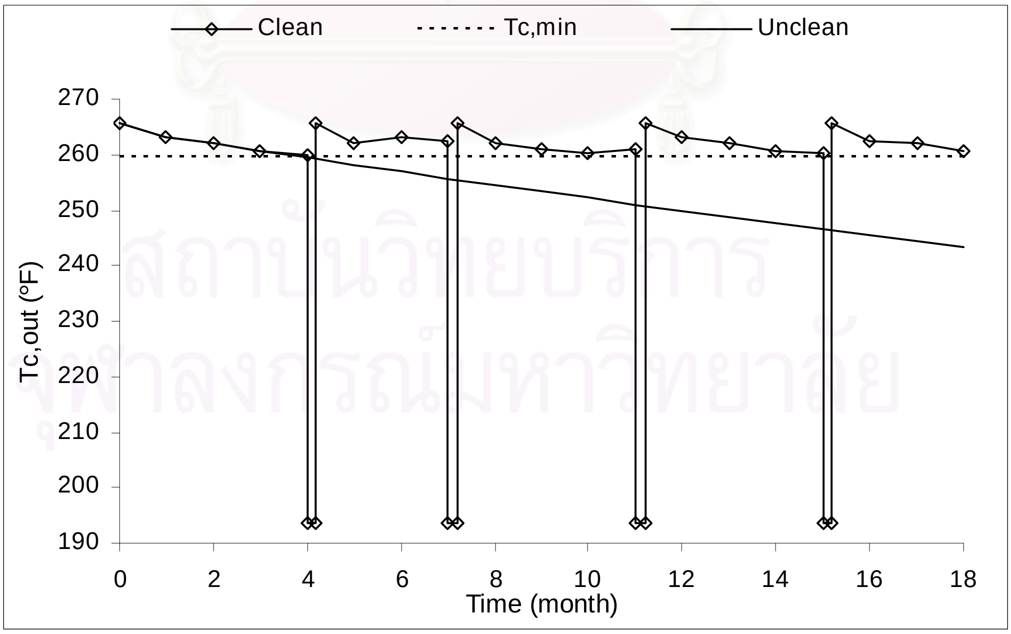

Figure 5.20: The schematic diagram of the variations of the outlet temperatures heat exchanger number 4 for linear fouling with cleaning cost = 8,000£

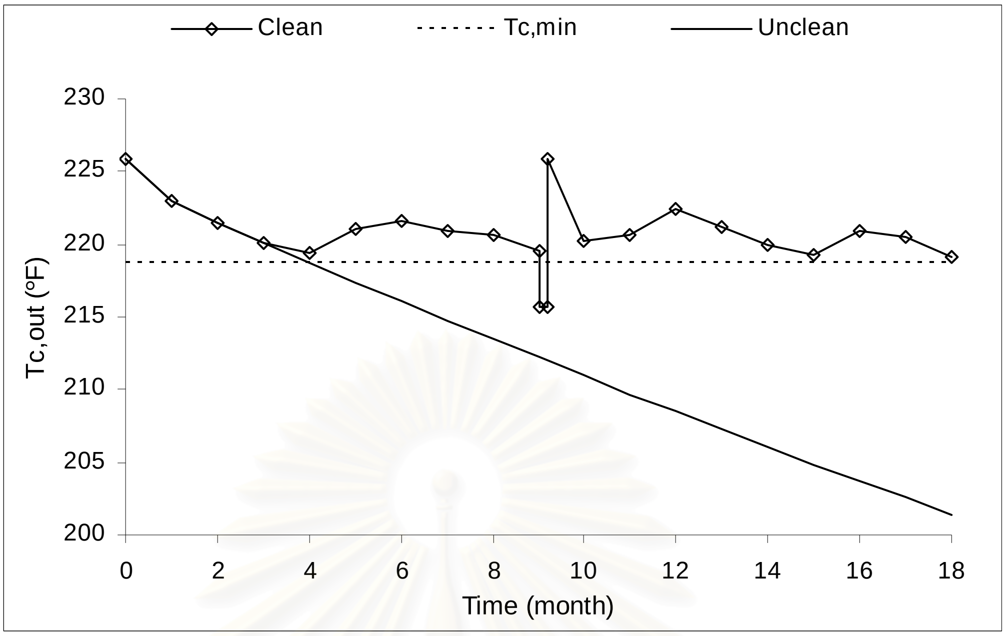

Figure 5.21: The schematic diagram of the variations of the outlet temperatures heat exchanger number 5 for linear fouling with cleaning cost = 8,000£

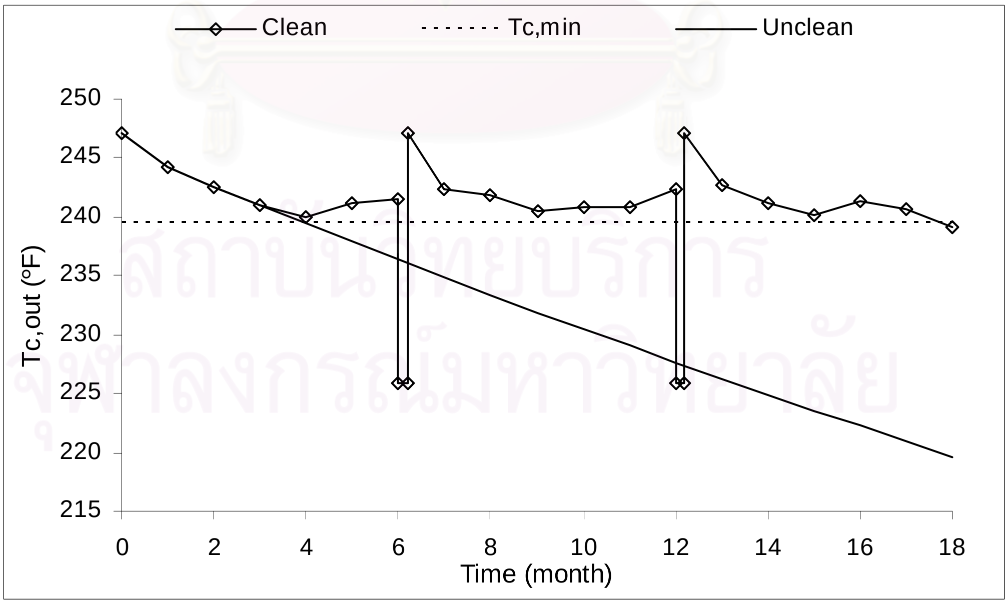

Figure 5.22: The schematic diagram of the variations of the outlet temperatures heat exchanger number 6 for linear fouling with cleaning cost = 8,000£

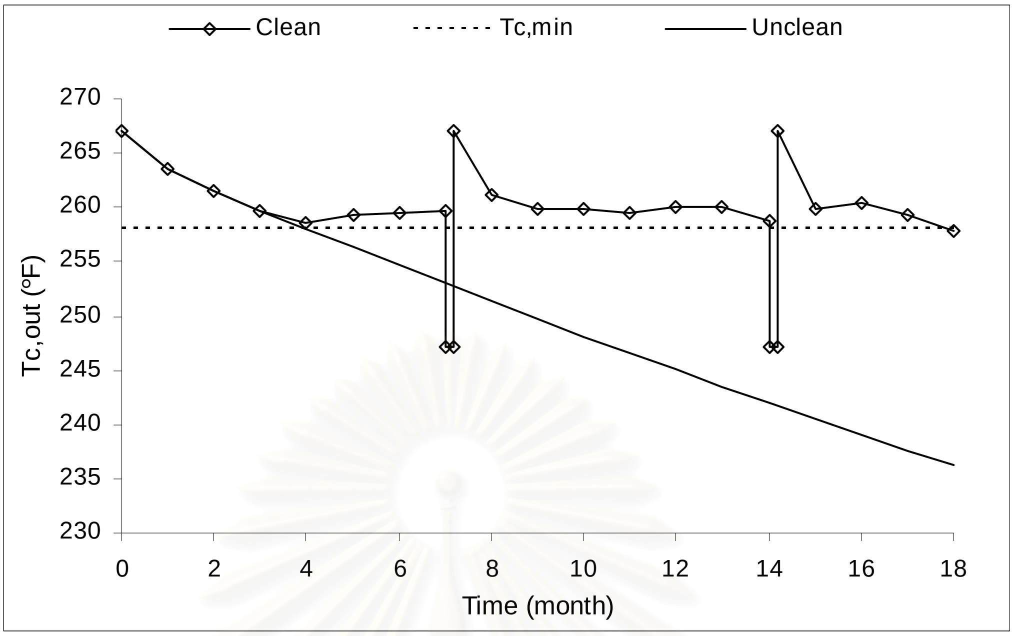

Figure 5.23: The schematic diagram of the variations of the outlet temperatures heat exchanger number 7 for linear fouling with cleaning cost = 8,000£

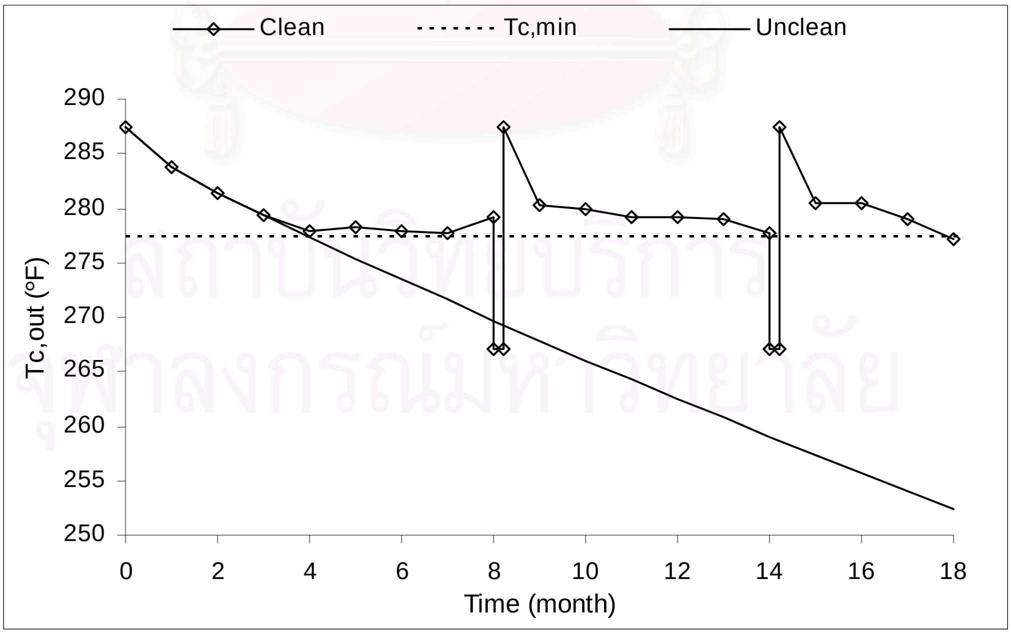

Figure 5.24: The schematic diagram of the variations of the outlet temperatures heat exchanger number 8 for linear fouling with cleaning cost = 8,000£

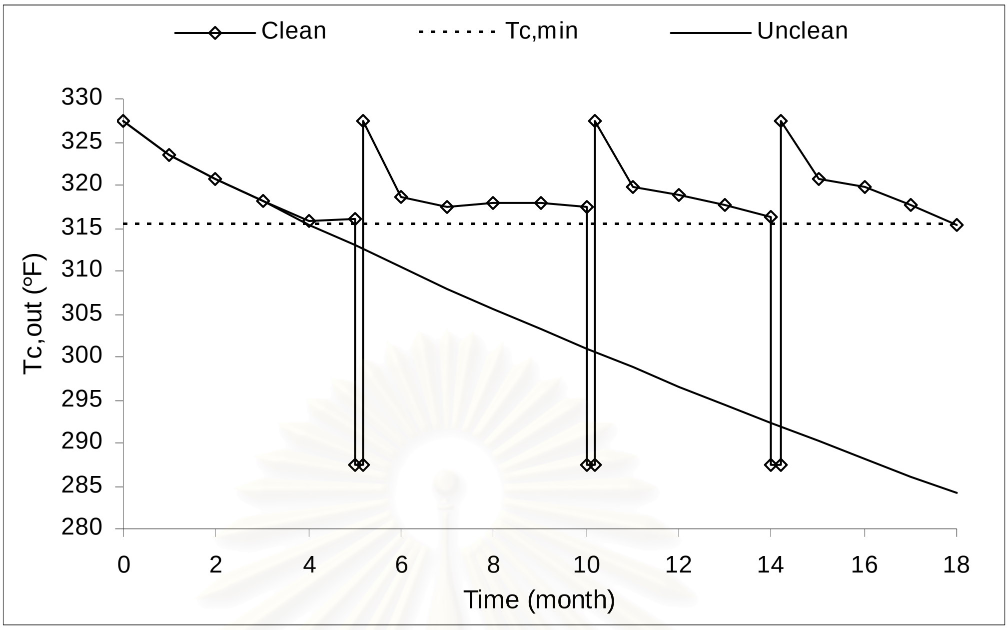

Figure 5.25: The schematic diagram of the variations of the outlet temperatures heat exchanger number 9 for linear fouling with cleaning cost = 8,000£

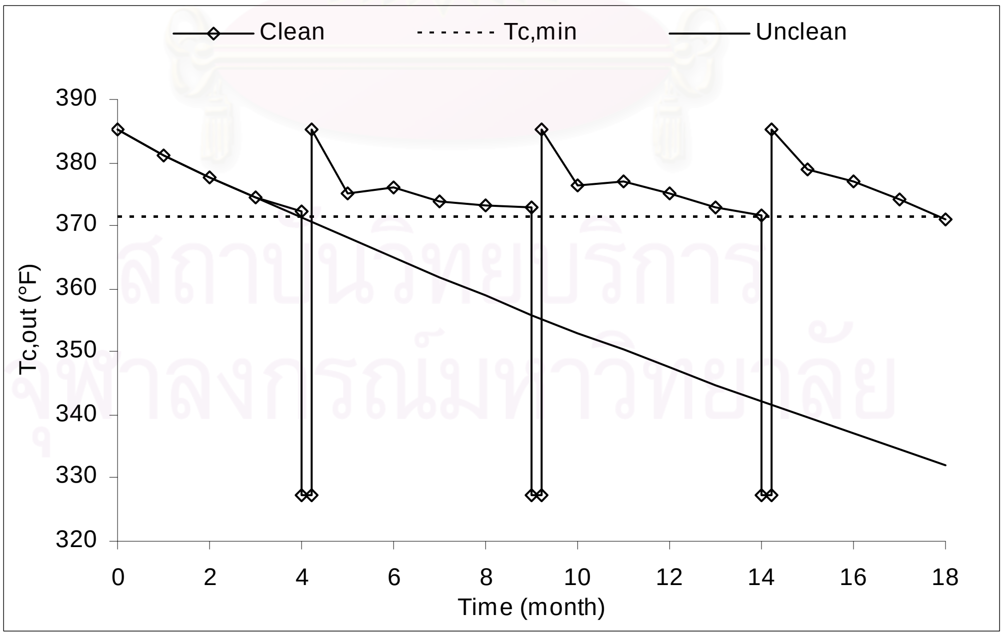

Figure 5.26: The schematic diagram of the variations of the outlet temperatures heat exchanger number 10 for linear fouling with cleaning cost = 8,000£

Table 5.8: Optimal cleaning schedule with different of cleaning cost in heat exchanger network: Asymptotic fouling.

(a) Ccl = 4000 £

No. \ Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1		/		/			/		/		/		/		/				7
2	/	/		/		/		/		/		/	/		/	/			10
3		/			/			/				/				/			5
4			/			/				/			/				/		5
5																			0
6			/			/			/				/						4
7			/					/						/					3
8			/			/					/			/					4
9		/		/		/		/		/		/		/		/			8
10	/	/		/	/	/	/	/	/	/	/	/	/	/	/	/			15
No. cleans / period	2	5	4	4	2	6	2	5	3	4	3	4	5	4	3	4	1	0	61

COST = 351,155 £

(b) Ccl = 8000 £

No. \ Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1		/	/				/				/			/		/			6
2	/			/		/			/		/				/				6
3					/					/				/					3
4			/				/				/				/	/			5
5																			0
6				/				/					/						3
7				/			/					/							3
8														/					1
9			/		/		/				/			/					5
10		/		/		/		/		/		/		/		/			8
No. cleans / period	1	2	3	4	2	2	4	2	1	2	4	2	1	5	2	3	0	0	40

COST =486,035 £

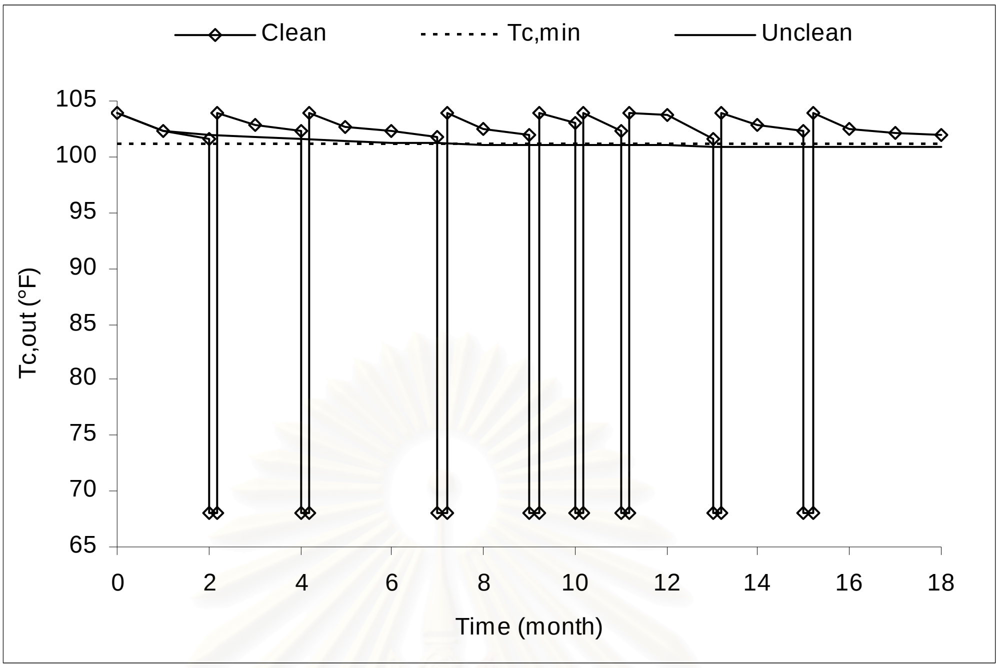

Figure 5.27: The schematic diagram of the variations of the outlet temperatures heat exchanger number 1 for asymptotic fouling with cleaning cost = 4,000£

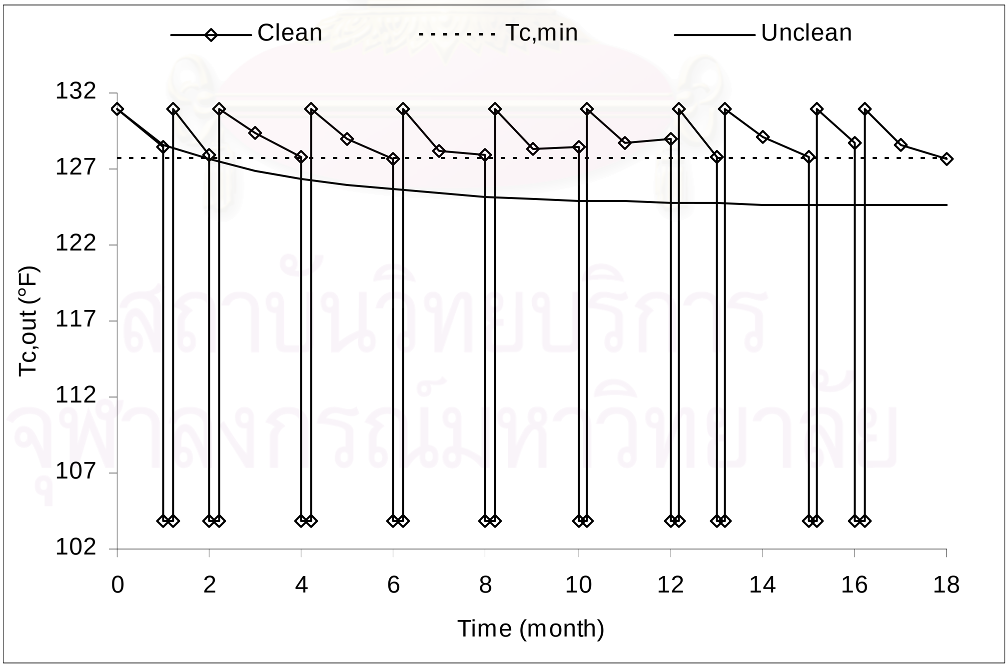

Figure 5.28: The schematic diagram of the variations of the outlet temperatures heat exchanger number 2 for asymptotic fouling with cleaning cost = 4,000£

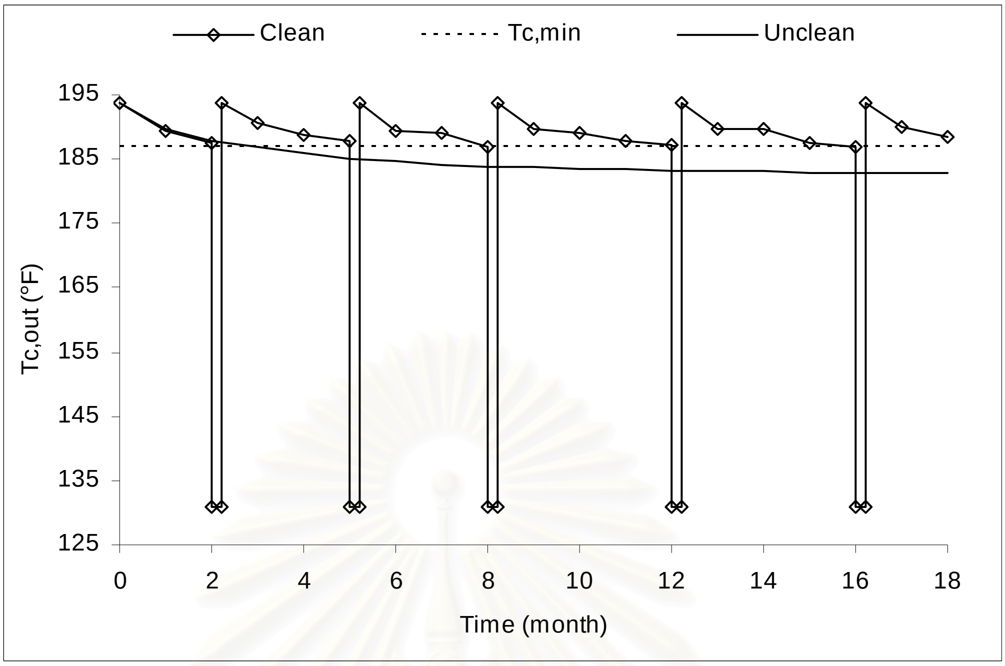

Figure 5.29: The schematic diagram of the variations of the outlet temperatures heat exchanger number 3 for asymptotic fouling with cleaning cost = 4,000£

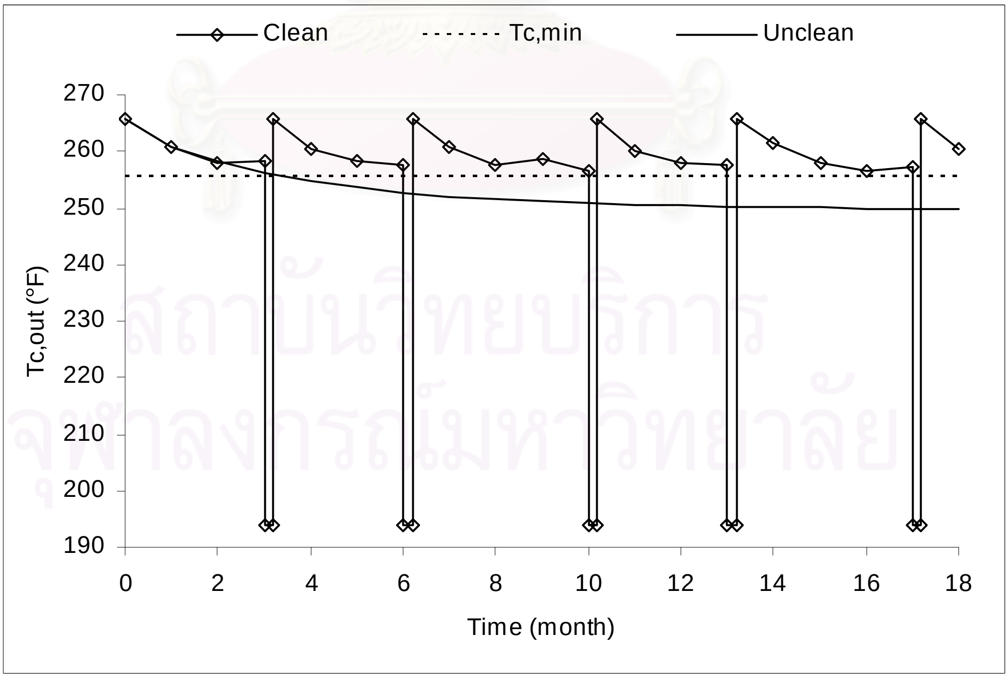

Figure 5.30: The schematic diagram of the variations of the outlet temperatures heat exchanger number 4 for asymptotic fouling with cleaning cost = 4,000£

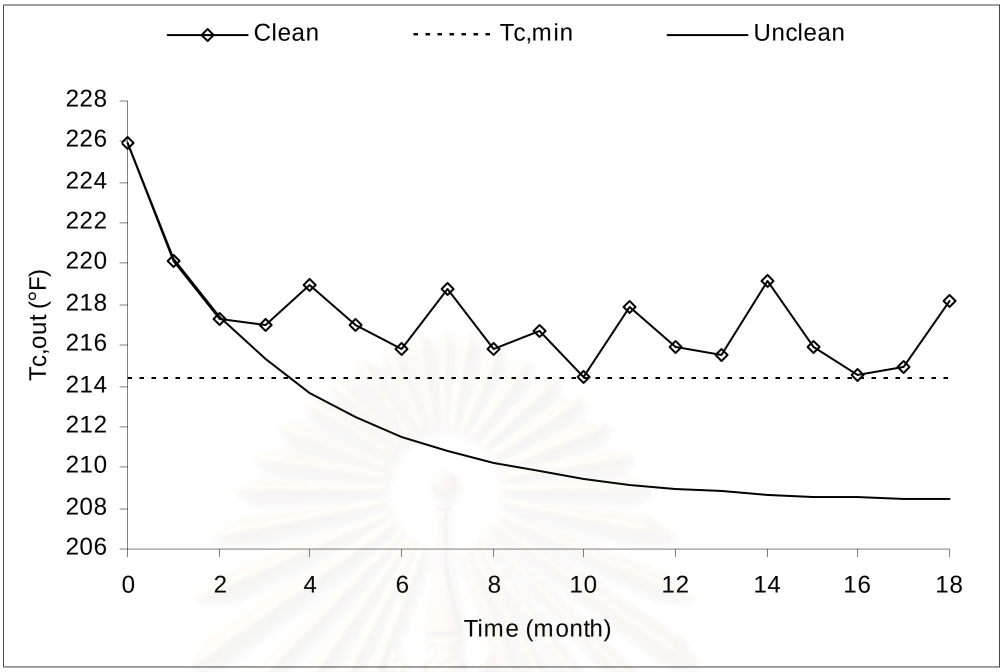

Figure 5.31: The schematic diagram of the variations of the outlet temperatures heat exchanger number 5 for asymptotic fouling with cleaning cost = 4,000£

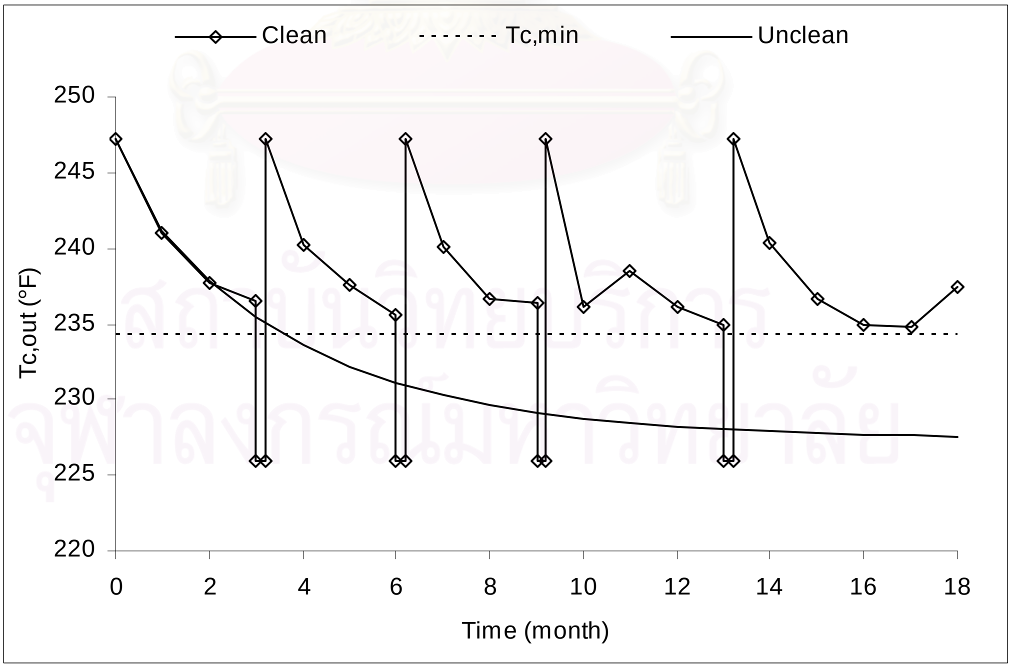

Figure 5.32: The schematic diagram of the variations of the outlet temperatures heat exchanger number 6 for asymptotic fouling with cleaning cost = 4,000£

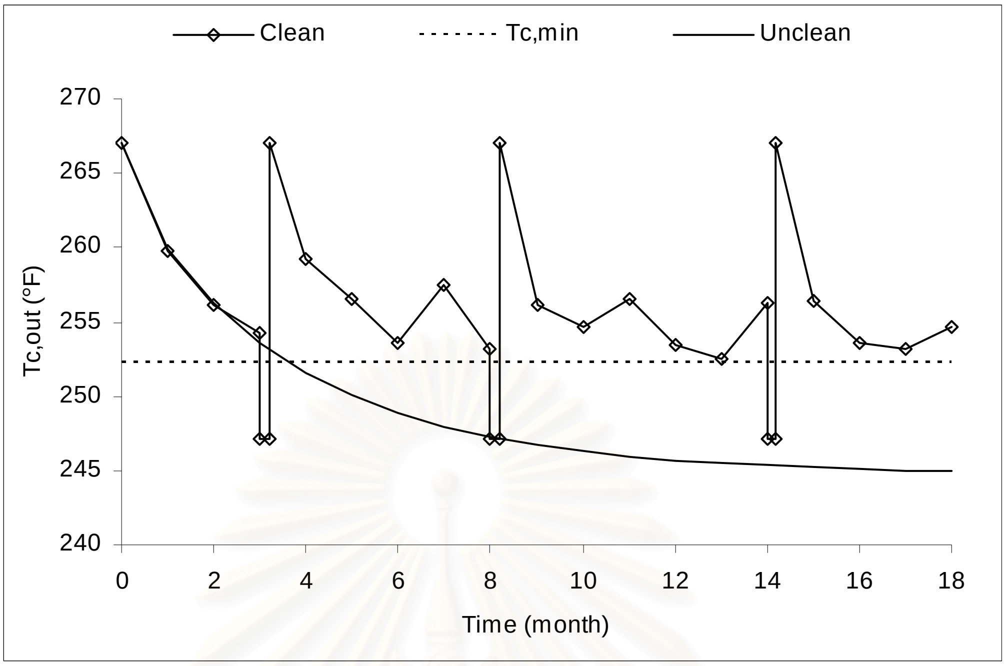

Figure 5.33: The schematic diagram of the variations of the outlet temperatures heat exchanger number 7 for asymptotic fouling with cleaning cost = 4,000£

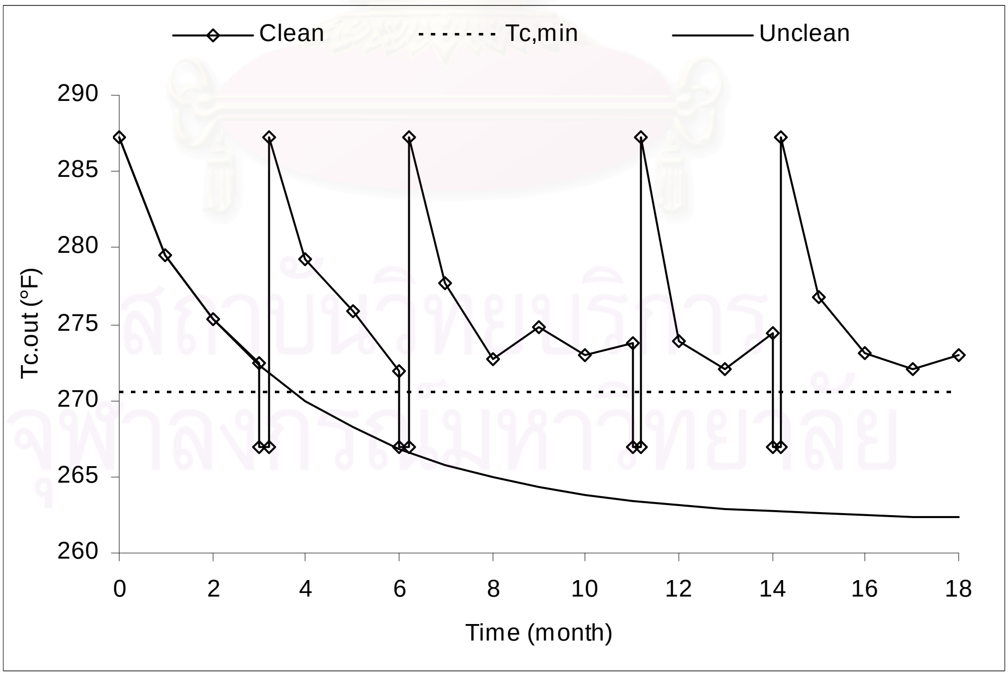

Figure 5.34: The schematic diagram of the variations of the outlet temperatures heat exchanger number 8 for asymptotic fouling with cleaning cost = 4,000£

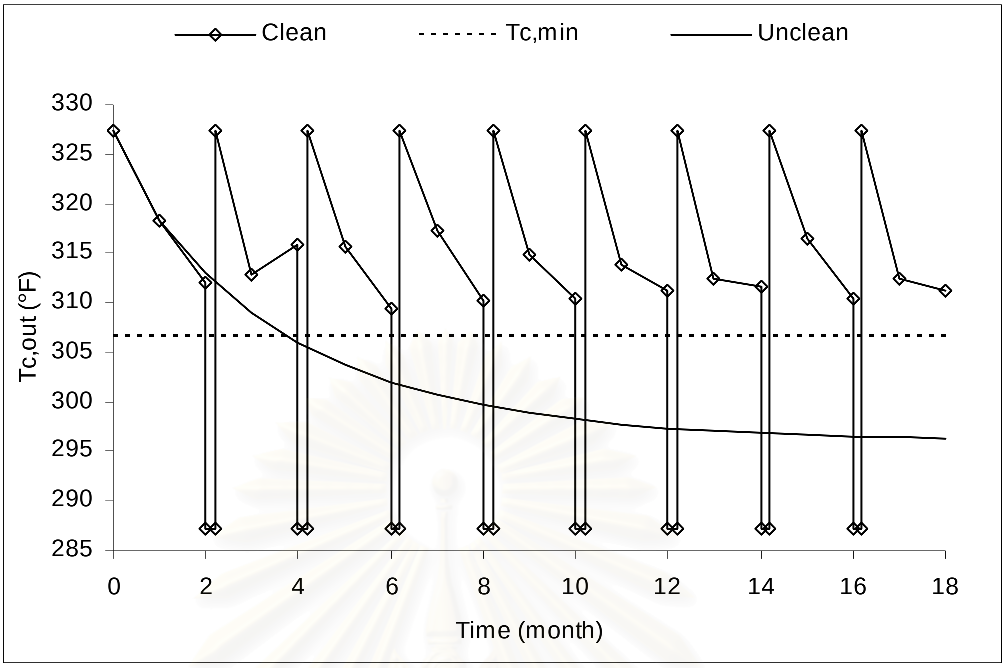

Figure 5.35: The schematic diagram of the variations of the outlet temperatures heat exchanger number 9 for asymptotic fouling with cleaning cost = 4,000£

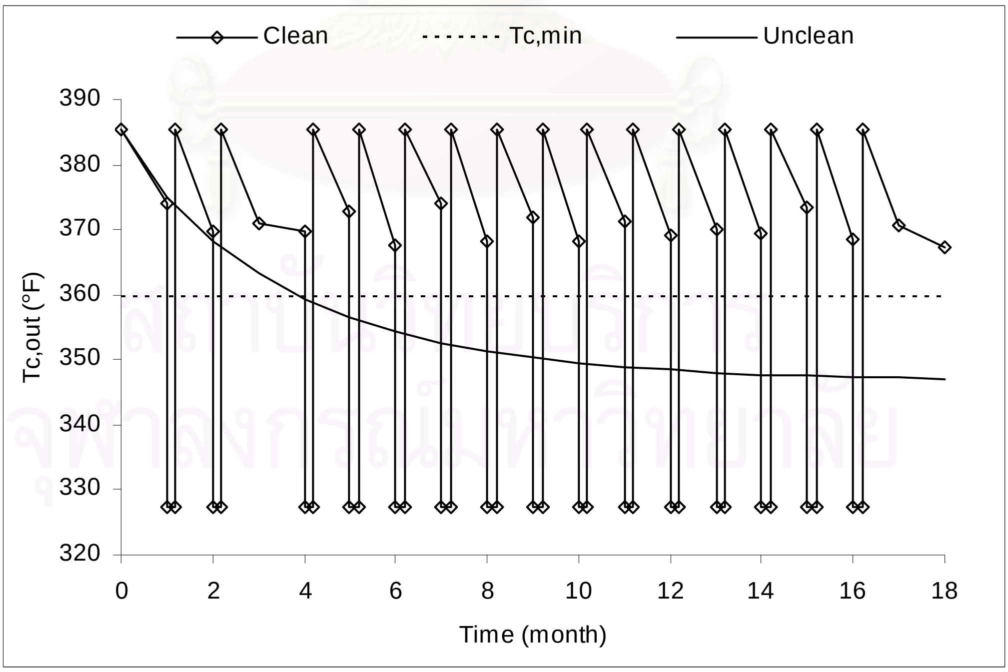

Figure 5.36: The schematic diagram of the variations of the outlet temperatures heat exchanger number 10 for asymptotic fouling with cleaning cost = 4,000£

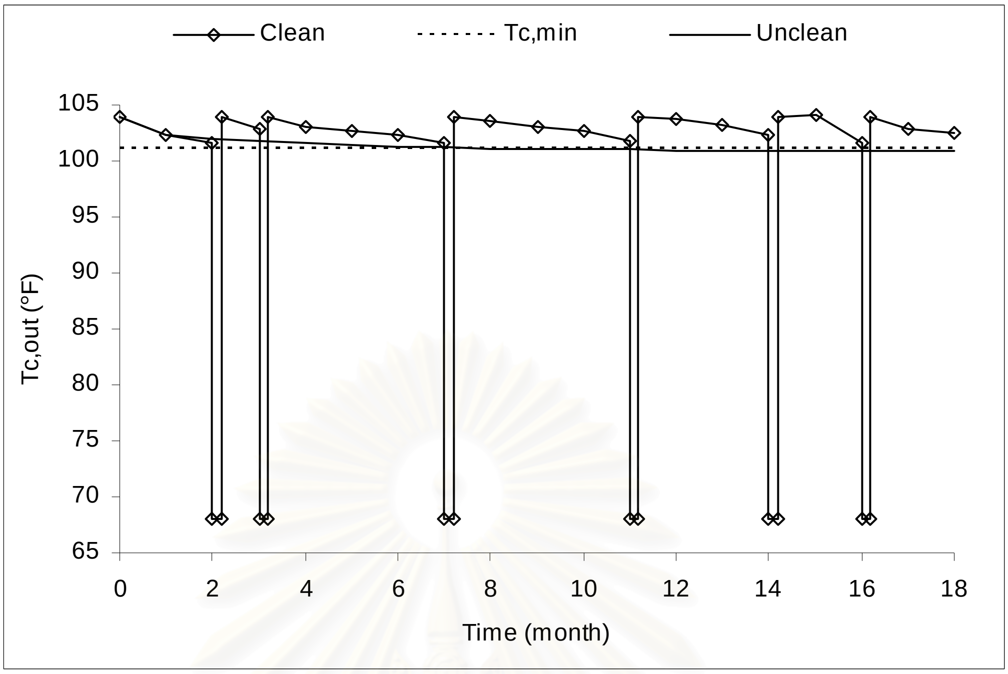

Figure 5.37: The schematic diagram of the variations of the outlet temperatures heat exchanger number 1 for asymptotic fouling with cleaning cost = 8,000£

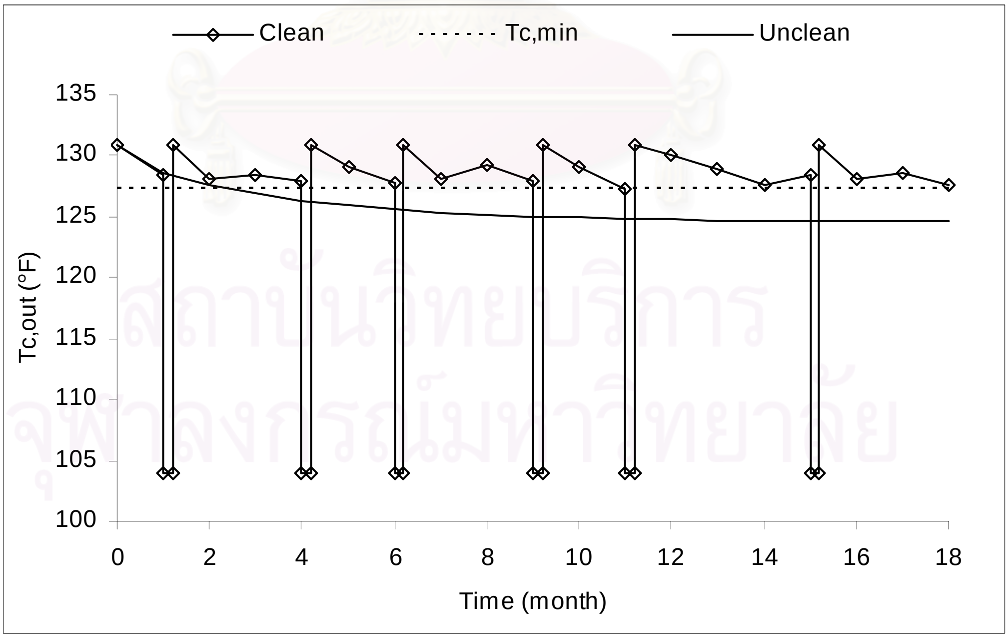

Figure 5.38: The schematic diagram of the variations of the outlet temperatures heat exchanger number 2 for asymptotic fouling with cleaning cost = 8,000£

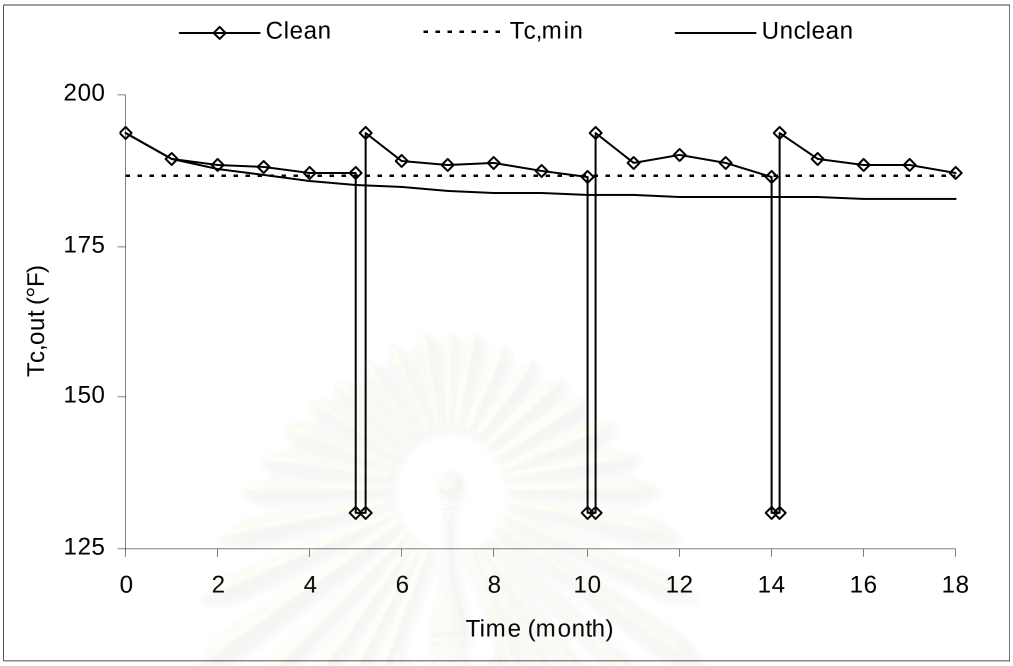

Figure 5.39: The schematic diagram of the variations of the outlet temperatures heat exchanger number 3 for asymptotic fouling with cleaning cost = 8,000£

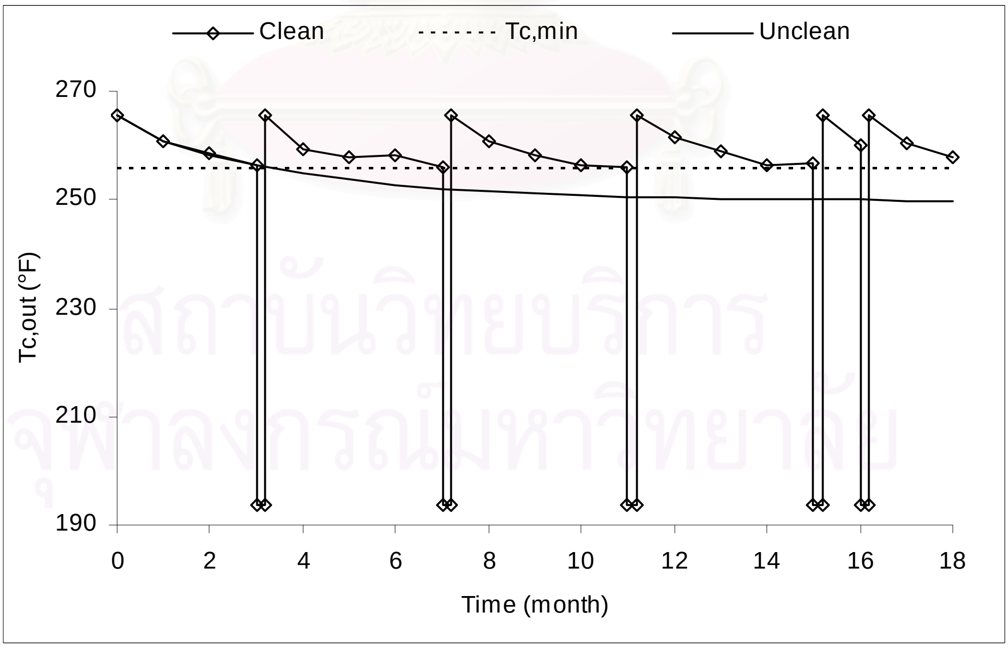

Figure 5.40: The schematic diagram of the variations of the outlet temperatures heat exchanger number 4 for asymptotic fouling with cleaning cost = 8,000£

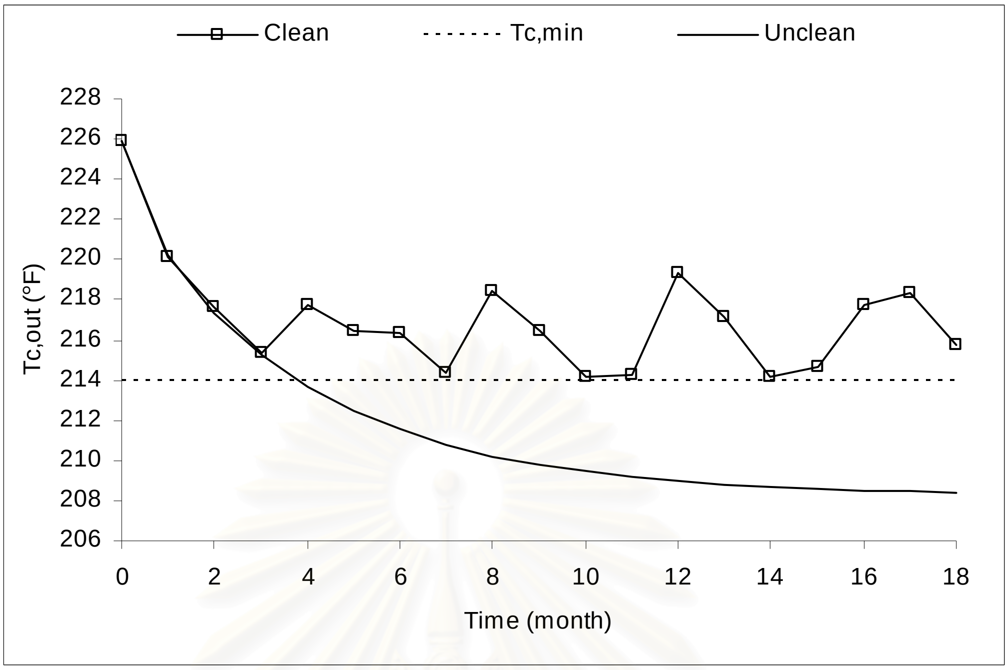

Figure 5.41: The schematic diagram of the variations of the outlet temperatures heat exchanger number 5 for asymptotic fouling with cleaning cost = 8,000£

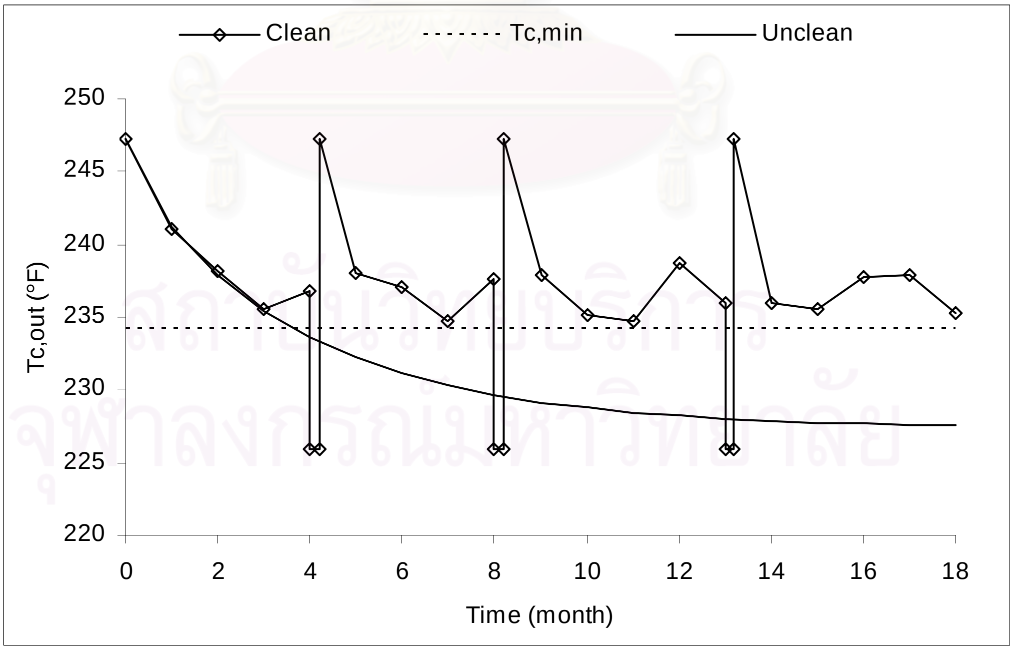

Figure 5.42: The schematic diagram of the variations of the outlet temperatures heat exchanger number 6 for asymptotic fouling with cleaning cost = 8,000£

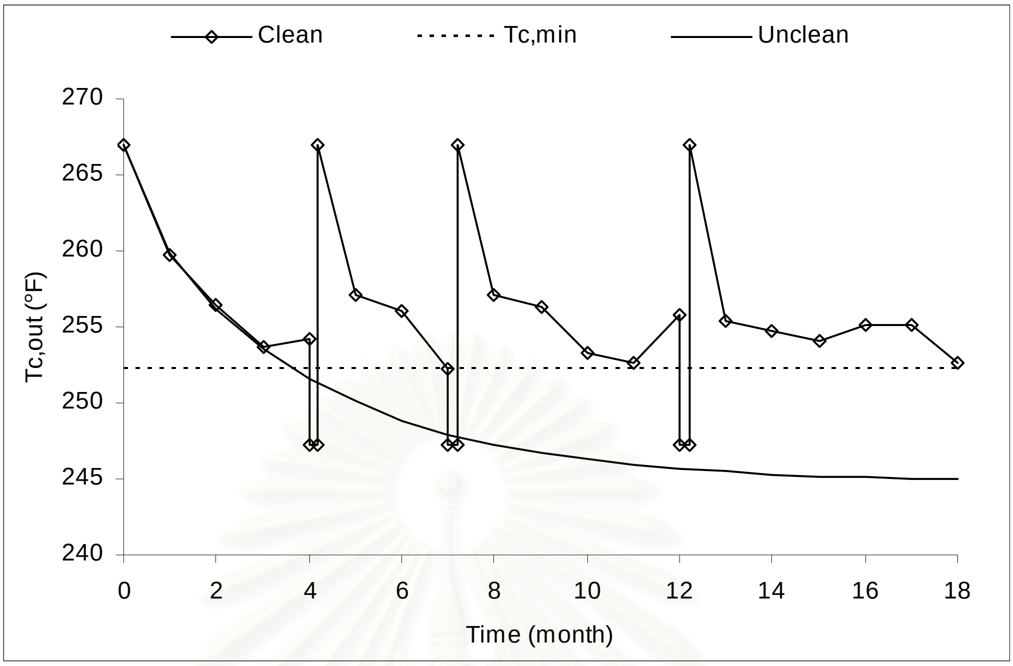

Figure 5.43: The schematic diagram of the variations of the outlet temperatures heat exchanger number 7 for asymptotic fouling with cleaning cost = 8,000£

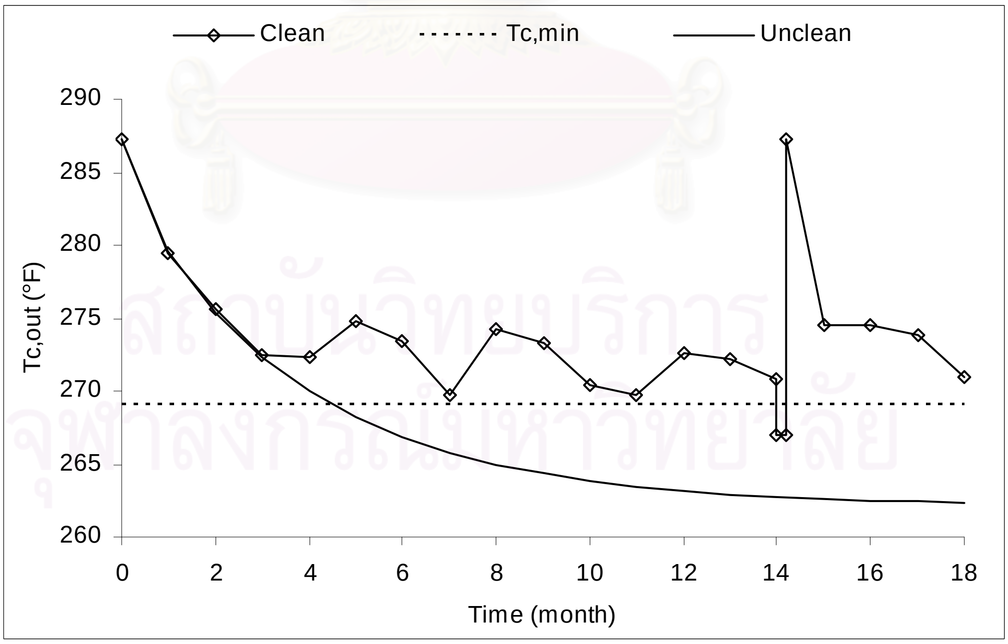

Figure 5.44: The schematic diagram of the variations of the outlet temperatures heat exchanger number 8 for asymptotic fouling with cleaning cost = 8,000£

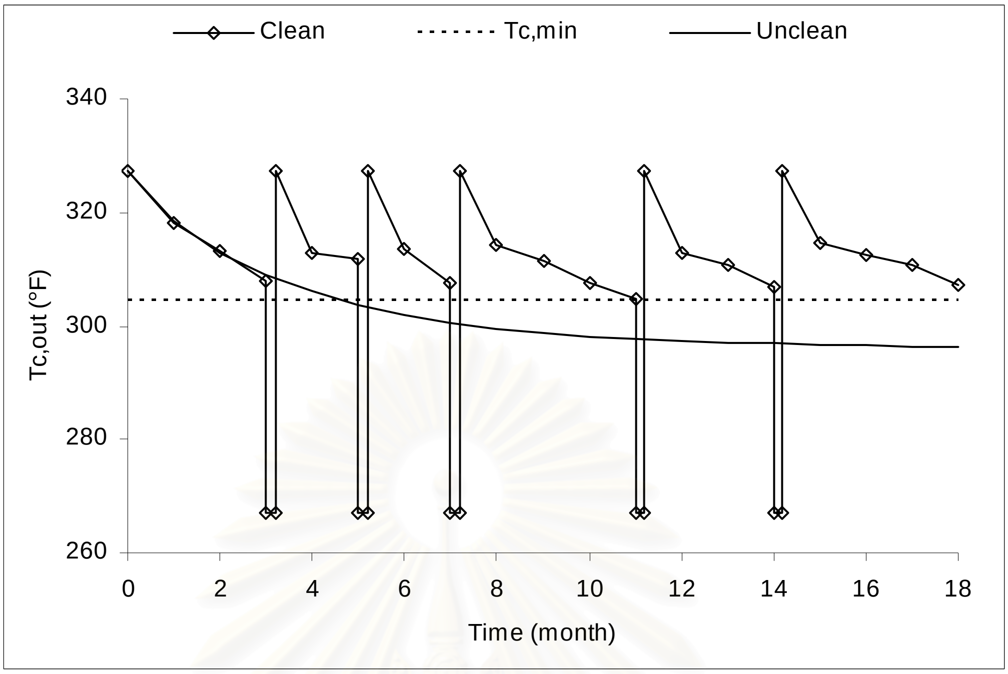

Figure 5.45: The schematic diagram of the variations of the outlet temperatures heat exchanger number 9 for asymptotic fouling with cleaning cost = 8,000£

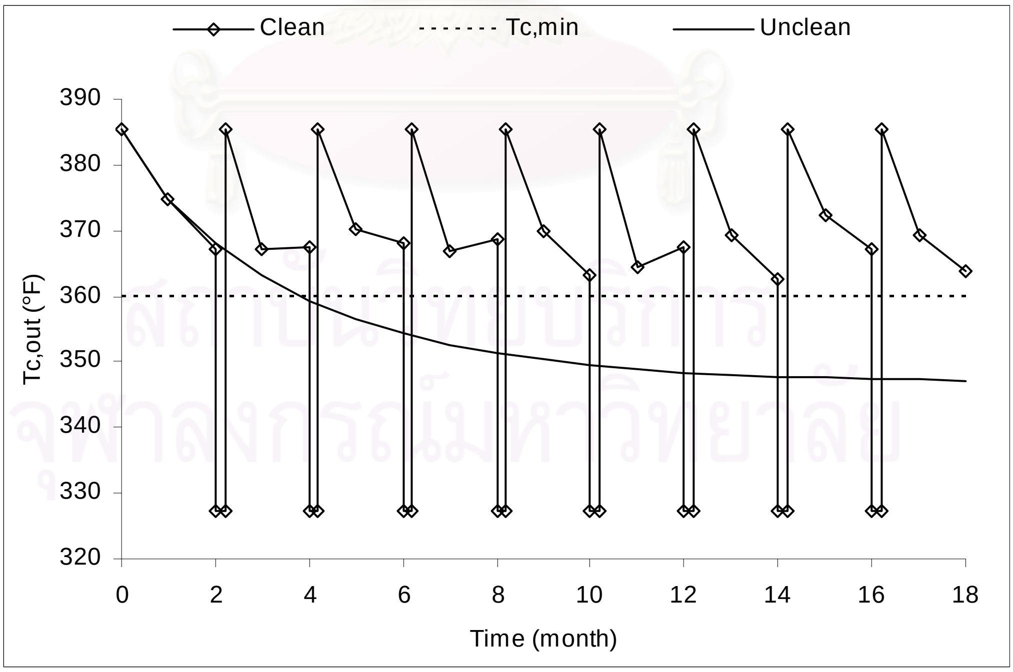

Figure 5.46: The schematic diagram of the variations of the outlet temperatures heat exchanger number 10 for asymptotic fouling with cleaning cost = 8,000£

Table 5.9: Summary result for heat exchanger network with 18 months for linear fouling

	Linear fouling			
	Smaili's work		This work	
Cleaning cost (£)	£	% saving	£	% saving
No cleaned	381,000	-	381,000	-
4,000	264,624	30.54	234,755	38.385
8,000	No reported	-	340,186	10.712

Table 5.10: Summary result for heat exchanger network with 18 months for asymptotic fouling

	Asymptotic fouling			
	Smaili's work		This work	
Cleaning cost (£)	£	% saving	£	% saving
No cleaned	577,000	-	577,000	-
4,000	392,294	32.01	351,155	39.14
8,000	No reported	-	486,035	15.76

Table 5.7 (a) and 5.7 (b) show the optimal cleaning schedule of heat exchanger network for linear fouling. For the case of cleaning cost equal to 4,000£, the operating cost of this heat exchanger network is 234,755 £. And, the case of cleaning cost equal to 8,000£, the operating cost is 340,186£. Considering in the numbers of cleaning, the number of cleaning in the case of cleaning cost equal to 4,000£ is 32 times. And, the number of cleaning is 26 times in the case of cleaning cost equal to 8,000£. It is observed that the increasing in the cleaning cost is resulting in the reduction of numbers of cleaning. The cleaning action occurred in the heat exchanger number 10 more than other heat exchanger. This is due to the fact that the heat exchanger number 10 is the highest of initial fouling rate. The heat exchanger number 1-4 have lower initial fouling rate so that they are cleaned less often than other heat exchangers.

Table 5.8 (a) shows the optimal cleaning schedule of the heat exchanger network for asymptotic fouling. From table 5.8(a), the heat exchanger number 10 is the highest number of cleaning. This is due to the fact that the initial fouling rate of this heat exchanger is largest. The rapid fouling formation is resulting in the rapid variation of heat transfer rate so that the number of cleaning is highest. Similarly, no cleaning action occurred in the heat exchanger number 5 because this heat exchanger connects to the heat exchanger number 10, as shown in Figure 5.1. The heat exchanger number 10 is cleaned every month so that the outlet temperature of the heat exchanger number 10 doesn't change. In addition, the numbers of cleaning in the heat exchanger number 9 are more than the heat exchanger number 8. Because the heat exchanger number 8 has initial fouling rate less than the heat exchanger number 9. Thus, the variation of the heat exchanger number 9 is faster than the heat exchanger number 8 so that the outlet temperature of cold stream in the heat exchanger number 9 reduced to target temperature before the heat exchanger number 8. In comparison of Table 5.8(a) and Table 5.8(b), the cleaning actions for the case of cleaning cost is equal to 4,000 £ are more than the cleaning actions for the case of cleaning cost is equal to 8,000 £. This due to the fact that the cleaning cost is major factor in objective function. In order to minimize the cost, cleaning actions are decreased when the cleaning cost is increased.

Table 5.9 and 5.10 show the summary of operating cost and % saving of operating cost in linear fouling and asymptotic fouling model, respectively. The % saving for linear fouling is more than asymptotic fouling in all case. This is due to the fouling formation. The fouling formation of asymptotic fouling is faster than linear fouling. Thus, the reduction of heat transfer rate and the decreasing of outlet temperature of cold stream rapidly change. This is resulting in linear fouling featuring lower cleaning actions than asymptotic fouling. These results are very dependent on the accuracy of the process simulation and especially the fouling model data. The uncertainty in fouling model will become more important for these problems with long horizons. The global optimal solutions must be considered alongside the reliability of input data.

5.4.2 Optimization of cleaning schedule of heat exchanger network for no minimum constraint case

In this studied, we considered the optimal cleaning schedule of heat exchanger network for no minimum constraint case. Table 5.11(a) and 5.11(b) are presented the optimal cleaning schedule of this heat exchanger network for linear fouling model. Table 5.12(a) and 5.12(b) are presented the optimal cleaning schedule of this heat exchanger network for asymptotic fouling model. The results are summarized in Table 5.13 and Table 5.14.

Table 5.11: Optimal cleaning schedule with different of cleaning cost in heat exchanger network for no minimum temperature case: (Linear fouling).

(a) Ccl = 4000 £

No. \ Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3																			0
4							/					/							2
5																			0
6																			0
7				/							/								2
8								/					/						2
9				/				/			/				/				4
10			/			/			/			/			/				5
No. cleans / period	0	0	1	2	0	1	1	2	1	0	2	2	1	0	2	0	0	0	15

COST = 221,867 £

(b) Ccl = 8000 £

Month / No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3																			0
4											/								1
5													/						1
6																			0
7													/						1
8																			0
9						/					/								2
10					/				/				/						3
No. cleans / period	0	0	0	0	1	1	0	0	1	0	2	0	3	0	0	0	0	0	8

COST = 291,443 £

Table 5.12: Optimal cleaning schedule with different of cleaning cost in heat exchanger network for no minimum temperature case: (Asymptotic fouling).

(a) Ccl = 4000 £

Month / No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3																			0
4																			0
5											/								1
6		/			/			/			/			/					5
7																			0
8		/			/			/			/			/					5
9	/		/		/		/		/		/		/		/				8
10	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/			16
No. cleans / period	2	3	2	1	4	1	2	3	2	1	5	1	2	3	2	1	0	0	35

COST = 221,933 £

(b) Ccl = 8000 £

Month / No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3																			0
4																			0
5										/									1
6						/					/								2
7																			0
8				/					/				/						3
9		/			/			/			/			/					5
10	/		/		/		/		/		/		/		/				8
No. cleans / period	1	1	1	1	2	1	1	1	2	1	3	0	2	1	1	0	0	0	19

COST = 348,762 £

Table 5.13 Summary of optimal result for no minimum temperature case

	Fouling model			
	Linear fouling		Asymptotic fouling	
Cleaning cost (£)	£	% saving	£	% saving
No cleaned	381,000	-	577,000	-
4,000	221,867	41.767	221,933	61.537
8,000	291,443	23.506	348,762	39.556

Table 5.11 (a) and 5.11 (b) show the optimal cleaning schedule of heat exchanger network for linear fouling. For the case of cleaning cost is 4,000£, the operating cost of this heat exchanger network is 221,867 £. And, the case of cleaning cost is 8,000£, the operating cost is 291,443 £. Considering in the numbers of cleaning, the number of cleaning in the case of cleaning cost equal to 4,000£ is 15 times. And, the number of cleaning is 8 times in the case of cleaning cost equal to 8,000£. In addition, the optimal cleaning schedules of heat exchanger network for asymptotic fouling model are shown in table 5.12(a) and 5.12(b). For the case of cleaning cost is 4,000£, the operating cost of this heat exchanger network is 221,933£. And, the case of cleaning cost is 8,000£, the operating cost is 348,762 £. Considering in the numbers of cleaning, the number of cleaning in the case of cleaning cost equal

to 4,000£ is 35 times. And, the number of cleaning is 19 times in the case of cleaning cost equal to 8,000£. It can be seen in table 5.14 that the operating cost and cleaning action of no minimum temperature case are lower than the using minimum temperature.

In the no minimum temperature case studied, the outlet temperatures of cold streams can be reduced to the lowest temperature of each stream. This result is causing in the small value of operating cost and low cleaning actions. It can be seen in table 5.11 and 5.12, there are many heat exchangers no cleaning action along the operating time. This is due to the small initial fouling rate that is causing in the low reduction of heat transfer rate. It is resulting in the small value of difference of heat transfer rate from initial value (ΔQ). Therefore, the fuel cost of heat exchanger is lower than the cleaning cost. It is leading to no cleaning actions occurred. These results are causing in the less operating cost. On the other hand, the initial fouling rate of heat exchanger number 10 is largest. Therefore, the reduction of heat transfer rate from initial value is large. It is leading to the large value of fuel cost that is higher than cleaning cost. This result is causing in the more cleaning actions in this heat exchanger.

In comparison of cleaning cost, the cleaning actions for the case of 4,000 £ are more than the cleaning actions for the case of 8,000 £. This due to the fact that the cleaning cost is major factor in objective function. In order to minimize the cost, cleaning actions are decreased when the cleaning cost is increased. In addition, the operating cost and number of cleaning of linear fouling model are lower than asymptotic fouling model as same as the case of using minimum temperature constraint as shown in table 5.14.

Table 5.14 Comparison result of optimal cleaning schedule of heat exchanger network for all case

	Minimum constraint case						No minimum constraint case					
	Linear fouling			Asymptotic fouling			Linear fouling			Asymptotic fouling		
Cleaning cost (£)	£	% saving	No. of cleanig	£	% saving	No. of cleanig	£	% saving	No. of cleanig	£	% saving	No. of cleanig
No cleaned	381,000	-	-	577,000	-	-	381,000	-	-	577,000	-	-
4,000	234,755	38.3845	32	351,155	39.1412	61	221,867	41.7672	15	221,933	61.5367	35
8,000	340,186	10.7123	26	486,035	15.7652	40	291,443	23.5058	8	348,762	39.556	19

Table 5.15 Model parameter for heat exchanger network case

Parameters	Heat exchanger									
	1	2	3	4	5	6	7	8	9	10
Th(°F)		563		457		428		513	536	631
$T^{c}_{1,1}$(°F)	68									
Fh(lb/h)	141272	73811	423023	428579	207940	423023	210321	141272	282544	207940
Fc(lb/h)	721441	721441	721441	721441	721441	721441	721441	649217	649217	649217
Ch(Btu/(lb °F))	0.67	0.7	0.62	0.62	0.67	0.62	0.69	0.67	0.69	0.67
Cc(Btu/(lb °F))	0.46	0.46	0.46	0.46	0.55	0.55	0.55	0.57	0.57	0.57
Uo(Btu/(h ft^2 °F))	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1
Uc(Btu/(h ft2 oF))	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1
r (asymp)($x10^3$) (h ft^2 °F/Btu)	1.61	2.41	1.61	2.14	4.02	2.95	4.02	4.29	4.82	5.09
r (lin)($x10^4$) (h ft^2 °F/Btu)	1.23	1.84	1.23	1.64	3.07	2.25	3.07	3.27	3.68	3.88
A (ft^2)	465	287.4	1191.6	1487.6	183	545.7	491.9	437	884.8	1257.2

5.5 Realistic optimization of cleaning schedule for heat exchanger network

From previous section, the objective function is minimization of operating cost that refers to the tradeoff between furnace extra fuel costs due to fouling and heat exchanger cleaning costs in every heat exchanger in this heat exchanger network. In this section, we proposed the realistic model for optimization the cleaning schedule. From figure 5.1, the cold stream pass through the heat exchanger number 1, 2, 3 and 4 that the outlet temperature is decreased with time. This stream is not equal to the specification inlet temperature at desalter. Similarly, the outlet temperature at heat exchanger number 7 is not indicating the specification inlet temperature of flash unit. In addition, the outlet temperature at heat exchanger number 10 is not equivalent to the specification inlet temperature at distillation process. Thus, the objective function should be equation 5.12. In this model, the objective function is tradeoff between furnace extra fuel costs due to fouling and heat exchanger cleaning cost at heat exchanger number 4, 7 and 10.

$$Obj_{\cos t} = \sum_{p=1}^{NP} C_E (Q_{4,clean} - Q_{4,p}) + \sum_{p=1}^{NP} C_E (Q_{7,clean} - Q_{7,p})$$

$$+ \sum_{p=1}^{NP} C_E (Q_{10,clean} - Q_{10,p}) + \sum_{p=1}^{NP} \sum_{n=1}^{NE} C_{cl} (1 - y_{n,p}) \tag{5.12}$$

In this section, we studied the optimal cleaning schedule of heat exchanger network under fouling condition. This studied divided into two cases. The first case focuses on the optimization of cleaning schedule of heat exchanger network for linear fouling and asymptotic fouling model. The second one deals with the optimization of cleaning schedule of heat exchanger network for no minimum constraint case (no $T_{c,min}$). The operating time horizons are 18 months.

5.5.1 Realistic optimization of cleaning schedule of heat exchanger network for linear fouling and asymptotic fouling

In this studied, we considered the optimal cleaning schedule of heat exchanger network for no minimum constraint case. Table 5.16(a) and 5.16(b) are presented the optimal cleaning schedule of this heat exchanger network for linear fouling model. Table 5.17(a) and 5.17(b) are presented the optimal cleaning schedule of this heat exchanger network for asymptotic fouling model. The results are summarized in Table 5.18 and Table 5.19.

Table 5.16: Realistic optimal cleaning schedule with different of cleaning cost in heat exchanger network: (Linear fouling).

(a) Ccl = 4000 £

No. \ Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3						/				/							/		3
4			/			/			/		/		/			/			6
5											/								1
6								/											1
7					/				/				/			/			4
8																			0
9									/										1
10		/			/		/		/		/		/			/			7
No. cleans / period	0	1	1	0	2	2	1	1	4	1	3	0	3	0	0	3	1	0	23

COST = 94,422 £

(b) Ccl = 8000 £

Month No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2											/								1
3						/				/							/		3
4				/			/		/				/		/				5
5																			0
6									/										1
7					/			/				/			/				4
8																			0
9									/									/	2
10			/			/		/			/		/			/			6
No. cleans / period	0	0	1	1	1	2	1	2	3	1	2	1	2	0	2	1	1	1	22

COST = 196,422 £

Table 5.17: Realistic optimal cleaning schedule with different of cleaning cost in heat exchanger network: (Asymptotic fouling).

(a) Ccl = 4000 £

Month No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3					/						/								2
4		/		/		/		/		/		/		/		/		/	9
5																			0
6																			0
7						/			/				/						3
8																			0
9					/				/				/						3
10		/		/		/		/		/		/		/		/			8
No. cleans / period	0	2	0	2	2	3	0	2	2	2	1	2	2	2	0	2	0	1	25

COST =158,403 £

(b) Ccl = 8000 £

No. \ Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3						/					/								2
4		/		/	/		/		/			/			/		/		8
5																			0
6																			0
7			/				/			/			/						4
8																			0
9							/												1
10		/			/			/		/		/			/				6
No. cleans / period	0	2	1	1	2	1	3	1	1	2	1	2	1	0	2	0	1	0	21

COST = 271,048 £

Table 5.18 Summary of optimal result for realistic optimization

	Fouling model			
	Linear fouling		Asymptotic fouling	
Cleaning cost (£)	£	Number of cleaning	£	Number of cleaning
4,000	94,422	23	158,403	25
8,000	196,422	22	271,048	21

Table 5.16 (a) and 5.16 (b) show the optimal cleaning schedule of heat exchanger network for linear fouling. For the case of cleaning cost equal to 4,000£, the operating cost of this heat exchanger network is 94,422 £. And, the case of cleaning cost equal to 8,000£, the operating cost is 196,422£. Considering in the numbers of cleaning, the number of cleaning in the case of cleaning cost equal to 4,000£ is 23 times. And, the number of cleaning is 21 times in the case of cleaning cost equal to 8,000£. The cleaning action occurred in the heat exchanger number 10 more than other heat exchanger. This is due to the fact that the heat exchanger number 10 is the highest of initial fouling rate. From table 5.16, it is observed that there are no cleaning actions occurred in heat exchanger number 1 and 2. This result is causing in more cleaning actions in heat exchanger 4. The more cleaning actions in heat

exchanger 4 are effected on no cleaning action at heat exchanger number 5. Similarly, heat exchanger 8 is not featuring cleaning action.

Table 5.17 shows the optimal cleaning schedule of the heat exchanger network for asymptotic fouling. From table 5.17(a), the number of cleaning is 25 times for the case of cleaning cost equal to 4,000 £. The heat exchanger number 4 and 10 have more cleaning action than heat exchanger number 7. This is due to the initial fouling rate that it is larger than the initial fouling rate of heat exchanger number 7. From this table, it is observed that no cleaning action in heat exchanger number 1, 2, 5, 6, and 8. This result is due to the fact that the objective function is considered at the heat exchanger number 4, 7 and 10. In these heat exchangers, we are assigned the minimum temperature of outlet temperature in these heat exchangers that is the realistic approach. In addition, heat exchanger number 3 and 9 are featuring the cleaning actions 2 times and 3 times, respectively. This result is due to the outlet temperature of heat exchanger number 4 and 7 that reduced lower the minimum temperature. Thus, in order to escape the violation of constraint and improve the outlet temperatures, there are cleaning actions occurred in heat exchanger number 3 and 4. Moreover, In the case of cleaning cost is equal to 8,000 £ as show in table 5.17(b). It can be seen that the cleaning actions is reduced to 21 times, and the operating cost is increased. The cleaning cost is major factor in objective function. In order to minimize the operating cost, the cleaning actions are decreased when the cleaning cost is increased.

Table 5.18 show the summary of operating cost and number of cleaning in linear fouling and asymptotic fouling model, respectively. The operating cost of linear fouling is less than asymptotic fouling in all case. This is due to the fouling formation. The fouling formation of asymptotic fouling is faster than linear fouling. Thus, the reduction of heat transfer rate and the decreasing of outlet temperature of cold stream rapidly change. This is resulting in linear fouling featuring lower cleaning actions and operating cost than asymptotic fouling. The uncertainty in fouling model will become more important for these problems with long horizons. The global optimal solutions must be considered alongside the reliability of input data.

5.5.2 Realistic optimization of cleaning schedule of heat exchanger network for no minimum constraint case

In this studied, we considered the optimal cleaning schedule of heat exchanger network for no minimum constraint case. Table 5.19(a) and 5.19(b) are presented the optimal cleaning schedule of this heat exchanger network for linear fouling model. Table 5.20(a) and 5.20(b) are presented the optimal cleaning schedule of this heat exchanger network for asymptotic fouling model. The results are summarized in Table 5.21 and Table 5.22.

Table 5.19: Realistic optimal cleaning schedule with different of cleaning cost in heat exchanger network for no minimum temperature case: (Linear fouling).

(a) Ccl = 4000 £

No. \ Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3																			0
4				/				/			/				/				4
5																			0
6																			0
7					/			/					/			/			4
8																			0
9																			0
10		/			/		/		/				/		/				6
No. cleans / period	0	1	0	1	2	0	1	2	1	0	1	0	2	0	2	1	0	0	14

COST = 69,694 £

(b) Ccl = 8000 £

Month / No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3																			0
4										/									1
5																			0
6																			0
7								/						/					2
8																			0
9																			0
10				/					/				/						3
No. cleans / period	0	0	0	1	0	0	0	1	1	1	0	0	1	1	0	0	0	0	6

COST = 129,730 £

Table 5.20: Realistic optimal cleaning schedule with different of cleaning cost in heat exchanger network for no minimum temperature case: (Asymptotic fouling).

(a) Ccl = 4000 £

Month / No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3																			0
4		/			/			/				/				/			5
5																			0
6																			0
7			/					/			/				/				4
8																			0
9			/				/	/					/						4
10	/		/		/		/		/	/		/		/		/			9
No. cleans / period	1	1	3	0	2	0	2	3	1	1	1	2	1	1	1	2	0	0	22

COST =146,034 £

(b) Ccl = 8000 £

Month / No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	No. cleans / unit
1																			0
2																			0
3																			0
4							/						/						2
5																			0
6																			0
7																			0
8																			0
9											/								1
10			/			/	/			/		/		/			/	/	8
No. cleans / period	0	0	1	0	0	1	2	0	0	1	1	1	1	1	0	0	1	1	11

COST = 222,892 £

Table 5.21 Summary of optimal result for realistic optimization with no minimum temperature case

	Fouling model			
	Linear fouling		Asymptotic fouling	
Cleaning cost (£)	£	Number of cleaning	£	Number of cleaing
4,000	69,694	14	146,034	22
8,000	129,730	16	222,892	11

Table 5.22 Comparison result of realistic optimal cleaning schedule of heat exchanger network for all case

	Minimum constraint case				No minimum constraint case			
	Linear fouling		Asymptotic fouling		Linear fouling		Asymptotic fouling	
Cleaning cost (£)	£	No. of cleanig	£	No. of cleanig	£	No. of cleanig	£	No. of cleanig
4,000	94,422	23	158,403	25	69,694	14	146,034	22
8,000	196,422	22	271,048	21	129,730	6	222,892	11

In this section, we are studied the realistic optimization of cleaning schedule with no minimum temperature of clod stream. Table 5.19 (a) and 5.19 (b) show the optimal cleaning schedule of heat exchanger network for linear fouling. For the case of cleaning cost equal to 4,000£, the operating cost of this heat exchanger network is 69,694£. And, the case of cleaning cost equal to 8,000£, the operating cost is 129,730£. Considering in the numbers of cleaning, the number of cleaning in the case of cleaning cost equal to 4,000£ is 14 times. And, the number of cleaning is 6 times in the case of cleaning cost equal to 8,000£. It is observed that the increasing in the cleaning cost is resulting in the reduction of numbers of cleaning. From table 5.19(a), it is observed that there are the cleaning actions occurred in heat exchanger number 4, 7 and 10. Similarly, heat exchanger number 4, 7 and 10 are featuring the cleaning actions as shown in table 5.19(b). The initial fouling rate of these heat exchangers is higher than others heat exchanger. This is causing in the rapid reduction of outlet temperature. Thus, the cleaning actions are occurred in these heat exchangers. Moreover, it can be seen in the objective function that trade off between the cleaning cost and fuel cost in order to minimize the operating cost. The cleaning cost of heat exchanger 4, 7 and 10 are lower than the fuel cost. This result is also causing in the cleaning actions occurred in these heat exchangers.

Table 5.20 shows the optimal cleaning schedule of the heat exchanger network for asymptotic fouling. From table 5.20(a), the number of cleaning is 22 times. And, the operating cost is 146,034 £ for the case of cleaning cost equal to 4,000 £. It can be seen from table 5.20(a) that the cleaning actions occurred in heat exchanger 4, 7, 9 and 10. This is due to the fact that the large value of initial fouling rate. Thus, the outlet temperatures change rapidly in there heat exchanger. This result is causing in the large value of different heat transfer rate from initial value (ΔQ). Therefore, the fuel cost is higher than the cleaning cost. It is resulting in the occurrence of cleaning action. In addition from table 5.20(b), considering in the case of cleaning cost is equal to 8,000£. The number of cleaning is 11 times, and the operating cost is 222,892£. It is can be seen that the increasing in the cleaning cost is resulting in the reduction of numbers of cleaning. From table 5.20(b), it is observed that heat exchanger number 10 is featuring highest number of cleaning. This is due to the largest initial fouling rate.

In addition, there are less cleaning actions occurred in heat exchanger 1 - 9. This result is causing in the reduction of outlet temperature and more value of different heat transfer rate. Table 5.18 show the summary of operating cost and number of cleaning in linear fouling and asymptotic fouling model, respectively. The operating cost for linear fouling is less than asymptotic fouling in all case. The fouling formation of asymptotic fouling is faster than linear fouling. Thus, the reduction of heat transfer rate and the decreasing of outlet temperature of cold stream rapidly change. This is resulting in linear fouling featuring lower cleaning actions than asymptotic fouling.

Moreover, we are studied the optimization of cleaning schedule in no minimum temperature case. In the no minimum temperature case studied, the outlet temperatures of cold streams can be reduced to the lowest temperature of each stream. This result is causing in the small value of operating cost and low cleaning actions. It can be seen in table 5.19, 5.20 and 5.22. In addition, there are many heat exchangers no cleaning action along the operating time. This is due to the small initial fouling rate that is resulting in the small value of different heat transfer rate from initial value (ΔQ). Therefore, the fuel cost of heat exchanger is lower than the cleaning cost. It is leading to no cleaning actions occurred. These results are also causing in the less operating cost.

CHAPTER VI

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The optimal cleaning schedules in heat exchanger networks subject to fouling are studied in this work. The aim of this work is to minimize the operating cost of heat exchanger network. The optimization of cleaning schedule is mixed integer nonlinear programming problem (MINLP). This is due to the constraint, as these involve binary variables ($y_{n,p}$) indicating which unit has to be cleaned and continuous variables indicating the heat exchanger network performance. In addition, the log means temperature different introduced nonlinearlity into this problem. Because of the multiperiod formulation, the problem of when a unit has to be cleaned can be considered directly. The certain units may be selected to be cleaned because the problem can be constrained.

The simulations of the variation of outlet temperature of hot stream and cold stream, heat transfer coefficient and heat transfer rate of single heat exchanger with time are studied in first part (Chapter IV). It is observed that the outlet temperature of hot stream increases with time, and cold stream reduces with time. While, fouling decrease the overall heat transfer coefficient and heat transfer rate. Additionally, the simulation results of heat transfer rate with different initial fouling formation and time decay of fouling formation are proposed. It is observed that the accuracy of fouling data is necessary.

Next, the optimization of cleaning schedule for single heat exchanger and heat exchanger network is performed (Chapter V). This studied are applied the time discretisation to model the optimal cleaning schedule problem. The optimal solution solved by differential evolution method. The studied are divided into two cases: the first one focuses on the cleaning schedule of single heat exchanger whereas the second one deal with the cleaning schedule of heat exchanger network. The influences of fouling models on cleaning schedule of heat exchanger are studied. The results shown that linear fouling model has cleaning actions less than asymptotic fouling model. In addition, the influence of parameter in fouling model on the optimal cleaning schedule is presented in this Chapter. It is observed that the operating cost increased when the initial fouling rate is increased. Considering in the operating cost, it is decreased when the time decay of fouling formation is increased. This result indicates the important of initial fouling rate and time decay of fouling formation. These parameters are sensitive to the optimal cleaning schedule. In addition, the influences of cleaning costs on the cleaning schedule of heat exchanger are studied. The results obtained that the cleaning actions decrease when the cleaning cost decrease. Moreover, this chapter presents the comparison of the optimization of cleaning schedule for using minimum temperature as constraint with no minimum temperature. It is observed that the no minimum temperature case studied is provided the less of operating cost and cleaning actions. In addition, there are many heat exchangers no cleaning action along the operating time. This is due to the small value of difference of heat transfer rate from initial value (ΔQ). Therefore, the fuel cost of heat exchanger is lower than the cleaning cost. It is leading to no cleaning actions occurred. These results are causing in the less operating cost. Additionally, we proposed the realistic optimization of cleaning schedule of heat exchange network for linear fouling and asymptotic fouling. This objective function is traded off between the fuel cost and cleaning cost in heat exchanger number 4, 7 and 10 only, as shown in Figure 5.1. From this section, it is observed that the operating cost and cleaning actions are lower than previous model.

6.2 Recommendation

For future direction, the variations of flow rate for cold stream and hot stream and throughput losses due to pressure drops should be studied. Because of the disturbance on flow rate that the problem should be updated the flow rate at real time. Thus, the real time optimization is should be considered. In order to achieve the accurate planning, the objective function and constrain should be considered the production plan and economic loss of the process. In addition, the discretisation of operating period should be considered. It can be lead to suboptimal solutions. If the period can adjustable, it will improve the optimal solution. Finally, the optimal cleaning schedule problem will be applied to the real process that the data reconcile of fouling in real process should be studied.

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APPENDICES

APPENDIX A

APPROXIMATION FOR ASYMPTOTIC FOULING

The fouling rate at time *t* is given by

$$\left.\frac{dr_f}{dt}\right|_t = \frac{r_f^{\infty}}{\tau}(\exp(-t/\tau) \tag{A.1}$$

and at time $t + \Delta t$

$$\left.\frac{dr_f}{dt}\right|_{t+\Delta t} = \frac{r_f^{\infty}}{\tau}(\exp(-t/\tau))(\exp(-\Delta t/\tau)) = \left.\frac{dr_f}{dt}\right|_t \exp(-\Delta t/\tau) \tag{A.2}$$

For discretisation, the fouling rate is calculated at the start of the subperiod. The asymptotic fouling rate in cleaning subperiod as follow

$$\dot{r}_{n,p}^{cl} = \dot{r}_{n,p-1}^{cl}\exp(-\Delta t_p^{op}/\tau) \tag{A.3}$$

The asymptotic fouling rate in operating subperiod is given by

$$\dot{r}_{n,p}^{op} = \dot{r}_{n,p}^{cl}\exp(-\Delta t_p^{cl}/\tau)y_{n,p} + \frac{r_n^{\infty}}{\tau}(1 - y_{n,p}) \tag{A.4}$$

The fouling rate in the first cleaning subperiod can be calculated from (A.1).

$$\dot{r}_{n,1}^{cl} = \frac{r_f^{\infty}}{\tau}\left(1 - \frac{r_n(0)}{r_n^{\infty}}\right) \tag{A.5}$$

APPENDIX B

SIMULATION OF HEAT EXCHANGER NETWORK

This appendix show outlet temperature of cold stream profiles for heat exchanger network in linear fouling model and asymptotic fouling model as shown in Figure 5.1. The operating time is 18 months.

B.1 Linear fouling model

$$\dot{r}_f = c \tag{4.3}$$

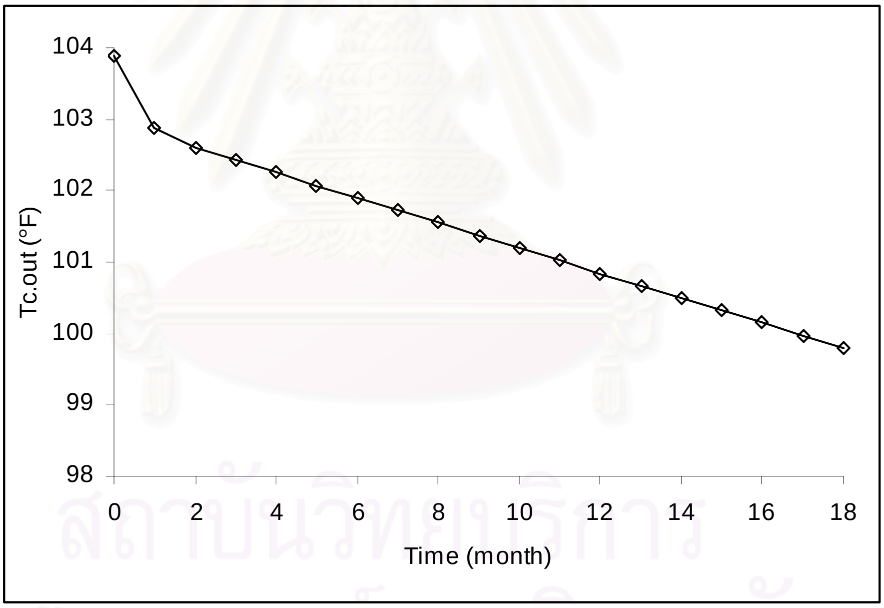

Figure B.1: The schematic diagram of the variations of the outlet temperature in heat exchanger number 1 with time. (linear fouling).

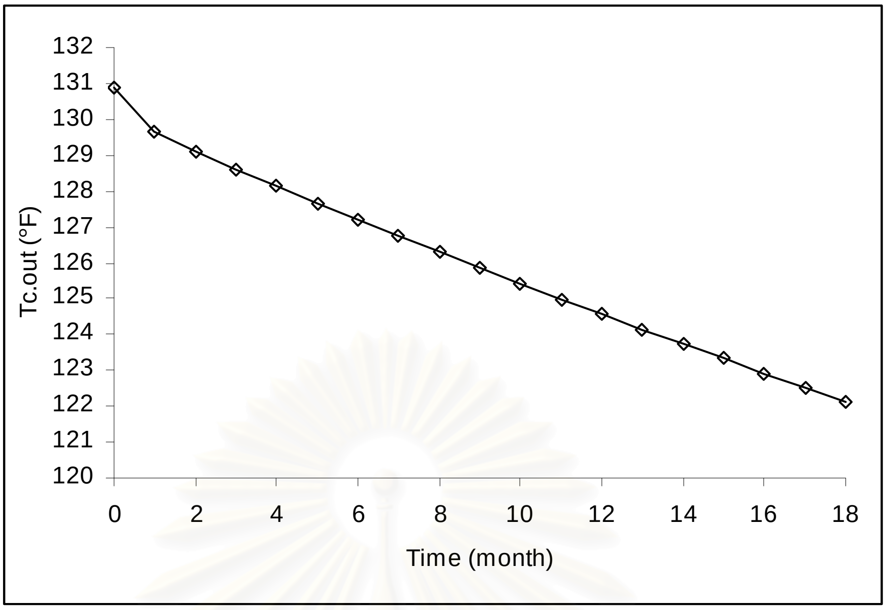

Figure B.2: The schematic diagram of the variations of the outlet temperature in heat exchanger number 2 with time. (linear fouling).

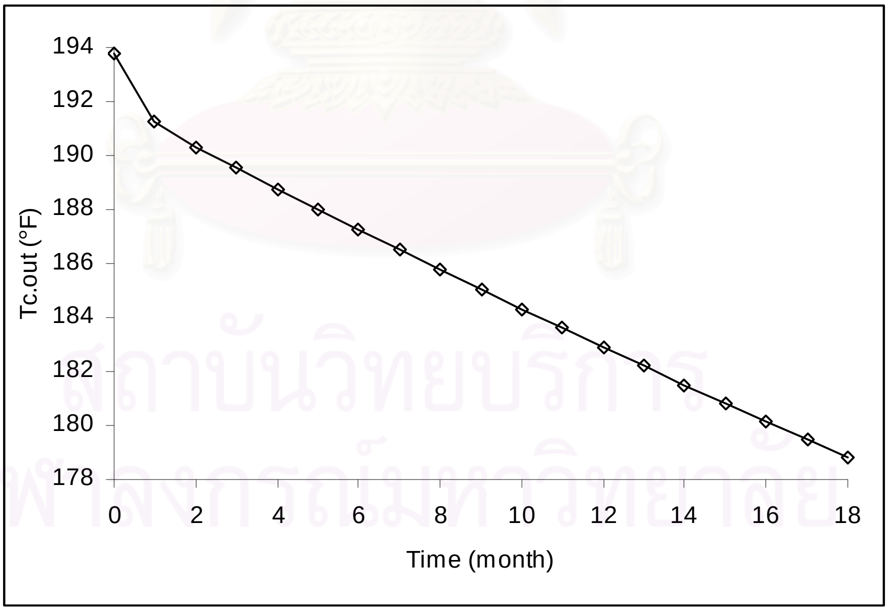

Figure B.3: The schematic diagram of the variations of the outlet temperature in heat exchanger number 3 with time. (linear fouling).

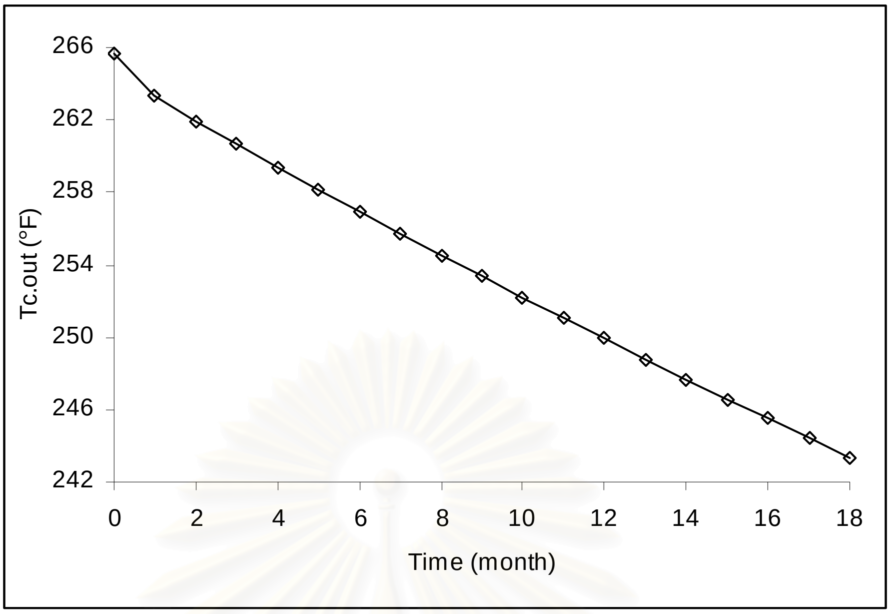

Figure B.4: The schematic diagram of the variations of the outlet temperature in heat exchanger number 4 with time. (linear fouling).

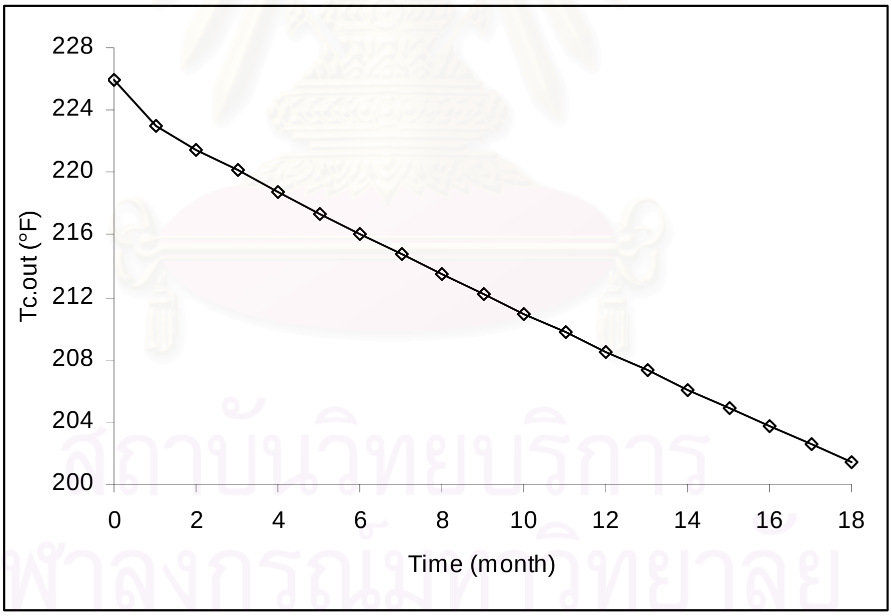

Figure B.5: The schematic diagram of the variations of the outlet temperature in heat exchanger number 5 with time. (linear fouling).

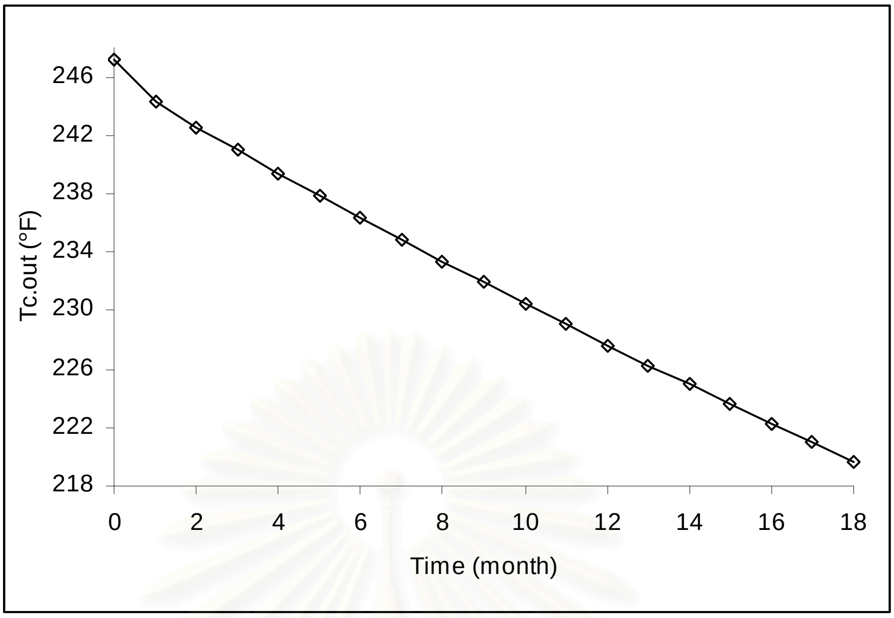

Figure B.6: The schematic diagram of the variations of the outlet temperature in heat exchanger number 6 with time. (linear fouling).

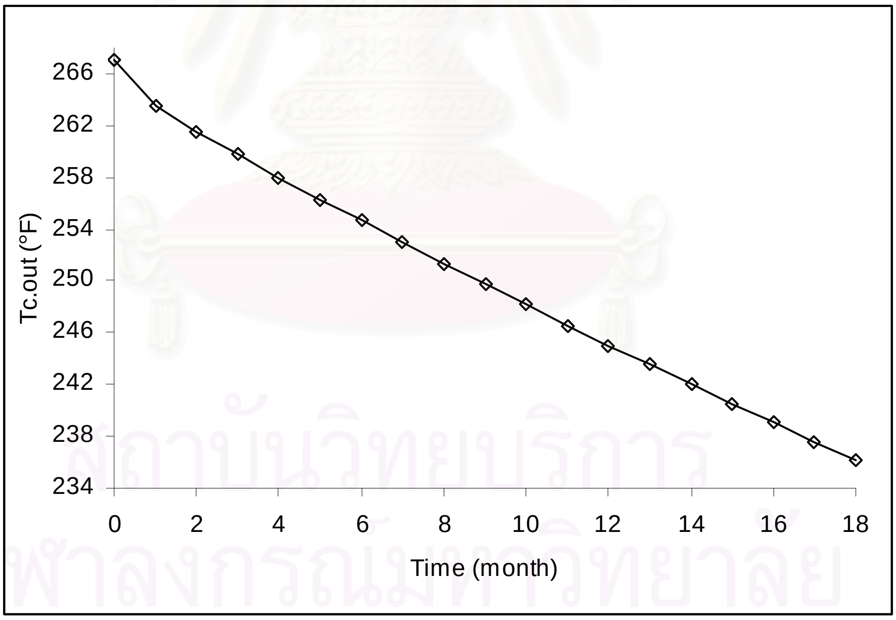

Figure B.7: The schematic diagram of the variations of the outlet temperature in heat exchanger number 7 with time. (linear fouling).

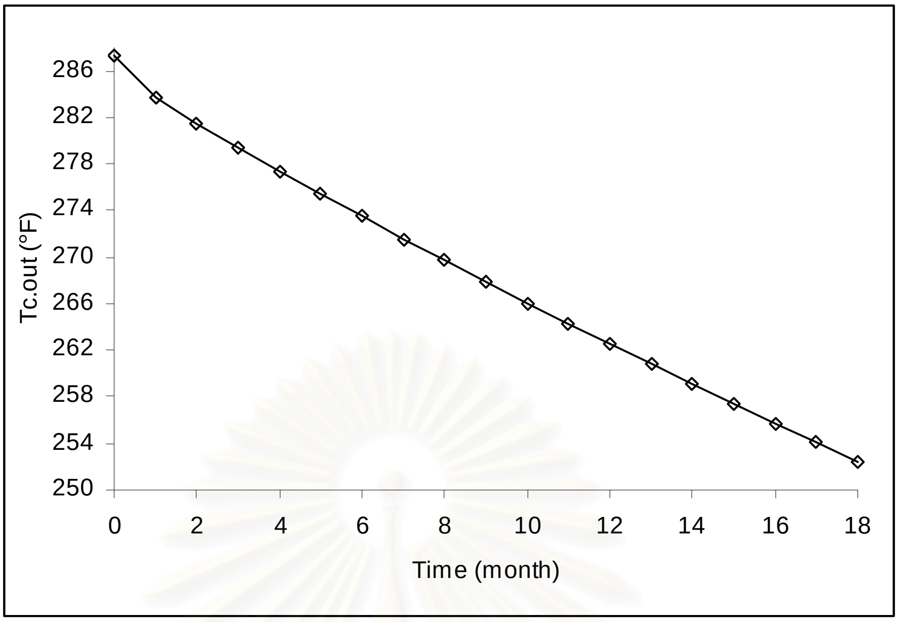

Figure B.8: The schematic diagram of the variations of the outlet temperature in heat exchanger number 8 with time. (linear fouling).

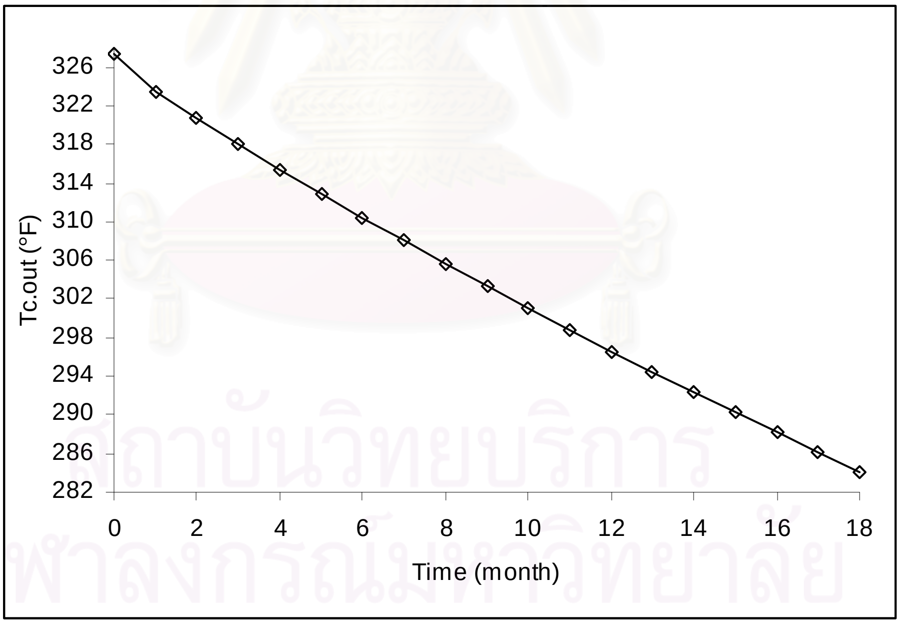

Figure B.9: The schematic diagram of the variations of the outlet temperature in heat exchanger number 9 with time. (linear fouling).

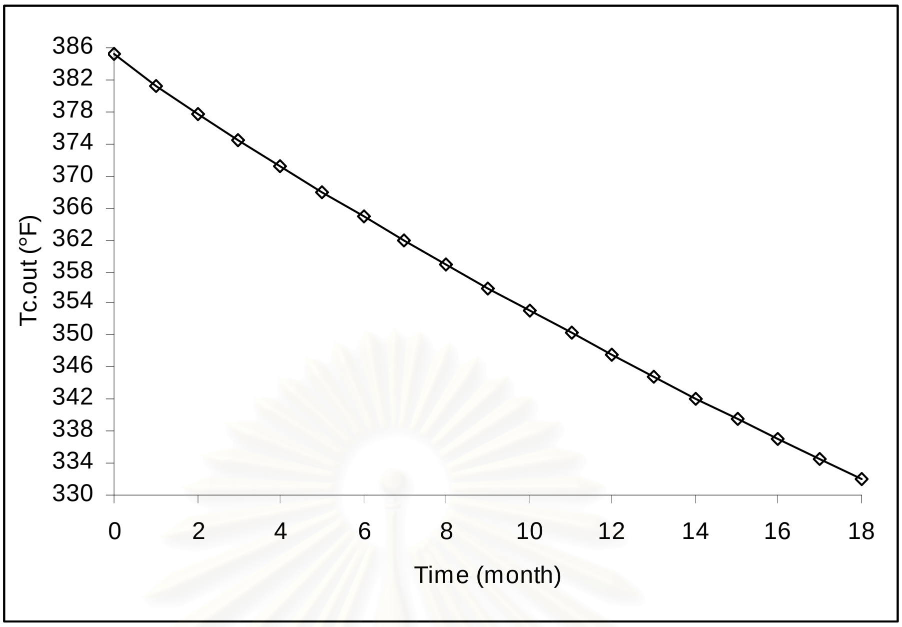

Figure B.10: The schematic diagram of the variations of the outlet temperature in heat exchanger number 10 with time. (linear fouling).

B.2 Asymptotic fouling model

$$\dot{r}_f(t) = r_f^{\infty}(1 - \exp(-t/\tau)) \tag{4.2}$$

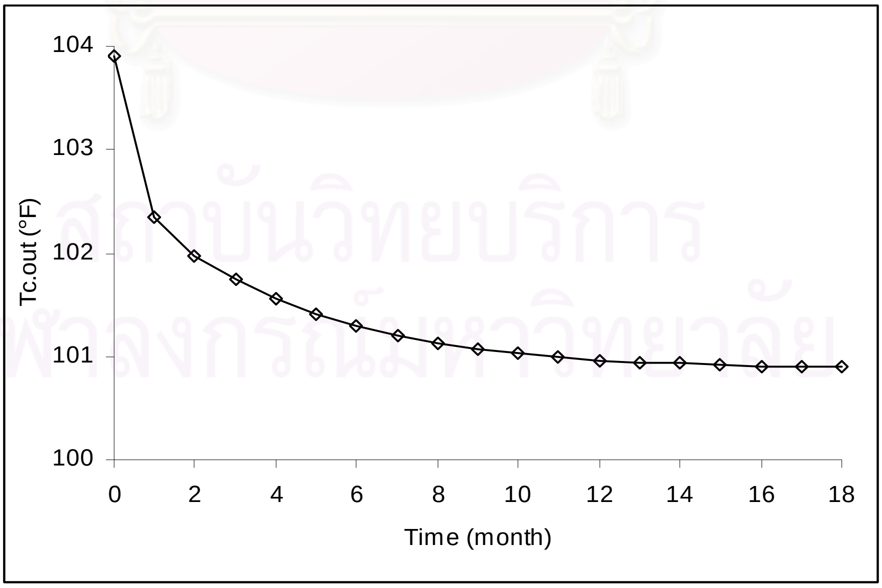

Figure B.11: The schematic diagram of the variations of the outlet temperature in heat exchanger number 1 with time. (asymptotic fouling).

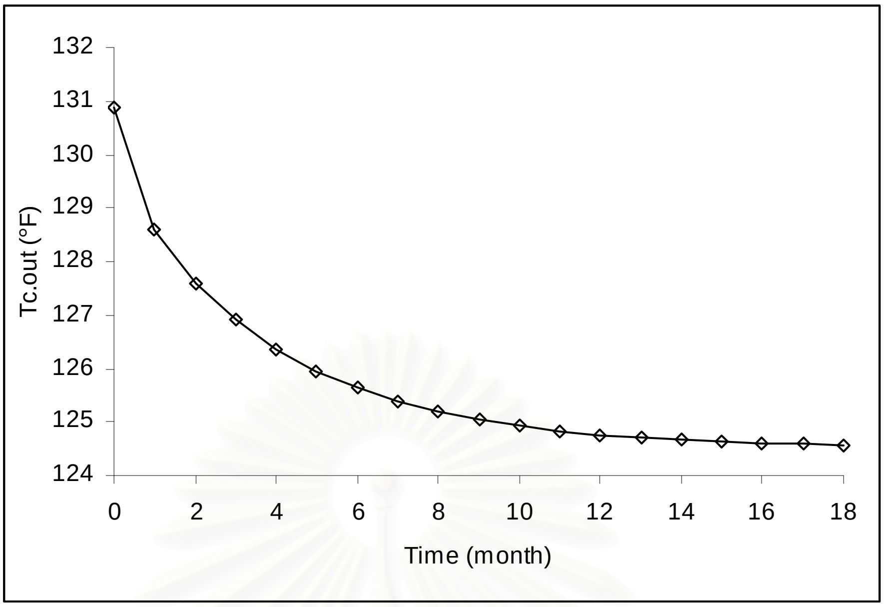

Figure B.12: The schematic diagram of the variations of the outlet temperature in heat exchanger number 2 with time. (asymptotic fouling).

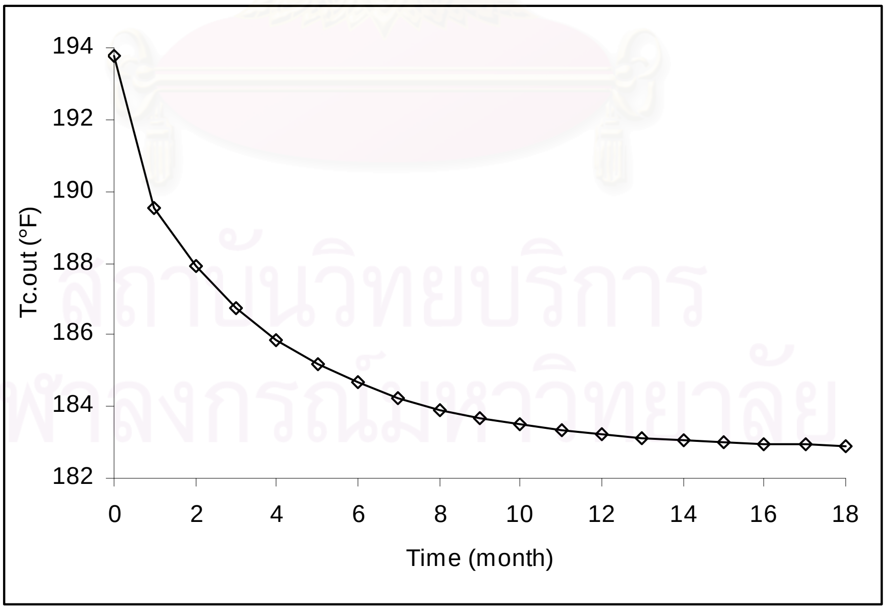

Figure B.13: The schematic diagram of the variations of the outlet temperature in heat exchanger number 3 with time. (asymptotic fouling).

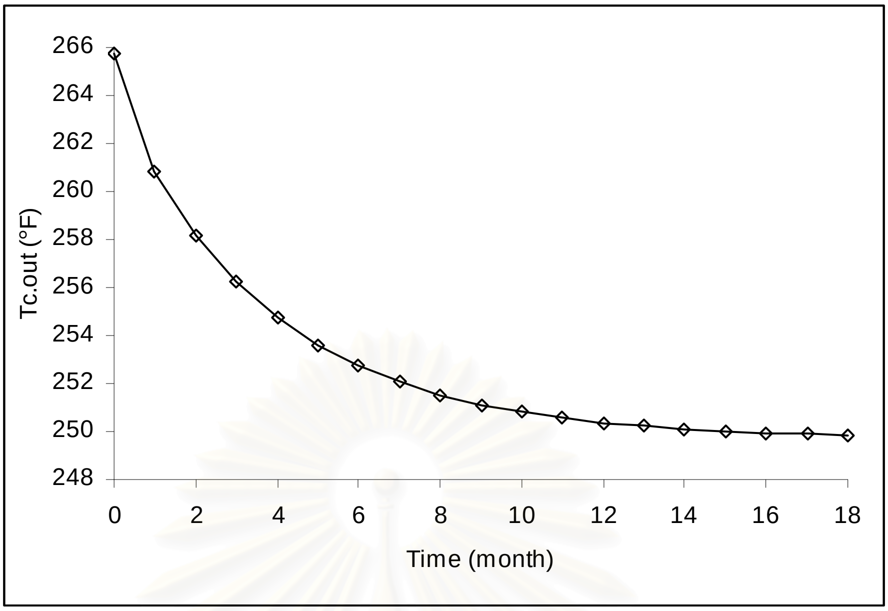

Figure B.14: The schematic diagram of the variations of the outlet temperature in heat exchanger number 4 with time. (asymptotic fouling).

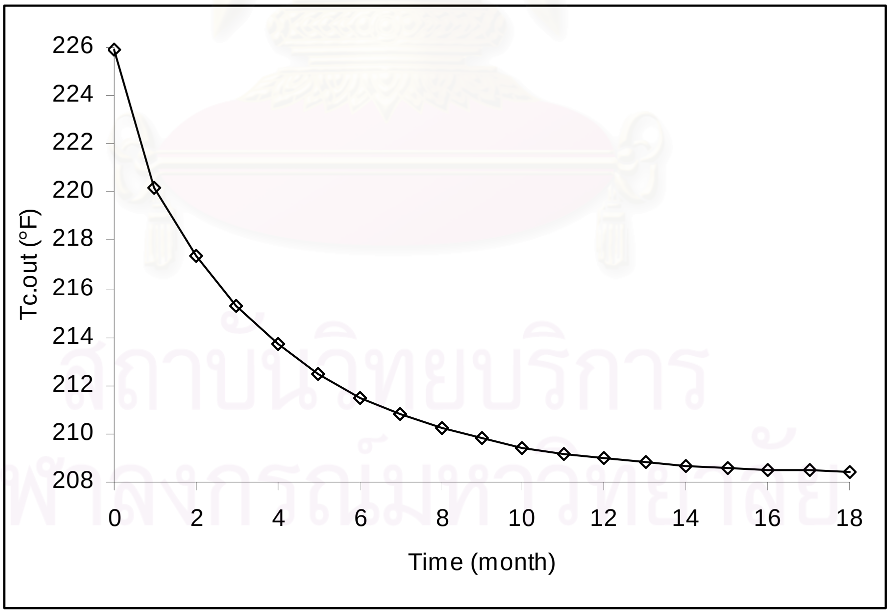

Figure B.15: The schematic diagram of the variations of the outlet temperature in heat exchanger number 5 with time. (asymptotic fouling).

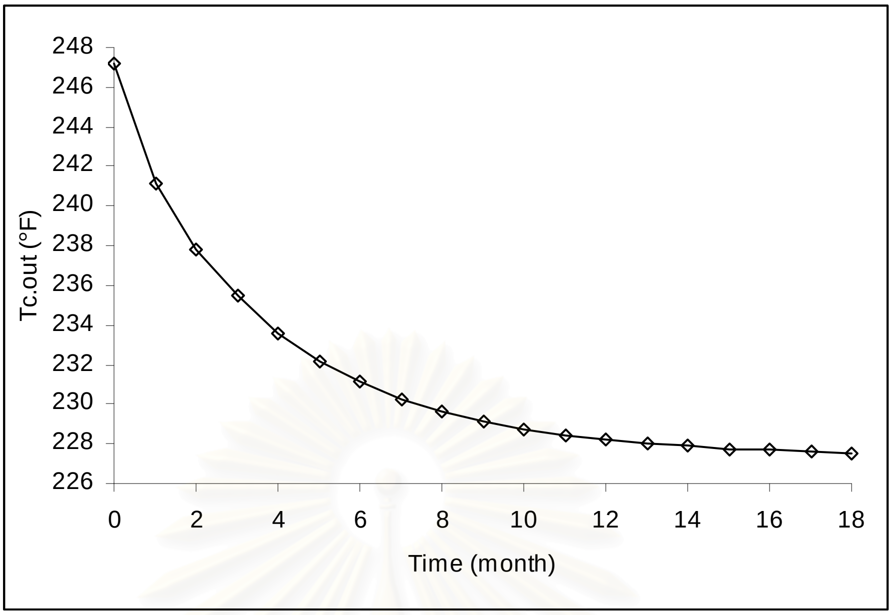

Figure B.16: The schematic diagram of the variations of the outlet temperature in heat exchanger number 6 with time. (asymptotic fouling).

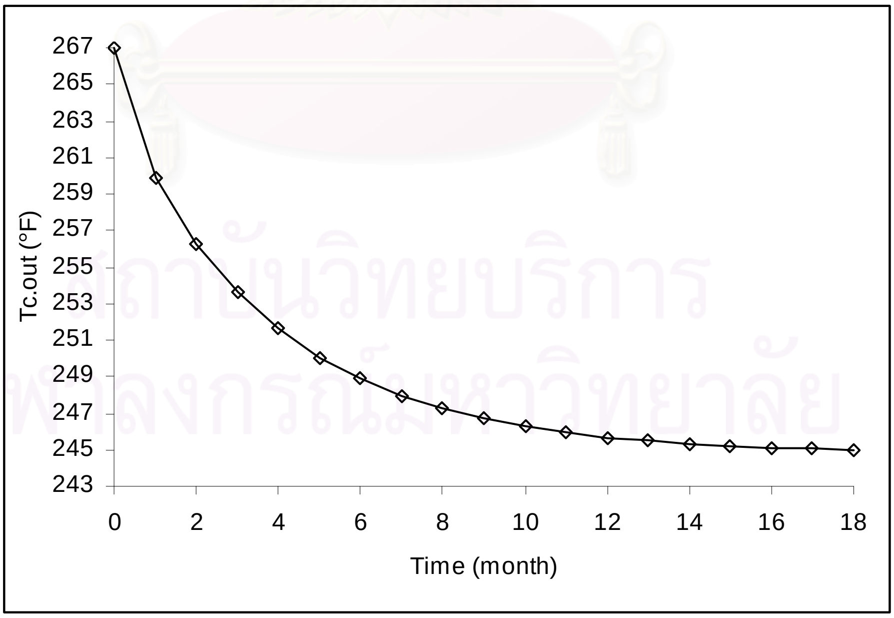

Figure B.17: The schematic diagram of the variations of the outlet temperature in heat exchanger number 7 with time. (asymptotic fouling).

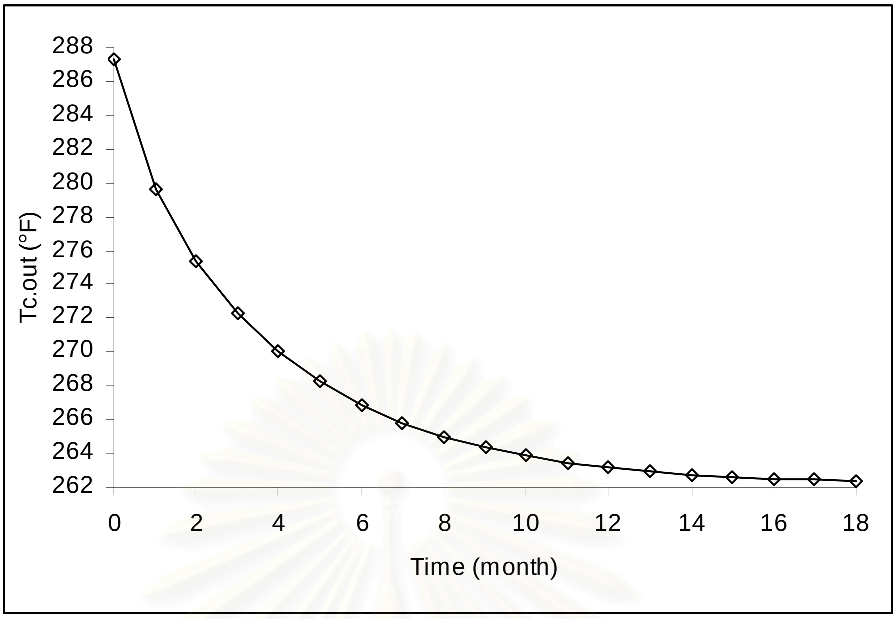

Figure B.18: The schematic diagram of the variations of the outlet temperature in heat exchanger number 8 with time. (asymptotic fouling).

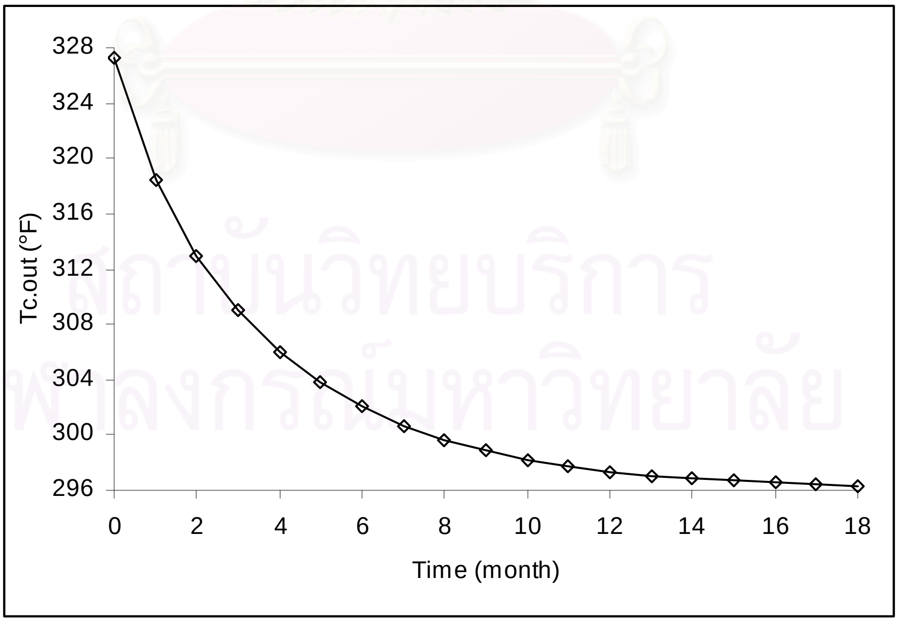

Figure B.19: The schematic diagram of the variations of the outlet temperature in heat exchanger number 9 with time. (asymptotic fouling).

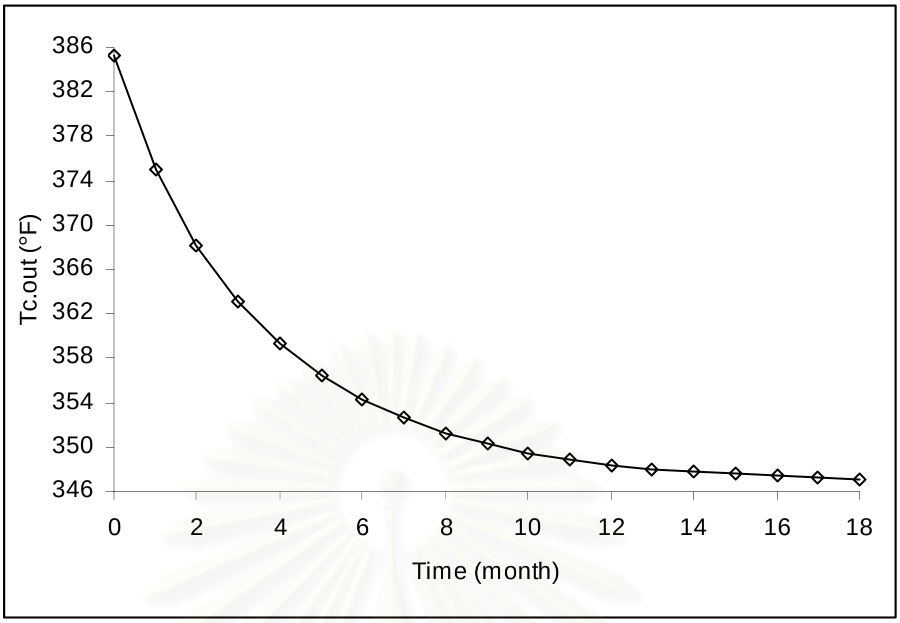

Figure B.20: The schematic diagram of the variations of the outlet temperature in heat exchanger number 10 with time. (asymptotic fouling).

VITA

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