การพัฒนาระเบียบวิธีออฟติไมเซชันแบบพลวัตของการทำความสะอาดข่ายงานเครื่องแลกเปลี่ยนความร้อน โดยใช้วิธีการสร้างปัญหาเวลาต่อเนื่อง

นางสาว กัลยลักษณ์ เอาเอกสิทธิ์

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ALGORITHM DEVELOPMENT FOR DYNAMIC OPTIMIZATION OF HEAT EXCHANGER NETWORK CLEANING USING CONTINUOUS TIME FORMULATION APPROACH

Miss Kanyaluk Ao-ekkasit

A Thesis Submitted in Partial Fulfillment of the Requirements

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กัลยลักษณ์ เอาเอกสิทธิ์ :การพัฒนาระเบียบวิธีออฟติไมเซชันแบบพลวัตของการทำความสะอาดของข่ายงานเครื่องแลกเปลี่ยนความร้อนโดยใช้วิธีการสร้างปัญหาเวลาต่อเนื่อง (ALGORITHM DEVELOPMENT FOR DYNAMIC OPTIMIZATION OF HEAT EXCHANGER NETWORK CLEANING USING CONTINUOUS TIME FORMULATION APPROACH)อ.ที่ปรึกษาวิทยานิพนธ์หลัก:อ.ดร.สุรเทพเขียวหอม 102 หน้า.

เครื่องแลกเปลี่ยนความร้อนมีความสำคัญอย่างมากและใช้ในเกือบทุกขั้นตอนของกระบวนการผลิต โดยปัญหาหลักของเครื่องแลกเปลี่ยนความร้อนคือการเกิดตะกรันที่ผิวแลกเปลี่ยนความร้อน ตะกรันที่เกิดขึ้นนี้เป็นสาเหตุให้ประสิทธิภาพการถ่ายเทความร้อนลดลงตามเวลา ซึ่งเป็นสาเหตุของการสูญเสียพลังงานและทำให้ค่าใช้จ่ายเพิ่มสูงขึ้น ดังนั้นการล้างเครื่องแลกเปลี่ยนความร้อนจึงเป็นสิ่งจำเป็นทั้งนี้เพื่อทำให้ประสิทธิภาพการถ่ายเทความร้อนสูงขึ้นดังเดิม ในงานวิจัยนี้ทำการเลียนแบบเครื่องแลกเปลี่ยนความร้อนชนิดเดี่ยวและข่ายงานเครื่องแลกเปลี่ยนความร้อน โดยใช้แบบจำลองการเกิดตะกรันแบบเชิงเส้นและแบบมีเส้นแนวโน้ม และศึกษาผลของปริมาณตะกรัน และได้ศึกษาสัมประสิทธิ์การถ่ายเทความร้อน, อุณหภูมิขาออกของสายร้อนและสายเย็น, และอัตราการถ่ายเทความร้อนที่เปลี่ยนแปลงตามเวลา

นอกจากนี้ได้พัฒนาวิธีการใหม่สำหรับการสร้างปัญหาออพติไมเซชันเพื่อหาตารางเวลาในการทำความสะอาดเครื่องแลกเปลี่ยนความร้อนที่เหมาะสมโดยใช้วิธีแบบเวลาต่อเนื่อง โดยวิธีการที่พัฒนาขึ้นใช้การคาดการณ์จำนวนครั้งในการทำความสะอาด และหาระยะเวลาดำเนินการระหว่างการล้างแต่ละครั้ง โดยฟังก์ชันวัตถุประสงค์ของปัญหาคือค่าใช้จ่ายในการดำเนินการน้อยที่สุด คำตอบที่ได้จากวิธีการที่พัฒนาขึ้นนี้ดีกว่าคำตอบที่ได้จากวิธีการสร้างปัญหาแบบไม่ต่อเนื่อง

ภาควิชา........วิศวกรรมเคมี........	ลายมือชื่อนิสิต..
สาขาวิชา......วิศวกรรมเคมี........	ลายมือชื่ออ.ที่ปรึกษาวิทยานิพนธ์หลัก……………..........
ปีการศึกษา.........2551…………	

4870218921 : MAJOR MAJOR CHEMICAL ENGINEERING
KEY WORD : FOULING / HEAT EXCHANGER NETWORK / CONTINUOUS TIME APPROACH

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Heat exchanger is important and employed in most stages of industrial processing. The main problem of heat exchanger is fouling on the heat transfer surfaces. The fouling causes the retardation of heat transfer efficiency with time. This is the reason for the loss in energy and the increment of operation cost. Therefore, the cleaning of fouled units is important in order to restore their hydrothermal performance. In this work, the simulations of heat exchanger in a case of single unit and also in network heat exchanger are performed based on linear and asymptotic fouling models. The effect of variation with time of fouling rate, overall heat transfer coefficient, temperatures of hot and cold streams, and heat transfer rate are studied.

Besides this, we developed a new technique to formulate the optimization problem of optimal cleaning time schedule of heat exchanger cleaning using continuous time approach. In this approach, the number of cleaning operation is predicted priorly, and the time period between each cleaning operation is then determined. The objective function of this problem is the minimizing of overall operating cost. The results obtained from this technique are better than the results obtained using the discrete time approach.

Department:……Chemical Engineering… Student's signature:……………………….

Field of study:…Chemical Engineering… Principal Advisor's signature:……………..

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NOMENCLATURE

A_o	total outer area available for heat transfer	ft^2
A_i	total inner area available for heat transfer	ft^2
A_t	total area available for heat transfer	ft^2
$C_{p,c}$	specific heat capacity of cold stream	Btu/lb °F
$C_{p,h}$	specific heat capacity of hot stream	Btu/lb °F
F	mass flow rate	lb/h
F_c	mass flow rate of cold stream	lb/hr
F_h	mass flow rate of hot stream	lb/hr
F_o	the fouling factor for outer surface	hr ft^2 °F/Btu
F_i	the fouling factor for inner surface	hr 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
k	thermal conductivity of tube	Btu/h ft^2 °F
L	length of heat exchanger	ft^2
Q	heat transfer rate	Btu/h
R_c	the conductive resistance for a cylindrical surface	hr ft^2 °F/Btu
R_f	the fouling factor	hr ft^2 °F/Btu
R_t	effective overall thermal resistance	hr ft^2 °F/Btu
r_f	fouling rate	hr ft^2 °F/Btu
r_i	inner fouling factor	hr ft^2 °F/Btu
r_o	outer fouling factor	hr ft^2 °F/Btu
R_f^∞	initial fouling rate	hr ft^2 °F/Btu
t	time	days
$T_{c,in}$	inlet temperature of cold streams	°F
$T_{c,out}$	outlet temperature of cold streams	°F
$T_{h,in}$	inner temperature of hot streams	°F
$T_{h,out}$	outlet temperature of hot streams	°F
U	overall heat transfer coefficient	Btu/h ft^2 °F
U_c	overall heat transfer coefficient in clean condition	Btu/h ft^2 °F
U_{dirt}	overall heat transfer coefficient in dirty condition	Btu/h ft^2 °F
ΔT_{lm}	log mean temperature difference	°F

GREEK LETTERS

τ	Time constant of fouling decay

SUBSCRIPTS

t	Time
h	Hot stream
c	Cold stream
in	Inlet
out	Outlet
cl	clean

CHAPTER I

INTRODUCTION

1.1 Introduction

Heat exchanger is important and used in most stages of industrial processing in order transfer heat between two fluids through a separating wall. Fouling in heat exchanger problem especially in the plant using heat exchanger networks (HENs). The heat exchanger networks are one important factor that changes the outlet temperature of the hot and cold streams. A heat exchanger network (HEN) is an arrangement of heat exchangers; in which cold and hot process streams and hot and cold utility streams interchange energy. Each heat exchanger will affect the efficiency of the others. Fouling reduces heat exchanger effectiveness resulting by reduction overall heat transfer coefficient, heat transfer rate and outlet temperature of cold stream. Thus, if the temperature deviation from the design values exceeds a specified limit, it may even result in system shutdown.

The heat transfer between two fluids will inevitably result in fouling. The formation of fouling in large continuously operating heat exchanger networks (HENs) in plant is the only factor that changes the outlet temperature of the hot and cold streams. Formation of deposits in the exchangers reduces heat exchanger effectiveness with time. It is one of major problems in process industries and important in continuous processes. Fouling may reduce heat transfer, impede fluid flow, increase the pressure drop across the heat exchanger, increase in energy loss, and reduce production and increase cleaning and maintenance costs.

There are effective fouling mitigation techniques (Smaili F. et al., 2001). The first techniques is reducing the rate of fouling by interrupting the mechanisms causing fouling such as adding anti fouling chemicals. This method, which adds directly, results in increasing the operating cost of the system. The second techniques is using more robust heat transfer equipment such as fluidized bed heat exchangers or a more flexible network configuration featuring oversized or duplicate units for such duties. This technique increases the capital cost of the system. Finally technique is regular cleaning of fouled units during the operating to restore thermal and hydraulic performance of the network. The technique of this cleaning affects both the operating and capital costs. Above technique of fouling mitigation techniques uses a combination in order to minimize the overall operating cost. On account of the cleaning of fouled units are restore their performance. Thus, it is necessary to plan a suitable cleaning schedule to conserve the network in the operating conditions of the design point.

There are many applications to the optimum cleaning schedule of heat exchanger network (Smaili F. et.al., 2001; Mariusz M. et al., 2004; Sepehr S. et.al., 2006). A number of previous studies have been focused on the problem of cleaning schedule formulated as discrete-time. However, there are disadvantages of discrete-time approach such as the step size must be specified priory. The large step size leads to an unacceptable solution. Therefore, in this work we consider the problem of cleaning schedule of heat exchanger network as continuous-time which is then solved by differential evolution optimization method.

Therefore, in this work is to study the optimum cleaning schedule of heat exchanger network. The aim of this study is the development of algorithm by formulation as continuous time approach. The problem of cleaning schedule of heat exchanger network is the nonlinear programming problem which is usually solved using differential evolution optimization algorithm.

1.2 Research Objectives

The objective of this research is to develop algorithm based on continuous time approach to optimize the problem of cleaning schedule of heat exchanger networks under fouling condition.

1.3 Scope of the research

1. The synthesis problem formulation is based on continuous time approach.

2. Mathematic models of the heat transfer coefficient and the temperature relations in a heat exchanger are studied.
3. The cleaning schedule models applied to a crude oil preheat train and the exponential asymptotic fouling behavior is a case study. The case studies of this research are as follows:

    Case 1: A single heat exchanger.

    Case 2: A heat exchanger network case of ten heat exchangers.
4. Programs written to optimize the cleaning schedule of heat exchanger network are based on C language.
5. Differential evolution optimization algorithm is used to optimize the cleaning schedule of heat exchanger network..
6. The results from continuous time approach are compared with the results from discrete time approach.

1.4 Contributions of research

The contribution of this research provide new algorithm to find optimum of cleaning schedule of continuous time dynamic model.

1.5 Research procedures

1. Study theory and review the literatures of solution methods of dynamic optimization problem, and optimization of heat exchanger network cleaning schedule.
2. Formulate the synthesis problem using continuous time approach.
3. Study the differential evolution optimization method.
4. An optimal the cleaning schedule of heat exchanger network as minimum operational cost.
5. Compare the performance of obtained solution from the developed algorithm.
6. Conclude this research.

1.6 Research framework

This thesis has been diveided into six chapters.

In Chapter I, Introduction, Objectives, Scope, Contributions and procedures of this research is introduced in this chapter.

In Chapter II, a review of the previous work on the simulation and the optimal cleaning of heat exchanger network are given.

In Chapter III, description of the theory of heat exchanger, fouling in heat exchanger and different evolution are presented.

In Chapter IV, description of heat exchanger model and the simulation of heat exchanger under fouling are presented.

In Chapter V, the optimization of single heat exchanger and heat exchanger network cleaning are the case study for this research.

The overall conclusions and recommendations for future work of this thesis are discussed in Chapter VI.

This is followed by:

Appendix A: numeric integration.

Appendix B: optimization results.

Appendix C: simulation of heat exchanger network.

Appendix D: list of publications.

CHAPTER II

LITERATURE REVIEW

In recent years, fouling of heat transfer equipment is one of the most common operational problems by the chemical processing industries. The fouling reduces heat transfer rate causing in the reduction of heat exchanger performance. In most of the cases, it is necessary to clean the fouled equipment during the operation time in order to minimize the overall operating cost. Systematic methods have been developed to determine the optimal cleaning sequence in heat exchanger networks affected by fouling. This chapter provides a review of the optimization of cleaning schedule of heat exchanger network.

Floudas et al. (1998) proposed mathematical formulation for the short-term scheduling of batch plants and formulation is based on a continuous time representation and results in a mixed integer linear programming problem. It is shown that clean up requirements are incorporated by considering cleanup times in the timing sequence constraints, thus avoiding the consideration of additional tasks. The clean up tasks can be formulated as additional batch tasks with fixed duration.

Vipul et al. (1998) studied cyclic scheduling of continuous parallel-process units with decaying performance. The process model considered is the one of exponential decay in conversion to ethylene with time. This type of scheduling problem in ethylene plants will be discussed, as well as the case of parallel reactors with catalyst deactivation. MINLP models for these problems are developed, and their mathematical properties and a branch-and bound algorithm to solve these models are presented. It was shown that the trade-off for the optimal solution is a function of the average performance, the maintenance cost, and the production loss because of the shutdown. MINLP the objective function is pseudoconcave and the constraints are linear. This property was exploited to solve the problem of global optimality using the

NLP-based B&B method. It was demonstrated that the schedules obtained using this model can lead to a considerable increase in profits.

Georgiadis M.C. et al. (2000) studied the cyclic cleaning and energy scheduling problem of complex heat exchanger network under fouling. Food processes are considered in this work where fouling is a severe problem with dramatic consequences such as significant production losses and increased energy requirements. Thus, Cleaning-In-Place (CIP) operations are necessary to be carried out every 4±8 hours so as to restore each heat exchanger area back to its original state. They studied two sections formulations for the basic building blocks related to serial and parallel heat exchanger arrangements. The GAMS modeling system was used to implement the mathematical models and first made to solve the MINLP model using the augmented penalty outer approximation method as implemented in DICOPT++. This problem is that the performance of processing units decreases with times which therefore have to be shut down for cleaning after regular time intervals. Due to its practical significance a special application in HENs under rapid milk fouling conditions constituted the major motivation for this work.

Michael et al. (2000) studied optimal cleaning policies in heat exchanger networks under rapid fouling. They consider the short-term cleaning scheduling problem of complex heat exchanger networks under fouling. The milk sterilization process is considered in this work. The formulations can model serial and parallel heat exchanger networks as well as network arrangements arising from the combination. Model of this problem is a mixed integer nonlinear programming (MINLP). This model is then linearized to a tight mixed-integer linear-programming (MILP) model which can be solved to global optimality. The mathematical of the problem, the time horizon of interest is discretized. The GAMS modeling system was used to implement the mathematical models. The problem was solved using the augmented penalty outer-approximation method as implemented. The result that the MINLP model cannot be used for the solution of problems with more than 10-12 exchangers over an operation horizon of 24 hours.

Smaili F. et al. (2001) studied mitigation of fouling in refinery heat exchanger networks by optimal management of cleaning. They developed mixed integer non linear programming model scheduling problem of oil refinery crude preheat, based on a regular time discretisation heuristic. Solution of the mixed integer nonlinear programming problem model is obtained by a commercial optimization solver that the equation representing the network and its constraints were written in the GAMS programming environment and solved using DICOPT++ on a Unix work station. The effectiveness of the MINLP approach is discussed, particularly with regard to obtaining globally optimal solutions. 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. Comparisons of the mixed integer non linear programming model with a simple greedy algorithm showed the former to converge faster, while the latter returned a sub-optimal result but proved to be robust.

Smaili F. et al. (2002,)studied optimization of cleaning schedules in heat exchanger networks subject to fouling. They considered both linear and asymptotic fouling behaviors. 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 is a single heat exchanger. An objective function postulated to energy and cleaning costs. The second case is 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. In addition to, 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.

Smaili et.al. (2002) studied management of cleaning of heat exchanger networks (HENs) in oil refinery heat recovery network economics. They study two case studies: one involving 14 heat exchanger units, and one involving 25 units. They focuses on presenting the HEN cleaning problem and scheduling of cleaning actions in a multi-period setting as a mathematical programming formulation. They developed the backtracking threshold accepting algorithm (BTA) in order to modify for the HEN cleaning problem and the results obtained over the same problems using the MINLP formulations utilizing the outer approximation method(OA), which accessed through the GAMS mathematical programming language. For case study first, 14 heat exchanger units, the % saving from BTA algorithm is equal to GAMS. For case study second, 25 heat exchanger units, the % saving from BTA algorithm is more than GAMS.

Mariela A. et al.(2003) applied a numerical method based on a combined discretization and simultaneous dynamic optimization approach to solve a system consisting of partial differential and algebraic equations. This method in order to the resolution of the dynamic optimization model of a gas-gas heat exchanger which is part of a larger model under development. The goal is to minimize the transient between two set points of an outlet stream temperature. The dynamic model provides profiles of controlled and manipulated variables which are in agreement with available data, and the remote optimization system performed very well.

Mariusz M. et al.(2004) studied optimal cleaning schedule for heat exchangers in a heat exchanger network, which comprising 10 heat exchangers. Fouling of heat transfer surfaces hinders correct production activity and increases energy consumption thus giving rise to economic losses. The losses can be reduced if on-line cleaning of heat exchangers is applied. The scheduling of cleaning interventions on the individual exchangers in the HEN can be based on a priori knowledge of the time behaviour of the thermal resistance. The mathematical model of the influence of fouling on heat exchanger and HEN operation is outlined. Heat exchanger cleaning is postulated to maximize the avoided loss understood as the value of energy recovered if cleaning is postulated to maxise the avoided loss understood as the value of energy recovered if cleaning the HEN, minus the value of energy recovered without HEN cleaning, minus the cost of HEN cleaning.

Markowski et al. (2005) illustrated the mathematical model of the fouling on heat exchanger. 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.

Sepehr S. et al. (2006) studied the simulation of heat exchanger network(HEN) and planning the optimum cleaning schedule. The simulation of the heat exchanger network based on the actual input data obtained for a specified petrochemical plant and by introducing an objective function, the optimal cleaning schedule of the heat exchanger network was obtained. The optimum that provides the minimum operation cost or maximum amount of savings. 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. In order to use simulation and to optimize the heat exchanger network cleaning schedule, a software program in Visual Basic 6. The results of finding the optimal cleaning schedules for time horizon is 12 for urea unit and 24 months for ammonia unit, 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.

Rodriguez et al. (2007) studied the approach combines the optimization of operating conditions with the optimal management of cleaning actions in a comprehensive mitigation strategy. They studied case study of a refinery crude oil preheat train. The cleaning schedule is optimized by using the same approach proposed by Smaili and co-workers (Smaili et al., 2001, 2002) of dividing the period of study into time slots and introducing binary variables to represent the cleaning status of each heat exchanger in each time slot.The optimization problem of heat exchanger network cleaning is solved by using simulated annealing (SA). The implementation of an optimal cleaning policy will reduce the operating cost of the network significantly. As a result of this optimal cleaning schedule, the energy penalties caused by fouling are reduced to almost half of those observed for the base case. The application of the new approach compared with the existing mitigation strategy, the proposed approach leads to higher savings.

CHAPTER III

THEORY

3.1 Heat exchangers

Heat exchangers are equipment for the transfer of heat between two fluids through a separating wall. This heat exchange take place between a heating medium at a higher temperature and another medium, in our case water, at a lower temperature, in a piece of equipment called a heat exchanger specifically manufactured.

3.1.1 Overall heat transfer coefficient

Heat transfer between a fluid and a solid wall can be represented by conduction and convection terms. It is assumed that the difference in temperature between fluid and wall is due entirely to a stagnant film of liquid adhering to the wall and in which the temperature profile is linear. Heat transfer in a steam generator involves convection from the bulk to the stream generator inner tube surface, conduction through the tube wall, and convection from the outer tube surface to the secondary side fluid Fig. 3.1.

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.

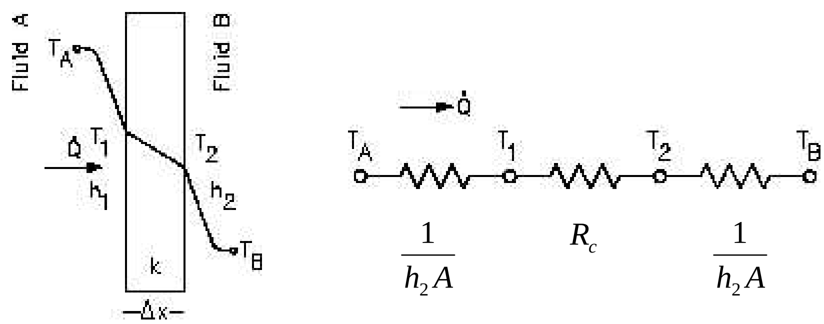


Figure 3.1 Temperature profile of heat through equivalent fluid through fouling resistances and metal wall.

From Fig. 3.1, Therefore the overall resistance as

$$R_t = \frac{1}{h_1 A} + R_c + \frac{1}{h_2 A} \tag{3.2}$$

where Rc is the conductive resistance for a cylindrical surface derived as

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

The subscripts 1 is i and 2 is o pertain to the inside and outside of the smaller inner tube. The overall heat-transfer coefficient may be based on either the inside or outside area of the tube at the discretion of the designer. Accordingly,

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

Similarly, for overall heat transfer coefficient of outside was follow,

$$U_o = \frac{1}{A_o R_t} = \frac{1}{\frac{A_o}{A_i h_i} + \frac{A_o \ln(r_o / r_i)}{2\pi L k} + \frac{1}{h_o}} \tag{3.5}$$

3.1.2 Fouling factors

After a period of 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 event, 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 factors 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

$$R_f = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}} \tag{3.6}$$

3.1.3 The log mean temperature difference

In a heat exchanger, heat is transferred between hot and cold fluids through a solid wall. The fluids may be process streams or independent sources of heat. Fig. 3.2 shows such a process with inlet and outlet streams, but with the internal flow pattern unidentified because it varies from case to case. At any cross section, the differential rate of heat transfer is

$$dQ = U(T - T')dA = -mcdT = m'c'dT' \tag{3.7}$$

The overall heat transfer rate is represented formally by

$$Q = UA(\Delta T)_m \tag{3.8}$$

where U = overall heat-transfer coefficient

A = surface area for heat transfer consistent with definition of U

ΔT = suitable mean temperature difference across heat exchanger

The mean temperature difference $(\Delta T)_m$ depends on the terminal temperatures (Fig. 3.2), the thermal properties of the two fluids and on the flow pattern through the exchanger.

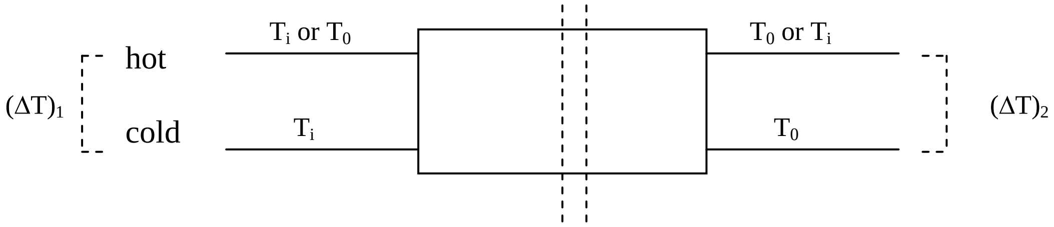


Figure 3.2 Terminal temperatures and temperature differences of a heat exchanger, with unidentified internal flow pattern.

The simplest flow patterns are single pass of each fluid, in either the same or opposite directions. The mean temperature is expressed in terms of the terminal differences by

$$(\Delta T)_m = (\Delta T)_{\log mean} = \frac{(\Delta T)_2 - (\Delta T)_1}{\ln\left[(\Delta T)_2 / (\Delta T)_1\right]} \quad (3.9)$$

This temperature difference is called the *log mean temperature* diference (LMTD). 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.

3.1.4 Effectiveness-NTU method

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 on 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,

We define the heat-exchanger effectiveness as

$$\text{Effectiveness} = \varepsilon = \frac{\text{actual heat transfer}}{\text{maximum possible heat transfer}} \quad (3.10)$$

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 parallel-flow heat exchanger

$$q = \dot{m}_h c_h (T_{h1} - T_{h2}) = \dot{m}_c c_c (T_{c2} - T_{c1}) \quad (3.11)$$

and for the counterflow heat exchanger

$$q = \dot{m}_h c_h (T_{h1} - T_{h2}) = \dot{m}_c c_c (T_{c1} - T_{c2}) \quad (3.12)$$

To determine the maximum possible heat transfer for the exchanger, we first recognize that this maximum value could be attained if one of the fluids were to undergo a temperature change equal to 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 $\dot{m}\, c$ because the energy balance requires that the energy received by one fluid be equal to that given up by the other fluid; if we let the fluid with the larger value of $\dot{m}\, c$ go through the maximum temperature difference, this would require that the other fluid undergo a temperature difference greater than the maximum, and this is impossible. So, maximum possible heat transfer is expressed as

$$q_{\max} = (\dot{m}c)_{\min}(T_{h_{inlet}} - T_{c_{inlet}}) \quad (3.13)$$

The minimum fluid may be either the hot or cold fluid, depending on the mass-flow rates and specific heats. For the parallel-flow exchanger

$$\varepsilon_h = \frac{\dot{m}_h c_h (T_{h1} - T_{h2})}{\dot{m}_h c_h (T_{h1} - T_{c1})} = \frac{T_{h1} - T_{h2}}{T_{h1} - T_{c1}} \quad (3.14)$$

$$\varepsilon_h = \frac{\dot{m}_c c_c (T_{c2} - T_{c1})}{\dot{m}_c c_c (T_{h1} - T_{c1})} = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{c1}} \quad (3.15)$$

The subscripts on the effectiveness symbols designate the fluid which has the minimum value of $\dot{m}\,c$. For the counterflow exchanger:

$$\varepsilon_h = \frac{\dot{m}_h\, c_h (T_{h1} - T_{h2})}{\dot{m}_h\, c_h (T_{h1} - T_{c2})} = \frac{T_{h1} - T_{h2}}{T_{h1} - T_{c2}} \qquad (3.16)$$

$$\varepsilon_h = \frac{\dot{m}_c\, c_c (T_{c1} - T_{c2})}{\dot{m}_c\, c_c (T_{h1} - T_{c2})} = \frac{T_{c1} - T_{c2}}{T_{h1} - T_{c2}} \qquad (3.17)$$

In a general way the effectiveness is expressed as

$$\varepsilon = \frac{\Delta T(\text{min}imum \quad fluid)}{Maximum \quad temperature \quad difference \quad in \quad heat \quad exchanger} \qquad (3.18)$$

3.2 Fouling in heat exchanger

3.2.1 Fouling Mechanisms

Somerscales and Knudsen (1981) have identified six categories of fouling:

1. *Particulate fouling.* The accumulation of solid particles is suspended in the process stream on the heat transfer surfaces. Typical examples include dust deposition, particles carried in condenser cooling water, and unburned fuel, or fly ash. If the solid deposition is due to gravity, the process is referred to as sedimentation fouling.

2. *Precipitation fouling.* Dissolved substances carried in the process stream are precipitated on the heat transfer surfaces. Examples include carbonates, sulfates, and carbonates. *Scaling* occurs when precipitation occurs on heated rather than cooled surfaces.

3. *Chemical reaction fouling.* In certain cases, deposits on the heat transfer surfaces which are not, in themselves, reactants are formed by chemical reactions. In this type of fouling, cracking and coking of hydrocarbons and polymerization are typical examples.

4. *Corrosion fouling.* In this type of fouling, the heat transfer surface reacts, at certain pH levels, to produce products that adhere to the heat transfer

surfaces, and in turn, this may promote the attachment of additional fouling materials. Sulfur in fuel oil and sulfur products in the flue gas, such as sulfur dioxide, can lead to sulfuric acid. This has caused, for example, significant damage to heat exchange surfaces in air heaters in the power industry.

5. *Biological fouling.* Materials such as algae, bacteria, molds, seaweed, and barnacles carried in the process stream cause biological fouling of the heat transfer surfaces. A prime example of biological fouling is in marine power plant condensers.

6. *Freezing fouling.* In this type of fouling, a liquid, or some of its higher-melting point components will deposit on a sub cooled heat transfer surface.

3.2.2 Effect of fouling on heat transfer

As noted above 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 as previously discussed.

Fouling effects inside the tube usually cause no particular problems 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 reason for 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.

3.2.3 Fouling factor

The most common way to account for the effects of fouling in a tubular heat exchanger is the application of a fouling factor. The fouling factor is a predetermined number that represents the amount of fouling a particular heat exchanger transferring a particular fluid will sustain. In the heat transfer equation the fouling factor is added to the other thermal resistances to calculate the Total Thermal Resistance which is the reciprocal of U clean. There is no direct calculation to determine the appropriate fouling factor to use for a given fluid in a particular application, however guidelines do exist to help determine an appropriate fouling factor. The most common compilation of fouling factors, to be used for a variety of fluid in various applications, is supplied by Tubular Exchanger Manufacturers Association (TEMA).

3.3 optimization problem statement

3.3.1 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, g is equality constraint and h is inequality constraint both g and h is 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 the objective function and constraints are linear, then this is a linear programming problem. If the objective function is quadratic and constraints are linear, then it is a quadratic programming problem. If the objective function and constraints are nonlinear, then it is a nonlinear programming problem.

3.3.2 Dynamic optimization problem solutions

Dynamic optimization problem or optimal control problem is solved to obtain an input profile that minimize or maximize the objective function subject to process model and specified constraints, i.e. safety, environmental and operating constraints. In general, the process model consisting of mass and energy balance equations is decribed by differential and algebraic equations (DAEs). There are several approaches that can solve optimal control problems. These can be divided into analytical methods that have been used originally and numerical methods preferred nowadays.

The optimized dynamic model can be described either by an ODE system or by an DAE system. Consider the following general control problem for $t \in [t_0, t_f]$:

$$\text{Min } \{G(x(t_f), p, t_f), \qquad u(t_0) = x_0(p) \tag{3.19}$$

such that

$$M\dot{x}(t) = f(x(t),u(t), p, t),\ x(t_0) = x_0(p)$$

$$h(x(t),u(t),p, t) = 0$$

$$g(x(t),u(t),p, t) \leq 0$$

$$x(t)^L \leq x(t) \leq x(t)^U$$

$$u(t)^L \leq u(t) \leq u(t)^U$$

$$p^L \leq p \leq p^U$$

It should be noticed that the variables x and u in general are vectors of variables, g is equality constraint and h is inequality constraint both g and h are vectors of function. The objective function (G) is to be an integral equation.

3.4 Different 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. The DE algorithm is a population based like genetic algorithm using similar operators; mutation, crossover and selection.

3.4.1 Differential evolutionary algorithm

Differential evolutionary (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 3.3 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 Xi of the generated population in order to create a trial vector Ui. The basic DE/rand/1/bin scheme starts by randomly selecting three vectors in the populations. The perturbed vector Vi is then generated based on the three previously selected vectors

as follows:

$$V_i = X_{r3} + F(X_{r2} - X_{r1}) \tag{3.20}$$

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:

$$V_i = \frac{(X_{r1} + X_{r2} + X_{r3})}{3} + (p_2 - p_1)(X_{r1} - X_{r2})$$
$$+(p_3 - p_2)(X_{r2} - X_{r3}) + (p_1 - p_3)(X_{r3} - X_{r1}) \qquad (3.21)$$

where,

$$p_1 = \frac{|f(X_{r1})|}{|f(X_{r1})| + |f(X_{r2})| + |f(X_{r3})|} \qquad (3.22)$$

$$p_2 = \frac{|f(X_{r2})|}{|f(X_{r1})| + |f(X_{r2})| + |f(X_{r3})|} \qquad (3.23)$$

$$p_3 = \frac{|f(X_{r3})|}{|f(X_{r1})| + |f(X_{r2})| + |f(X_{r3})|} \qquad (3.24)$$

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:

$$u_{i,j} = \begin{cases} v_{i,j}, & if \quad random[0,1) \leq CR \vee j = random[1,n); \\ x_{i,j}, & otherwise \end{cases} \qquad (3.25)$$

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:

$$X_{i+1} = \begin{cases} U_{i}, & if \quad f(U_i) \le f(X_i); \\ X_i, & otherwise \end{cases} \tag{3.26}$$

The evolutionary process repeats until the stopping criteria is satisfied.

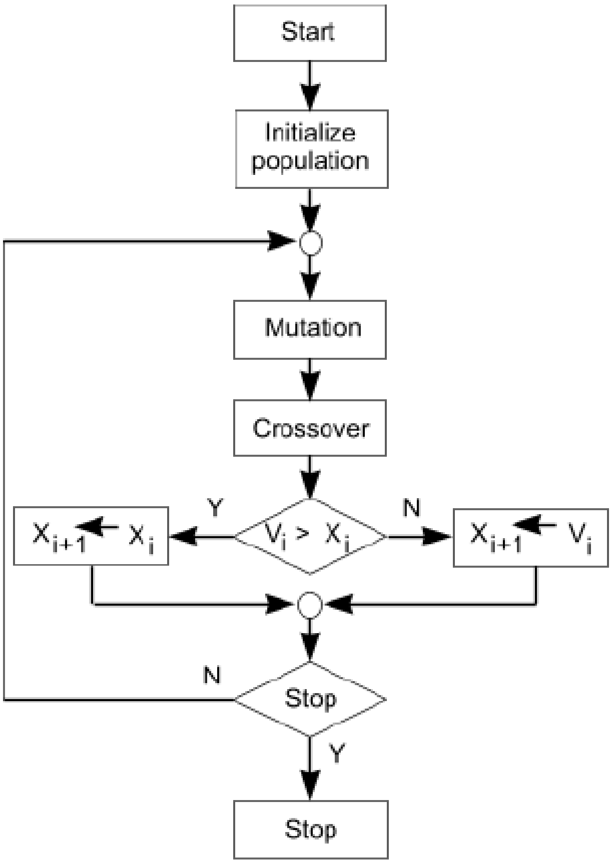


Figure 3.3 The flowchart of the differential evolutionary algorithm.

3.4.2 The constrain handling scheme

3.4.2.1. 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:

$$x' = (\text{int})\ x; \tag{3.27}$$

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.

3.4.2.2. 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:

$$x' \begin{cases} x_i^{(L)}, & if \quad x < x_i^{(L)}; \\ x, & if \quad x_i^{(L)} \le x \le x_i^{(U)}; \\ x_i^{(U)}, & if \quad x > x_i^{(U)}; \end{cases} \tag{3.28}$$

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

3.4.2.3. 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:

$$X_{i+1} = \begin{cases} X_{i,} & X_i \prec U_i; \\ U_i, & otherwise; \end{cases} \tag{3.29}$$

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.

3.4.2.4. 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.

$$X_{i+1} = X_i - J^{-1}(X_i)H(X_i) \tag{3.30}$$

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 UNDER FOULING

This chapter is divided into two sections: heat exchanger model and preliminary study of single heat exchanger which are the simulation of heat exchanger. The simulation method of the heat exchanger was performed using energy balance equations and relationships between the heat transfer coefficients of the hot and cold streams and fouling factors. The exchanger is single heat exchanger in heat exchanger network for preheating crude oil in refinery process. 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 next chapter in Figure 5.7. In this chapter describes mathematical model and the simulation of single heat exchanger in heat exchanger network. Detail of the models was discussed below.

4.1 Heat exchanger model

Each heat exchanger unit in heat exchanger network was modeled as a single pass counter current unit. The following equations was written for one unit and repeated for each exchanger in the heat exchanger network (HEN).

4.1.1. Hot and cold stream outlet temperatures

The heat transfer rate in an exchanger is explained as

$$Q = UA\Delta T_{lm} \tag{4.1}$$

Where the log mean temperature difference, ΔT_{lm}, is given by

$$\Delta T_{lm} = \frac{(T_{h,out} - T_{c,in}) - (T_{h,in} - T_{c,out})}{\ln\left[(T_{h,out} - T_{c,in})/(T_{h,in} - T_{c,out})\right]} \tag{4.2}$$

Assuming no energy loss, an energy balance for the cold and hot streams of an exchanger gives

$$Q_c = F_c C_{p,c}(T_{c,out} - T_{c,in}) \tag{4.3}$$

$$Q_h = F_h C_{p,h}(T_{h,in} - T_{h,out}) \tag{4.4}$$

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

$$\alpha = \frac{UA}{F_h C_{p,h}} \tag{4.5}$$

$$R = \frac{F_h c_{p,h}}{F_c c_{p,c}} \tag{4.6}$$

The outlet temperatures are calculated from the inlet temperature via the rearranged equations (4.1) to (4.6). Therefore, the hot and cold stream outlet temperatures can be computed from

$$T_{c,out} = \left\{ \frac{(1-R)\exp\left(-\alpha(R-1)\right)}{\exp\left(-\alpha(R-1)\right) - R} \right\} T_{c,in} + \left\{ \frac{R\left(\exp\left(-\alpha(R-1)\right) - 1\right)}{\exp\left(-\alpha(R-1)\right) - R} \right\} T_{h,in} \tag{4.7}$$

$$T_{h,out} = \left\{ \frac{\exp\left(-\alpha(R-1)\right) - 1}{\exp\left(-\alpha(R-1)\right) - R} \right\} T_{c,in} - \left\{ \frac{R-1}{\exp\left(-\alpha(R-1)\right) - R} \right\} T_{h,in} \tag{4.8}$$

By defining Z_h and Z_c as

$$Z_h = \left\{ \frac{R\left(\exp\left(-\alpha(R-1)\right)-1\right)}{\exp\left(-\alpha(R-1)\right)-R} \right\} \tag{4.9}$$

$$Z_c = \left\{ \frac{(1-R)\exp\left(-\alpha(R-1)\right)}{\exp\left(-\alpha(R-1)\right)-R} \right\} \tag{4.10}$$

And substituting these values in Eq.(4.7) the outlet temperature of a cold stream and from an exchanger is obtained in the form of:

$$T_{c,out} = Z_c T_{c,in} + Z_h T_{h,in} \tag{4.11}$$

Also, the outlet temperature of a hot stream may be expressed as

$$T_{h,out} = T_{h,in} - \frac{1}{R}(T_{c,out} - T_{c,in}) \tag{4.12}$$

The inlet of the hot stream and cold stream($T_{h,in}$ and $T_{c,in}$), the mass flow rate of hot stream and cold stream (F_h, and F_c), the overall heat transfer coefficient (U_c), the heat transfer area (A) and specific heat capacity of hot stream and cold stream ($C_{p,h}$ and $C_{p,c}$) are known. The values of α, R, $T_{c,out}$ and $T_{h,out}$ are obtained by solving equation (4.5), (4.6), (4.11) and (4.12) simultaneously. Therefore, the overall heat transfer coefficient and the heat transfer rate are also obtained.

4.1.2. Fouling rate models

Fouling is modeled using the fouling resistance approach.

$$R_f(t) = \frac{1}{U(t)} - \frac{1}{U_c} \tag{4.13}$$

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)

The rate of fouling varies with fluid composition, flow rate and temperature. The variation of temperature is a strong effect on fouling deposition. The two most common forms of fouling model are considered. Both linear and asymptotic fouling behaviors are considered in this work. The fouling models are discussed below.

1. Linear fouling

$$\dot{R} \equiv \frac{dR_f}{dt} = a \tag{4.14}$$

2. Asymptotic fouling

$$R_f(t) = R_f^{\infty}(1 - \exp(-t/\tau)) \tag{4.15}$$

where a is a constant for a particular exchanger depending on cold/hot stream compositions, temperature, etc., R_f^{∞} is the asymptotic fouling resistance (hr ft^2 ^{o}F/Btu), τ is a fouling time constant (days), and t is time interval since the last cleaning (days)

4.2 Preliminary study of single heat exchanger

In this section, preliminary studies of single heat exchanger under fouling condition are first addressed. Formation of deposits in the exchangers, variations in overall heat transfer coefficient, variations in outlet temperatures of hot and cold streams and variations of heat transfer rate with time have been performed by simulations. The operating time is 730 days.

The simulation model used here is based on the following assumptions:

Constant flow rates. The mass flow rates of streams entering are fixed. Changes due to cleaning actions are considered.

Constant physical parameters. The heat capacity of each stream is assumed not to vary significantly with temperature.

Fouling models used. Fouling is modeled using the fouling resistance approach, based on Equation (4.13).

Direction of flow. A single counter current shell and tube heat exchanger are considered in this here.

For all simulations, it was used information from the parameter in Table 4.1 which obtained from data reconciliation in order to simulation, as described by Smaili et al.

Table 4.1 Data for the Single-Heat exchanger Case

Parameter	**Value**
$T_{h,in}$ (°F)	631.4
$T_{c,in}$(°F)	347
F_h (lb/hr)	207940
F_c (lb/hr)	649217
$C_{p,h}$ (Btu/lb °F)	0.67
$C_{p,c}$ (Btu/lb °F)	0.57
A (ft^2)	1257.2
U_{clean} (Btu/hr ft^2 °F)	88.1
R_f^{∞} (hr ft^2 °F/ Btu)	6.73×10^{-3}
r (linear) (ft^2 °F/Btu)	2.9×10^{-4}
t (days)	120

4.2.1. The influence of fouling model on performance of heat exchanger under fouling condition

The overall heat transfer coefficient and heat transfer rate were decreased by fouling deposition which was result in reduction of heat exchanger performance. The linear fouling model behavior and asymptotic fouling model behavior were considered in this work as shown in equation (4.14) and (4.15), respectively. The results of fouling formation and the variation of heat transfer rate with time were shown in Figure 4.1 and Figure 4.2, respectively.

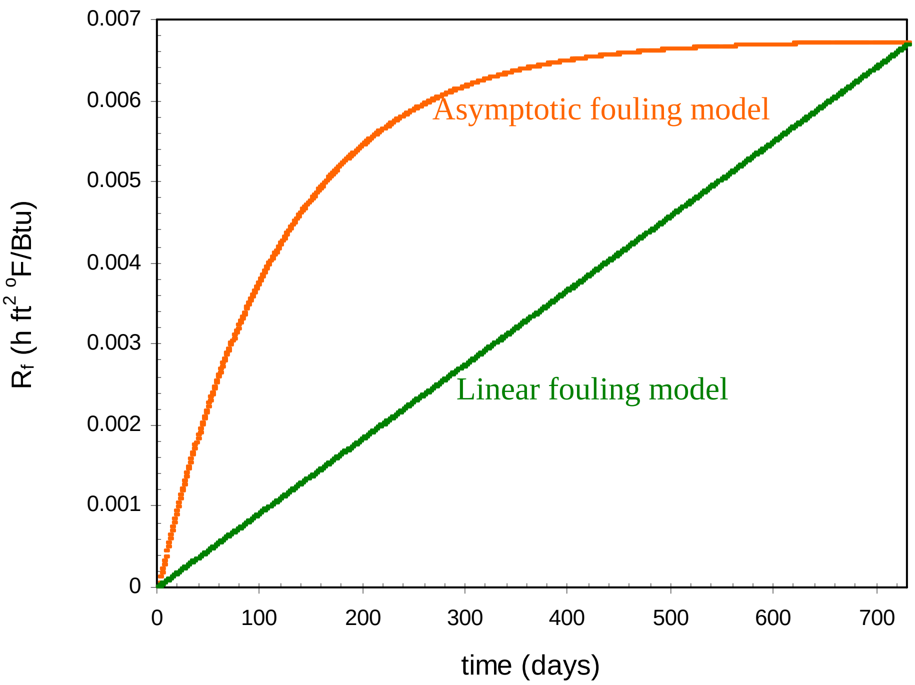


Figure 4.1 The variation of fouling formation with time.

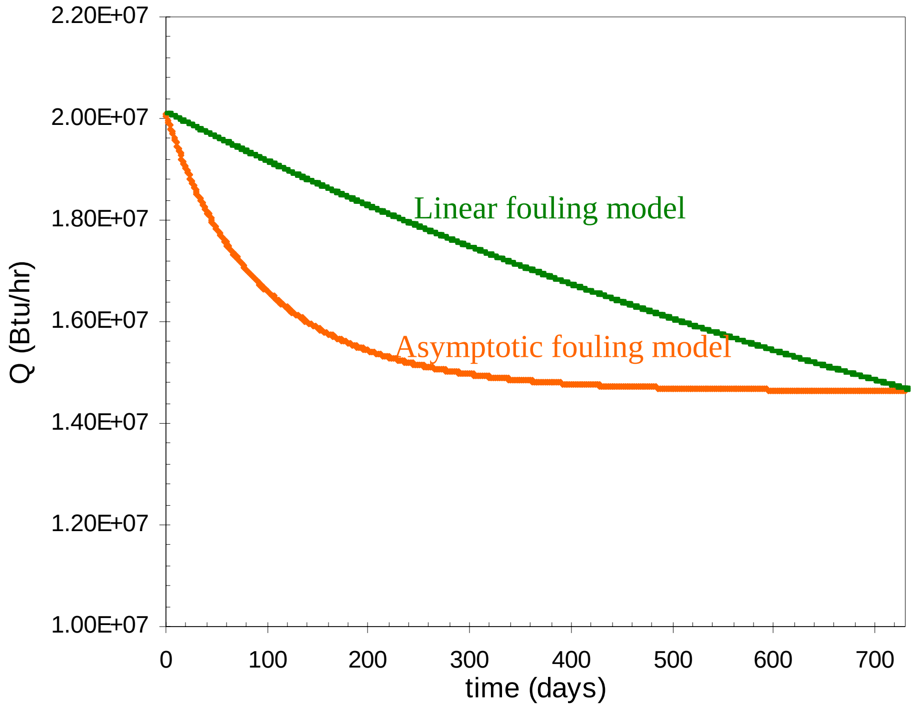


Figure 4.2 The variation of heat transfer rate with time.

The fouling formation of asymptotic fouling model and linear fouling model are shown in Figure 4.1 without cleaning in 730 days. It is observed that fouling formation rate of asymptotic fouling model behavior is larger than linear fouling model behavior. The variation of asymptotic fouling model behavior is rapidly changed in initial time and then stabilizes to the initial stages at asymptote. This result is due to exponential term in equation 4.15 which is first order model. The linear fouling model behavior is slowly changed. This is due to the fact that linear fouling model is simple model.

The variation of heat transfer rate was shown in Figure 4.2 by without cleaning in 730 days. The heat transfer rate is decreased with continuous time. It is noted that from equation 4.13, the fouling and overall heat transfer coefficient are reverse variation. This result is effect on heat transfer rate that vary follow to overall heat transfer rate (see in equation 4.1). Therefore, fouling formation that increase was cause for decreasing of overall heat transfer coefficient and heat transfer rate. It is observed that heat transfer rate is rapidly changed in initial for asymptotic fouling behavior model but slowly changed for linear fouling behavior model. Therefore, the decrease of heat transfer rate of asymptotic fouling is faster than linear fouling.

4.2.2. The performance of heat exchanger under fouling condition

The performance of heat exchanger were presented in Figure 4.3, 4.5, 4.7 and 4.9 for asymptotic fouling behaviors and in Figure 4.4, 4.6, 4.8 and 4.10 for linear fouling behaviors. The inlet temperatures of the heat exchanger as operation starts, mass flow rate and specific heat capacity of the cold and hot fluids were presented in Table 4.1. Therefore, the other values of parameter such as Z_h, Z_c, $T_{c,out}$,$T_{h,out}$ and Q were computed. The result of simulation of asymptotic fouling behaviors that fouling rate, overall heat transfer coefficient, temperatures of the hot and cold streams are rapidly changed at initial time and then stabilize to equilibrium at final time. On the other hand, fouling rate, overall heat transfer coefficient, temperatures of the hot and cold streams are slowly changed with time for linear fouling behaviors. From Figure 4.3 and Figure 4.4, it was observed that increasing of fouling effect on decreasing of overall heat transfer coefficient that falls from an initial value of 88.1 to 55.65 Btu/hr ft^2 ^oF for both linear and asymptotic fouling behaviors. This result effect to decrease outlet temperature of cold stream about 3.98% as shown in Figure 4.5 and Figure 4.6 and increase outlet temperature of hot stream about 7.92% as shown in Figure 4.7 and Figure 4.8 for both linear and asymptotic fouling behaviors, respectively. The reducing of the overall heat transfer rate effect to reducing of the heat transfer rate about 27.20% as shown in Figure 4.9 and Figure 4.10 for both linear and asymptotic fouling behaviors. In equation 4.1, A and T_{in} in for the cold and hot streams are constant value so heat transfer rate depend on overall heat transfer rate.

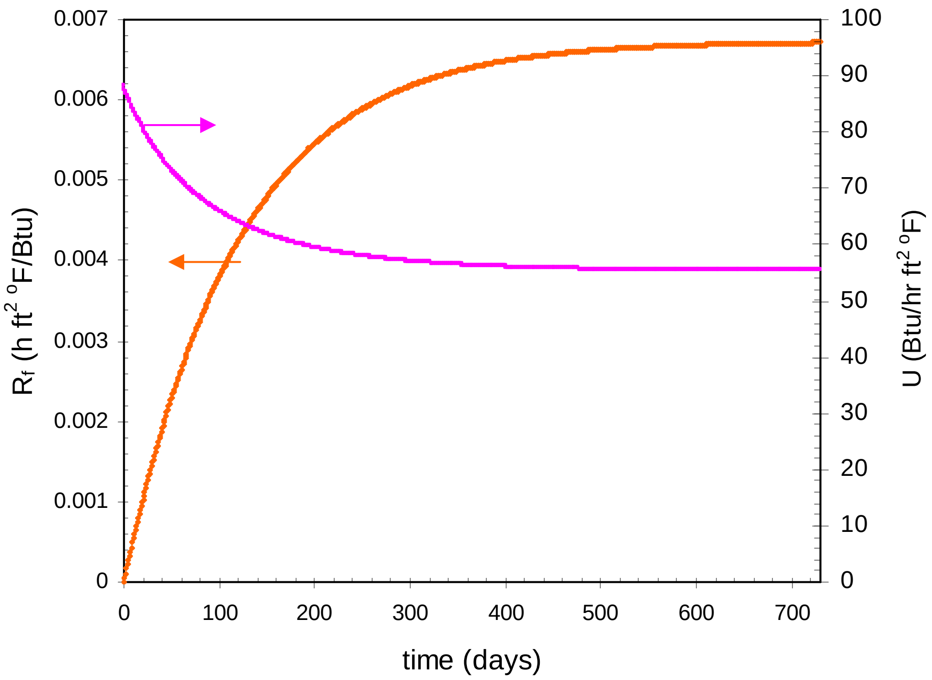


Figure 4.3 The schematic diagram of the fouling rate and overall heat transfer coefficient with time of asymptotic fouling equation.

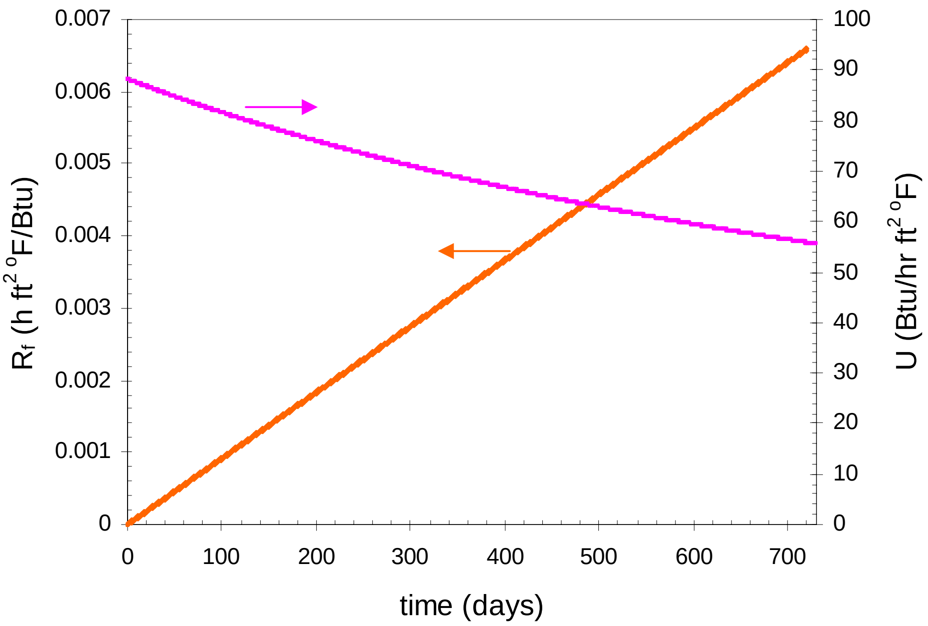


Figure 4.4 The schematic diagram of the fouling rate and overall heat transfer coefficient of single heat exchanger with time of linear fouling equation.

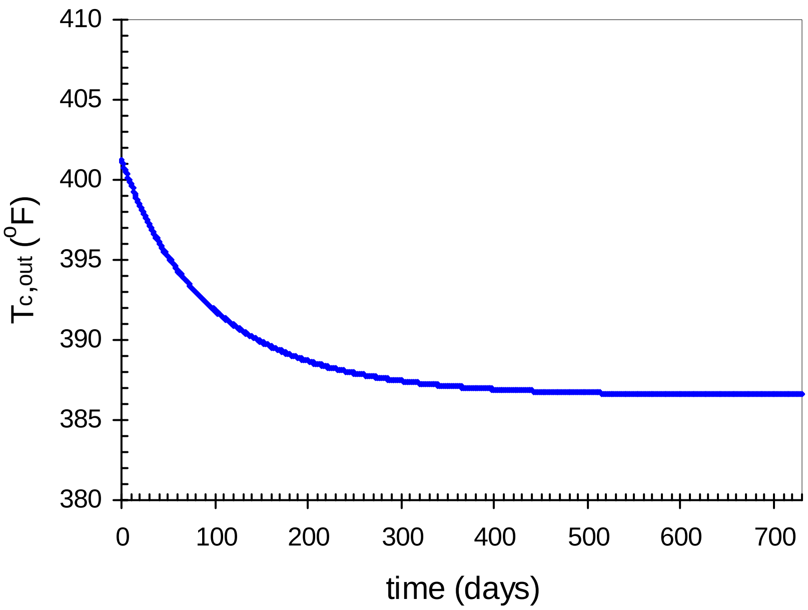


Figure 4.5 The schematic diagram of cold temperature with time of asymptotic fouling equation.

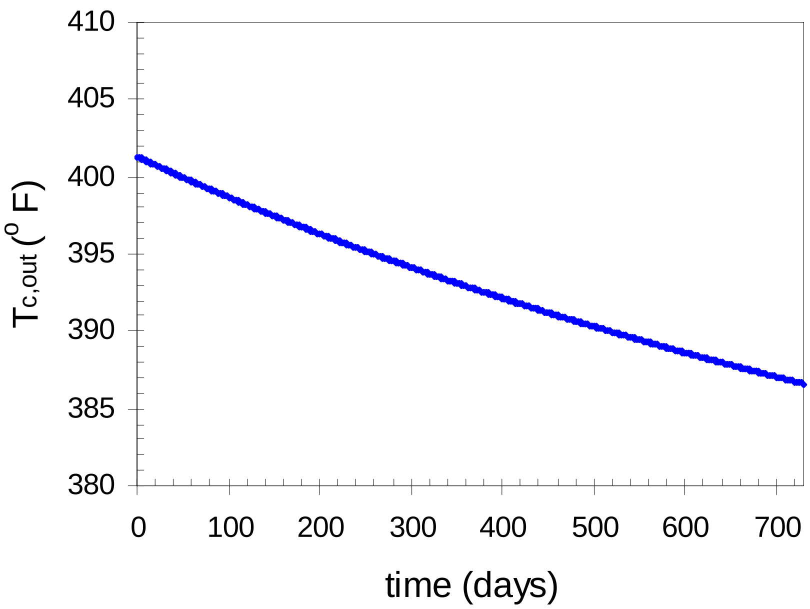


Figure 4.6 The schematic diagram of cold temperature with time of linear fouling equation.

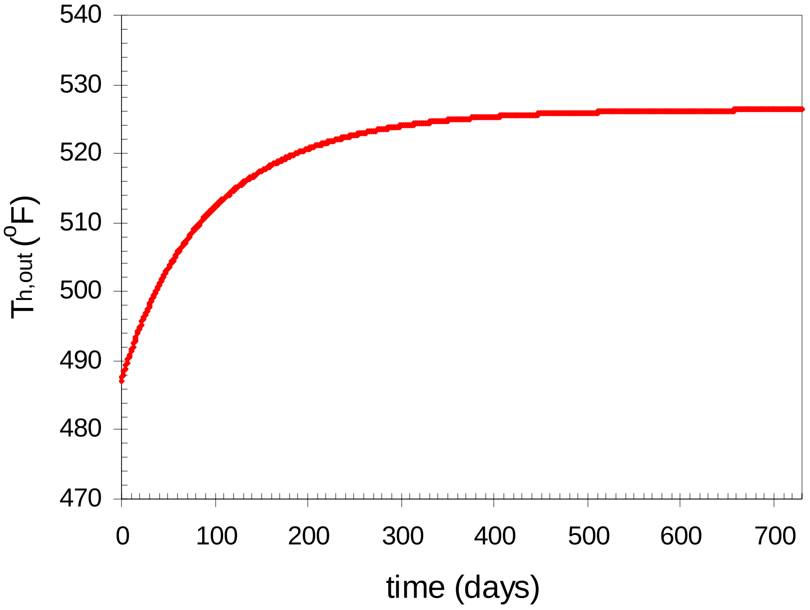


Figure 4.7 The schematic diagram of hot temperature with time of asymptotic fouling equation.

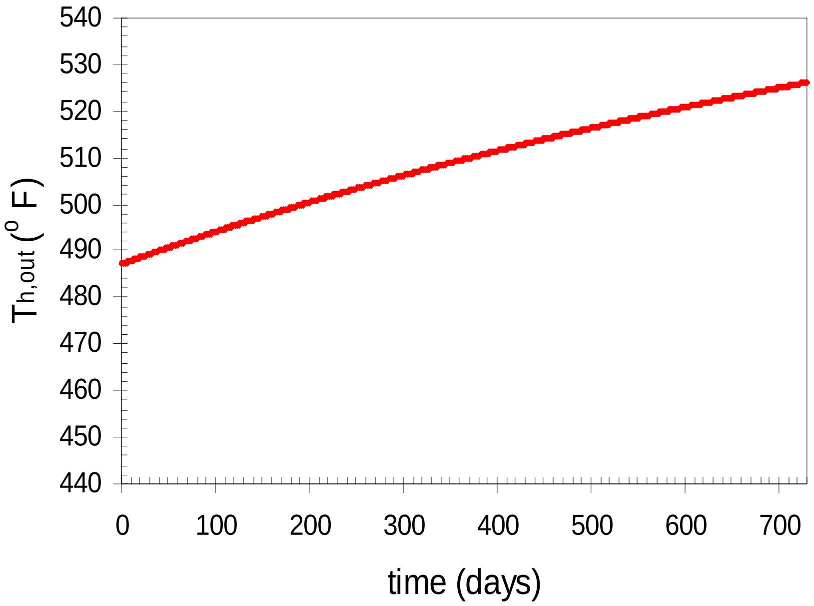


Figure 4.8 The schematic diagram of hot temperature with time of linear fouling equation.

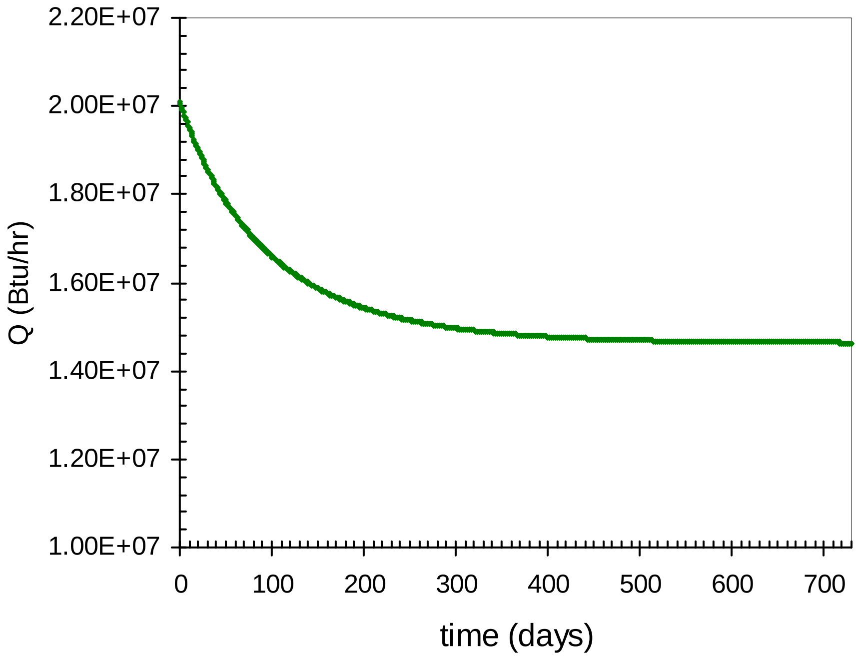


Figure 4.9 The schematic diagram of heat transfer with time of asymptotic fouling equation.

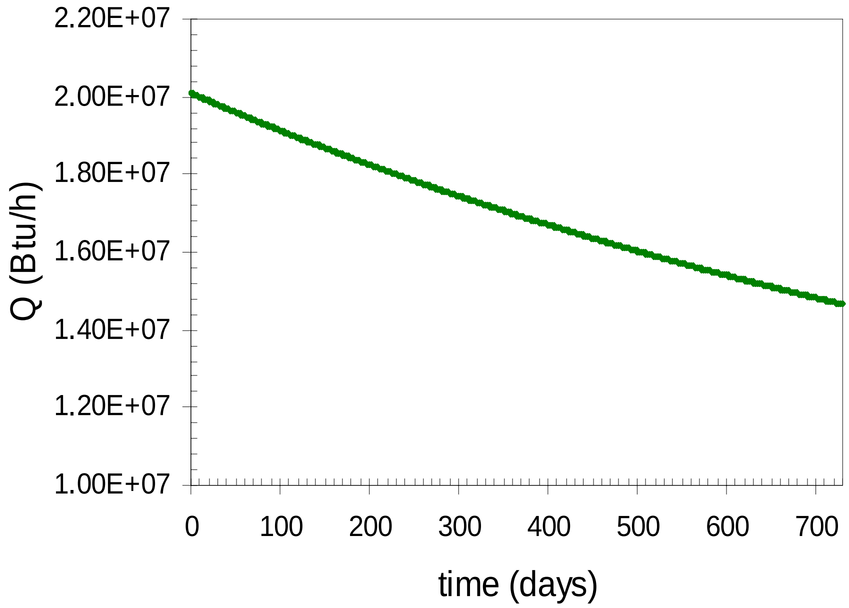


Figure 4.10 The schematic diagram of heat transfer with time of linear fouling equation.

4.2.3. Comparison of performance on heat exchanger of fouling parameter under fouling condition

From previous section (4.2.1 and 4.2.2), we can be seen that the variation of asymptotic fouling model is faster than linear fouling model. Thus, in this section studied the parameter in asymptotic fouling model. This parameter is fouling time constant formation and initial fouling rate which are parameter in asymptotic fouling model. The variations in heat transfer rate versus time for different values of time decay of fouling formation, τ (90, 120 and 210 days), and initial fouling rate, R_f^{∞} (0.00505, 0.00673 and 0.00774 hr ft^2 ^{o}F/Btu) are illustrated in Figure 4.11 to Figure 4.14.

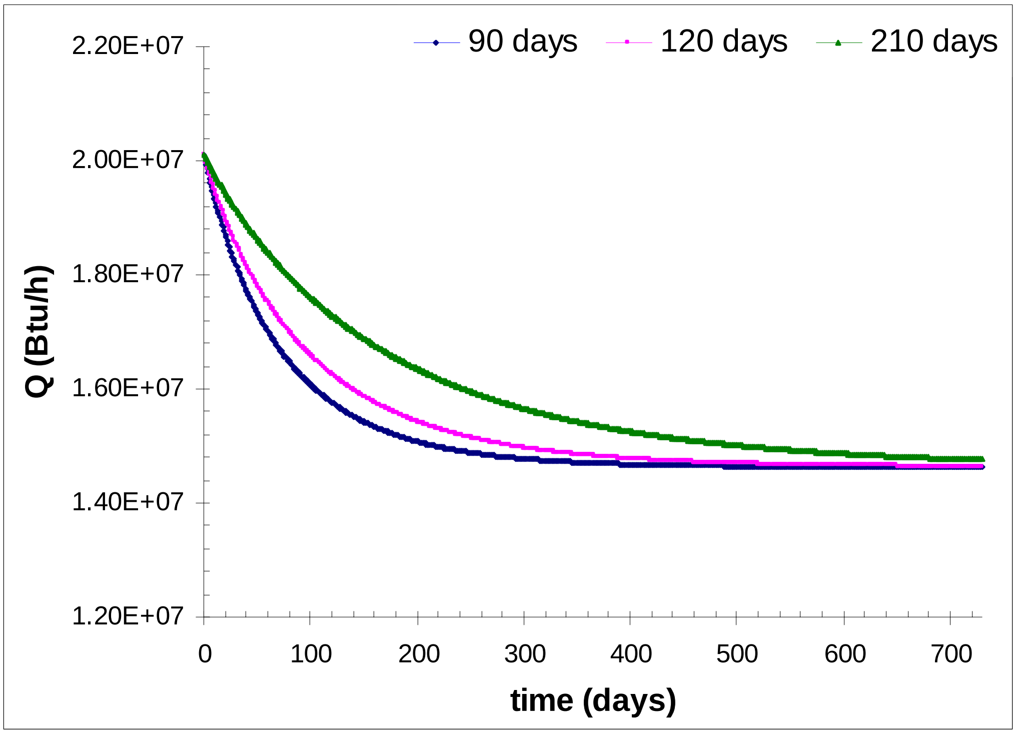


Figure 4.11 The comparison of heat transfer rate profile with time of variation of time decay at area 1257.2 ft^2 and asymptotic fouling0.00673 hft^{2}F/Btu

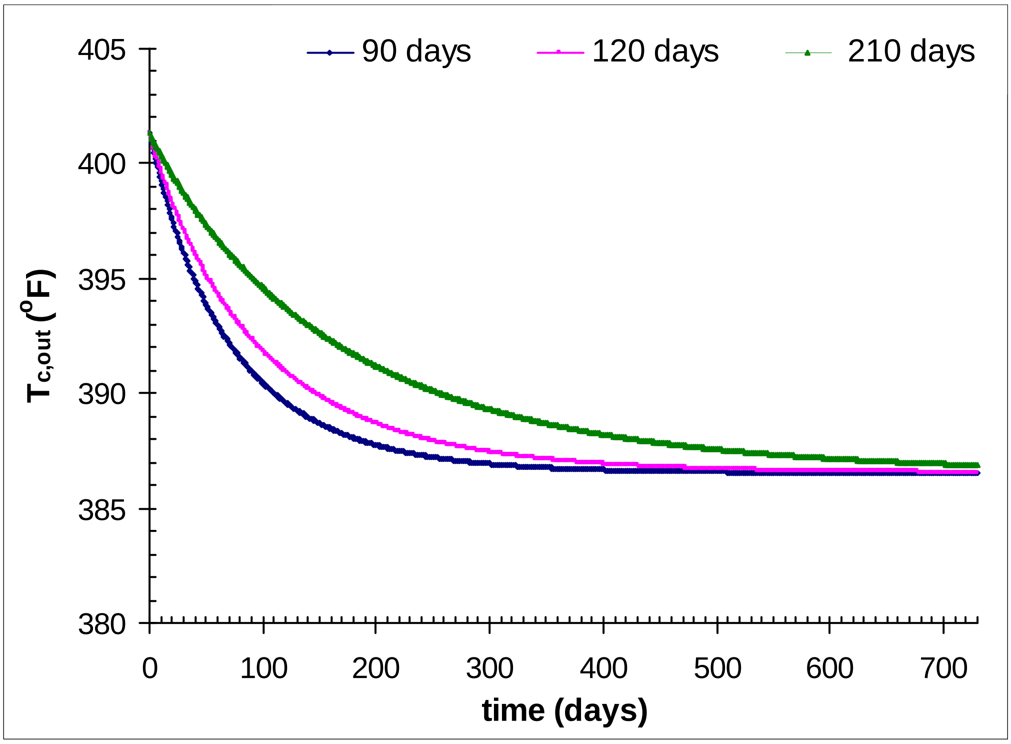


Figure 4.12 The comparison of outlet temperature of cold stream profile with time of variation of time decay at area 1257.2 ft^2 and asymptotic fouling0.00673 hft^2F/Btu

Figure 4.11 and Figure 4.12 have shown the comparison of variation the heat transfer rate and temperature profile of outlet temperature of cold stream with continuous time, respectively. While the fouling time constant formation is increased, heat transfer rate is slowly reduced under fouling formation. In the increasing time decay constant (τ), the value of term $\exp(-t/\tau)$ increases which is causes a reduction in fouling formation, $R_f(t)$, as seen in equation 4.14. This result leads to the increment of the heat transfer rate as seen in equation 4.1. Thus, the different of time decay constant is sensitive to heat transfer rate. Because of slow change of the outlet temperature as shown in Figure 4.12, the fouling on surfaces of heat exchanger are slowly deposited for most the fouling time constant formation value.

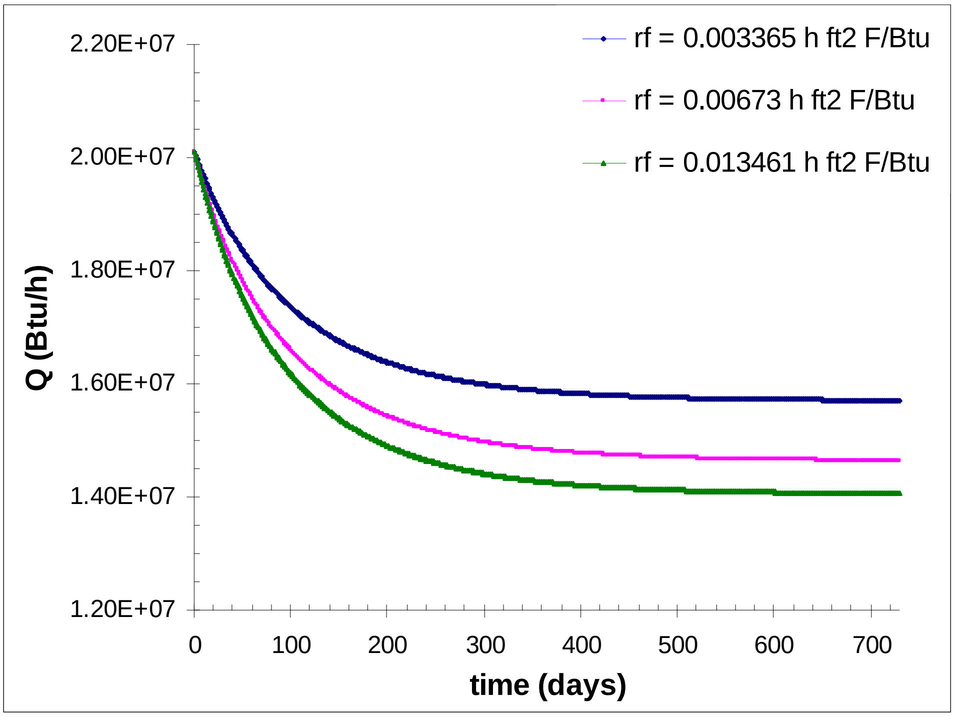


Figure 4.13 The comparison of heat transfer rate profile of initial fouling rate formation at area 1257.2 ft2 and time decay of fouling formation 120 days

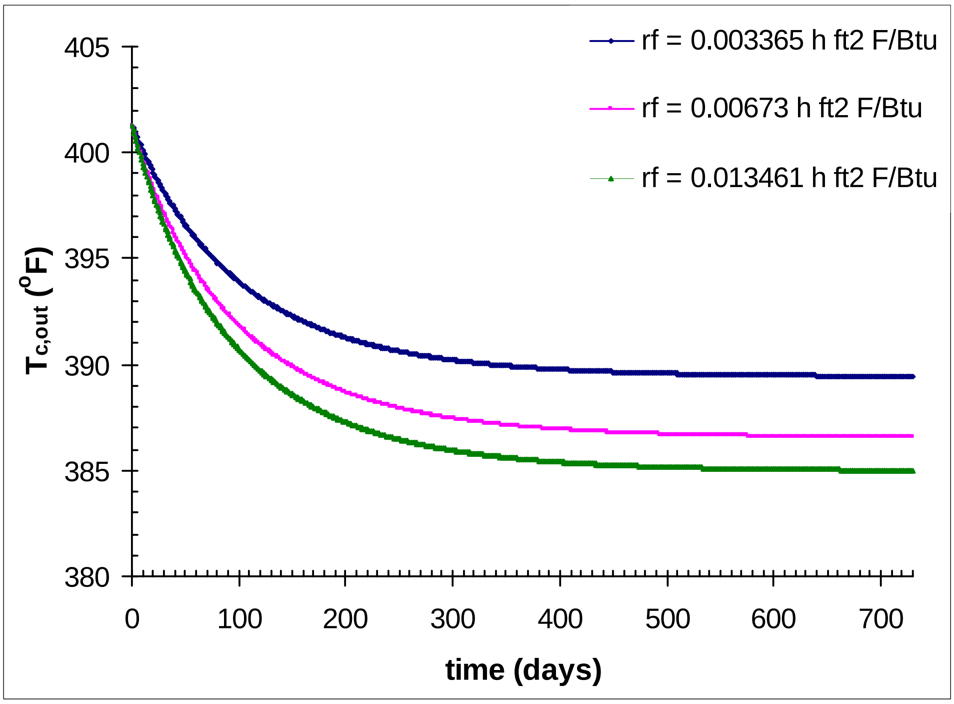


Figure 4.14 The comparison of outlet temperature of cold stream profile of initial fouling rate formation at area 1257.2 ft2 and time decay of fouling formation 120 days

The comparison of variation the heat transfer rate and temperature profile of outlet temperature of cold stream with continuous time as shown in Figure 4.13 and Figure 4.14, respectively. It was observed that increment of initial fouling rate decrease heat transfer rate. Considering equation 4.13, while initial fouling rate ($R_f^{\infty}(t)$) increases with time, it leads to the reduction of the overall heat transfer coefficient and heat transfer rate as seen in Equation 4.11. Which the larger initial fouling rate for asymptotic fouling cases result in a rapid decay in heat transfer rate. Therefore, the different of initial fouling rate is sensitive to heat transfer rate. The variations in heat transfer rate depend on initial fouling rate. These results increase the hot outlet temperature and decrease in the cold outlet temperature.

These results indicate the important of fouling time constant formation and initial fouling rate. The increasing fouling time constant formation (τ), the heat transfer rate increases at a given time, hence improving the effectiveness of the exchanger. Similarly, the decreasing initial fouling rate, the heat exchanger is improved the effectiveness of the exchanger. It has considerable effect on the fouling formation and performance of heat exchanger. Therefore, the optimization cleaning schedule problems require a reliable fouling model for predicting unit perform.

CHAPTER V

OPTIMIZATION OF HEAT EXCHANGER

USING CONTINUOUS TIME

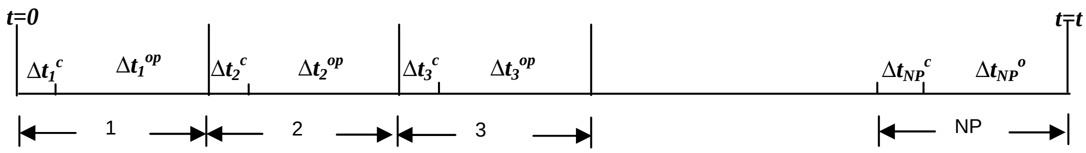
This section considers cleaning schedule of crude oil preheating heat exchanger network as shown in Figure 5.11. This heat exchanger network consists of 10 heat exchanger, which features 3 cold streams and 9 hot streams. The outlet temperature of cold stream after the desalter is decreased 50 ^{o}F. The second stream is crude oil from desalter to flash. The third ones is the crude oil after flash that sent to distillation process. The temperature change across the flash is negligible. In this chapter, the studies were divided into two sections: the optimization of cleaning schedule of single heat exchanger and the optimization of cleaning schedule of heat exchanger network. In both first section and second section of study, the optimizations have been formulated by using continuous time approach. This formulation was to determine time period between each cleaning operation of heat exchanger. The objective function of this problem is the minimization of total operation cost. The formulated optimization problem of heat exchanger cleaning was discussed below.

5.1 Problem formulation of scheduling formulations

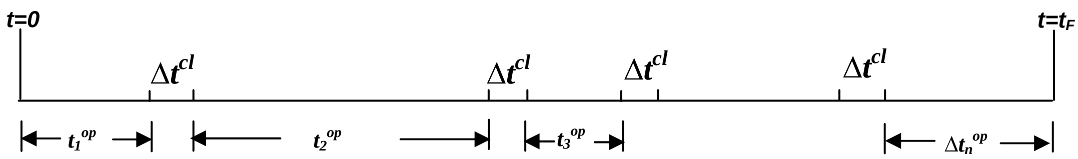
The key issue for process scheduling problems concerns the time representation. All existing scheduling formulations can be classified into two main categories: discrete-time approaches and continuous time approaches (Christodoulos A., and Xiaoxia L in 2004). In this section, the continuous time approaches of heat exchanger scheduling formulations are explained by comparison with discrete time approaches of both single heat exchanger and heat exchanger network.

5.1.1 Single heat exchanger formulation

The discrete time approaches, the time horizon is divided into a number of time intervals of uniform durations and events such as the beginning and ending of a task are associated with the boundaries of these time intervals. Because of the continuous nature of time and the concept of discretization, the discrete time formulations are just approximations of the actual problem. For discrete time approaches of heat exchanger cleaning schedule problems, the time horizon (t_F) of interest is divided into a number of periods (NP) of uniform durations, the length interval $\Delta t = t_F/NP$. 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. 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 concept of the discrete time approach is illustrated in Figure 5.1(a) for single heat exchanger and Figure 5.2(b) for heat exchanger network.



(a) Discrete time representation



(b) Continuous time representation

Figure 5.1 Discrete and continuous representations of time for single heat exchanger.

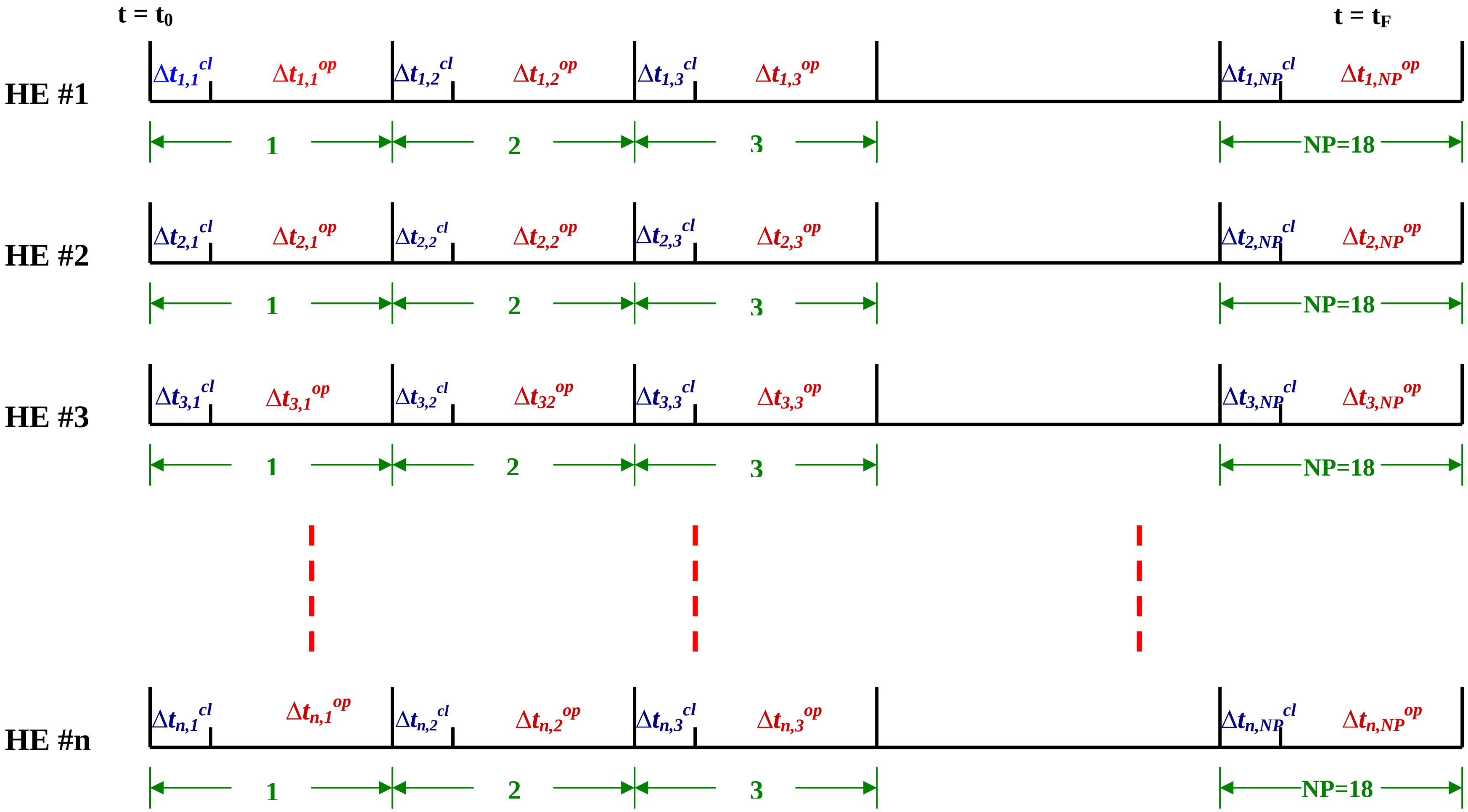
In this work, the continuous time approach is used to formulation of optimization cleaning time schedule. In these models, events are potentially allowed to take place at any point in the continuous domain of time. Modeling of this flexibility is accomplished by introducing the concepts of variable event times, which can be defined globally or for each unit. Variables are required to determine the timings of events. The idea of the continuous time approach is also illustrated in Figure 5.1(b) for single heat exchanger. The time for each cleaning operation is determined in this work. The cleaning time is equal to cleaning subperiod (Δt^{cl}) in discrete time approach. The approach in this work, the number of cleaning operation is predicted priority, and the time period for each cleaning operation is then determined. The continuous time approach of single heat exchanger repeats until the stopping criteria are satisfied. The stopping criterion is occurrence of violates constraints and minimum overall operating cost.

5.1.2 Heat exchanger network formulation

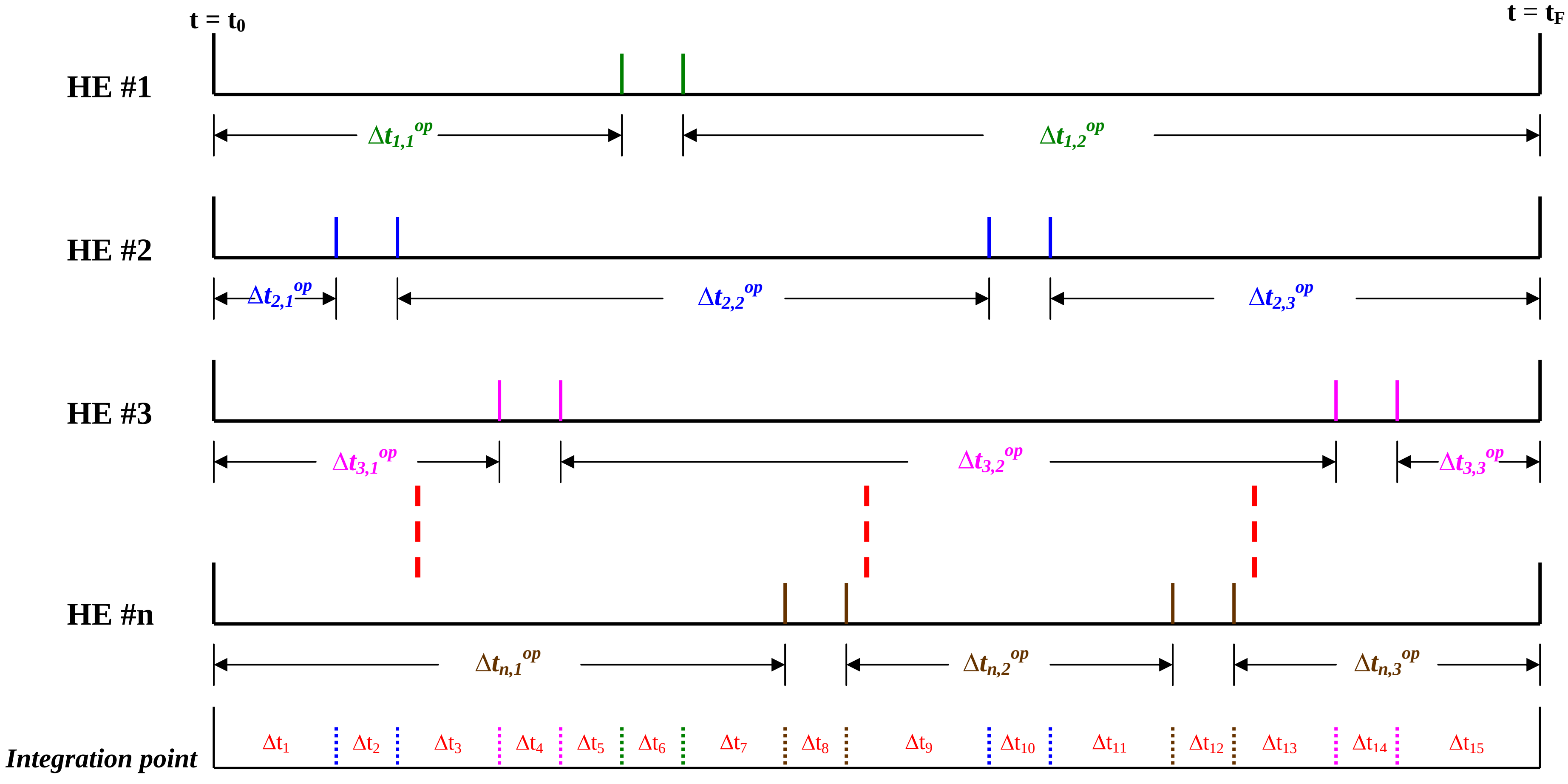
Similarly, for formulation of optimization cleaning time schedule for heat exchanger network, the time horizon (t_F) of the discrete time approach of interest is divided into a number of periods (NP) of uniform durations, the length interval $\Delta t = t_F/NP$. Time periods are divided into two subperiods as same single heat exchanger. This approach can be grids of equal each unit as seen in Figure 5.2(a). Therefore, the discrete time approach can be immediately computation. However, the continuous time approach can not be immediately computation because grids of each unit are not equal as seen in Figure 5.2(b). Such as, while cleaning of unit 8 is occurred, unit 1 cans not computation in this period of cleaning. On account of unit 1 is connected to unit 8, etc. Therefore, the integration points are determined after the number of cleaning operation is predicted. The integration points in Figure 5.2 (b) are dotted line for each unit.

Then, the fouling resistance, $R_f(t)$, heat transfer coefficient, U(t), outlet temperature of cold and hot streams, $T_{c,out}(t)$ and $T_{h,out}(t)$ and loss of heat transfer rate, ΔQ and objective function is calculated in each interval of integration point(Δt_n).

After that, if violate constraints are occurred and overall operating cost is not yet minimum, which are stopping criteria, the prediction of number of cleaning operation will be repeated. Finally, the continuous time approach repeats until the stopping criteria are satisfied. The flow chart of the continuous time approach is shown in Figure 5.3.



(a) Discrete time representation



(b) Continuous time representation

Figure 5.2 Discrete and continuous representations of time for heat exchanger network.

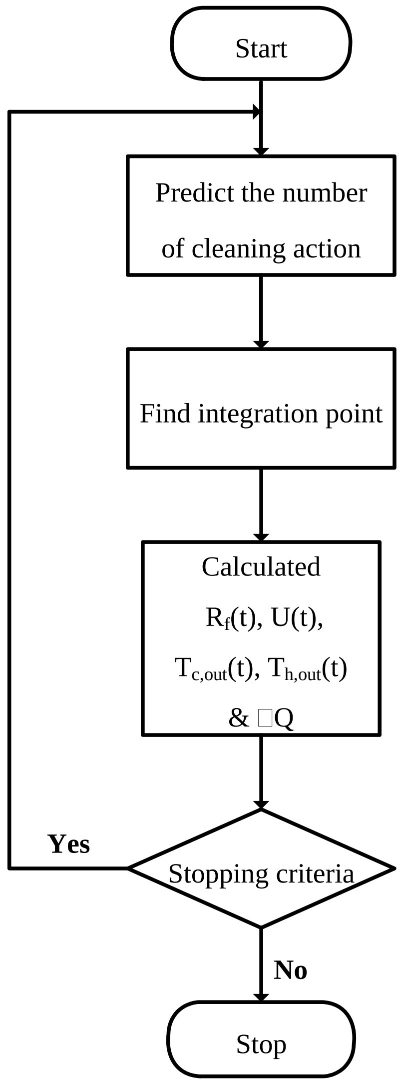


Figure 5.3 The flowchart of continuous time approach

5.1.3 The objective function

The purpose of finding the optimum heat exchanger network cleaning is to minimize the network operating costs (objective function) in a specific duration. Therefore, a function of total operating cost of the network due to fouling formation during the whole duration of operation. The model refers to the tradeoff between furnace extra fuel costs due to fouling and heat exchanger cleaning costs (Smaili et. al, 2001). The form of the objective function considered in all case of this work is based on

$$Min._{\cos t} = \int_0^{t_F} (C_E \theta(t)_n)dt + \sum_j^{N_c} C_{c,j} \tag{5.1}$$

or

$$Min._{\cos t} = \int_0^{t_F} (C_E [Q_{clean,n} - Q(t)_n])dt + \sum_j^{N_c} C_{c,j} \tag{5.2}$$

where

t_f	The time duration between system. The final time of 730 days and 540 days were considered for analysis of the case studies in this research. (days)
C_E	the cost of extra energy required due to fouling(£ hr days Btu^{-1})
θ(t)	loss in heat transfer rate due to fouling (Btu/hr)
C_c	the cost of heat exchanger cleaning (£/unit)
Q_{clean}	the heat transfer rate between hot and cold fluids in unit n in clean condition (Btu/hr)
Q(t)	the heat transfer rate between hot and cold fluids in unit *n* at period *p* with fouling (Btu/hr)
N_c	the number of cleaning events during t = 0 to t_f

5.1.4 Constraints

Constraints that are applied so as to reduce the solution space as well as the amount of computations for finding the optimal cleaning time by minimizing equation (5.2). The following constraints were applied:

- The outlet cold temperature of each heat exchanger must be greater than or equal than the inlet cold one:

$$T_{c,out} \geq T_{c,in} \tag{5.3}$$

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

$$T_{h,out} \leq T_{h,in} \tag{5.4}$$

- The total of time cleaning must smaller than final time:

$$t_f \leq \sum_{j}^{N_c} t_{cl,j} \tag{5.5}$$

where

t_f final time (days)

t_{cl} time of cleaning of each times

Subscripts j stands for the dependency of number of cleaning.

5.2 Optimization of single heat exchanger cleaning

In this section studied three cases: first one focuses on the influence of linear fouling model and asymptotic fouling model on optimal cleaning schedule whereas the second one deals with the influence of initial fouling. Finally, focuses on the influence of time decay of fouling formation. In this section consider the heat exchanger number 10 in figure 5.11. The operating time is 730 days. Duration of cleaning of heat exchanger unit was shown in figure 5.4 which time of cleaning is 6 day cleaning. The parameters for optimization of single heat exchanger case are shown in Table 5.1.

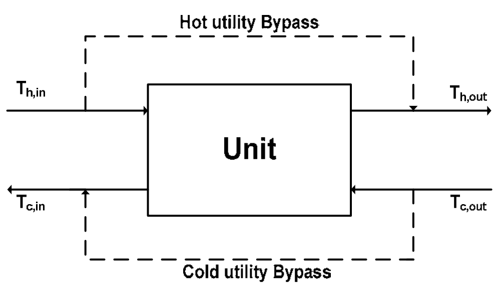


Figure 5.4 Schematic of heat exchanger unit showing bypasses for isolation during cleaning. Solid line: cold and hot temperature; dotted line: hot and cold utility bypass

Table 5.1 Data for the Single-Heat exchanger Case

Parameter	Value
$T_{h,in}$ (^oF)	631.4
$T_{c,in}$(^oF)	347
F_h (lb/hr)	207940
F_c (lb/hr)	649217
$C_{p,h}$ (Btu/lb ^oF)	0.65
$C_{p,c}$ (Btu/lb ^oF)	0.57
A (ft^2)	1257.2
U_{clean} (Btu/hr ft^2 ^oF)	88.1
R_f^{∞} (hr ft^2 ^oF/ Btu)	6.73×10^{-3}
r (linear) (ft^2 °F/Btu)	2.9×10^{-4}
t (days)	120

5.2.1 The influences of fouling model

The overall heat transfer coefficient is decreased by the fouling deposition on the surfaces of heat exchanger which effect on the reduction of heat exchanger performance. Therefore, the effect of fouling behaviors on heat exchanger is important. Different fouling models can be obtained from experimental laboratory, online monitoring and data reconciliation. Linear fouling behavior and asymptotic fouling behavior are studied in this work. The results of the outlet temperature profile of cold stream of both linear fouling behavior and asymptotic fouling behavior were shown in Figure 5.5 to Figure 5.6.

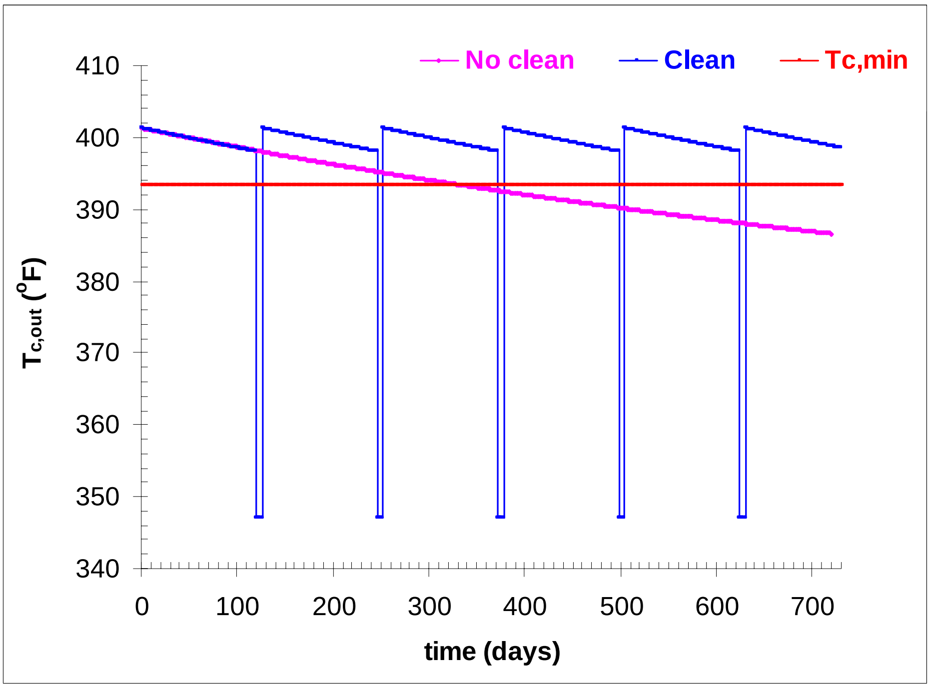


Figure 5.5 The variation of outlet temperature of cold stream for linear fouling with time. Blue line: clean case; Pink line: unclean case.

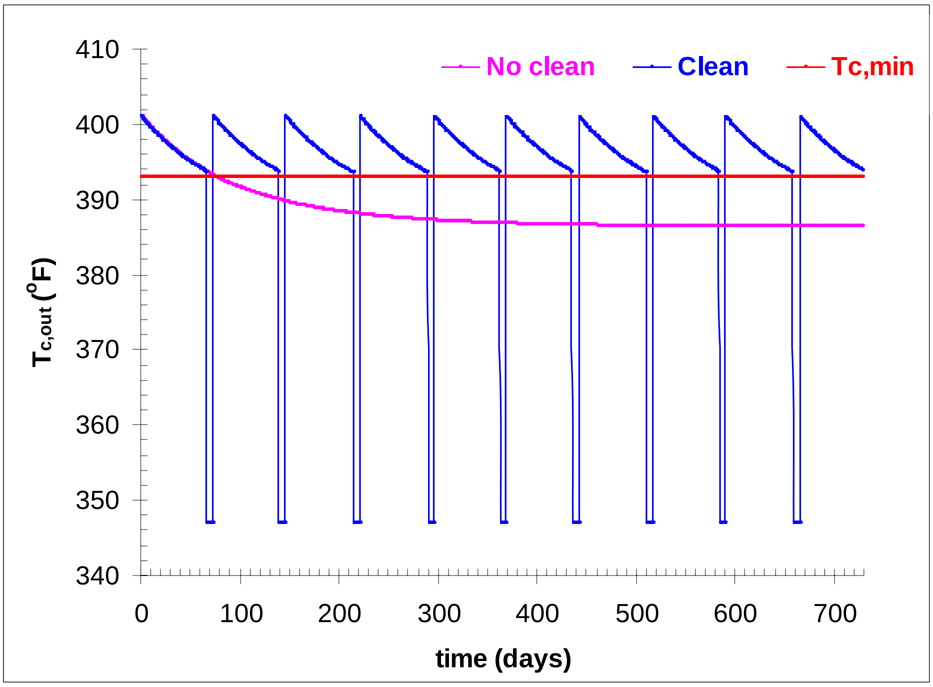


Figure 5.6 The variation of outlet temperature of cold stream for asymptotic fouling

The outlet temperature of cold stream profiles for linear fouling and asymptotic fouling are shown in Figure 5.5 and Figure 5.6, respectively. These figures show no cleaning condition, cleaning condition and minimum temperature. In linear fouling case, while the numbers of cleaning events are predicted 5 times, the result obtained minimum operating cost. Similarly, while the numbers of cleaning events are predicted 9 cleaning events for asymptotic fouling, the violate constraint is not first occurred. These results can be obtained minimum operating cost which is the best objective function. These results were observed that the outlet temperature of cold stream reaches down to minimum temperature ($T_{c,min}$) constraints which it should be cleaned immediately. However, the outlet temperature of cold stream fouling case don't reaches down to minimum temperature ($T_{c,min}$) constraints. Thus, the cleaning event of linear fouling case is occurred in order to can be obtained minimum operating cost (Figure 5.5). Therefore 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.

Table 5.2 the optimal cleaning time schedule with different of fouling model

fouling formation	**days of cleaning action (days)**									**Times**	**Operating cost**
	# 1	**# 2**	**# 3**	**# 4**	**# 5**	**# 6**	**# 7**	**# 8**	**# 9**		
Linear fouling	110	246	365	489	610	-	-	-	-	5	47,596
Asymptotic fouling	69	144	219	294	369	444	519	594	669	9	132,063

Table 5.2 presents the optimal cleaning time schedule of single heat exchanger in 730 days of linear fouling and asymptotic fouling model. It can be seen that operating time of asymptotic fouling is shorter time than linear fouling. The operating times of linear fouling case are 110 days and 69 days for asymptotic fouling case, respectively. Similarly, the number of cleaning action of asymptotic fouling case is more than linear fouling case. For no cleaning condition case, the reduction of outlet temperature of cold stream for asymptotic fouling is more rapid than linear fouling owing to the larger initial fouling rate. This result was observed that it reach down to minimum temperature constraint which should be cleaned before linear fouling case. Therefore, asymptotic fouling case is more cleaning action (9 as compared to 5)

required and operating time is short. From Figure 5.5 to Figure 5.6 and Table 5.2 shows that no cleaning occurs in the initial day of operating. This is due to the fact that the fouling is starting accumulating in initial time.

The result of cost saving were presented for linear fouling and asymptotic fouling, in comparison with the base case which is no cleaning condition case. The cost saving are computed by equation 5.6.

$$Saving = \frac{Cost(Uncleaned) - Cost(cleaned)}{Cost(Uncleaned)} x100 \qquad (5.6)$$

The minimum cost of linear fouling case is 47,596£ show in Table 5.3(a) and 132,063£ show in Table 5.3(b) for asymptotic fouling case. The cost saving are 76.9% and 58.99% for linear fouling case and asymptotic fouling case, respectively. When number of cleaning action are increased, the minimize cost is reduced which can be seen in asymptotic fouling. Because of decreasingly minimize cost, the loss in heat transfer rate due to fouling (Equation 5.1) in first term is decreased. From table 5.3 were observed that the results obtained from optimization of single heat exchanger in this technique have lower operating cost than the results obtained using the discrete time approach and Smaili's work, which using the discrete time approach. The discretization is too coarse for time interval. On the other hand, the time of this approach is considered at any point in the continuous domain of time. Therefore, the number of cleaning actions and total operating cost of this technique are less than discrete time approach.

Table 5.3 Summary the total cost saving in comparison with the no cleaning

(a) linear fouling

Cleaning cost (£)	**Linear fouling**								
	Smaili's work			**Discrete time**			**This work**		
	£	**% saving**	**# cleans**	**£**	**% saving**	**# cleans**	**£**	**% saving**	**# cleans**
No cleaned	206,000	-	-	206,000	-	-	206,000	-	-
Cleaning	81,547	60.4	4	59,834	70.9	7	47,596	76.9	5

(b) asymptotic fouling

Cleaning cost (£)	Asymptotic fouling								
	Smaili's work			Discrete time			This work		
	£	% saving	# cleans	£	% saving	# cleans	£	% saving	# cleans
No cleaned	322,000	-	-	322,000	-	-	322,000	-	-
Cleaning	178,066	44.7	11	176,912	45.06	11	132,063	58.99	9

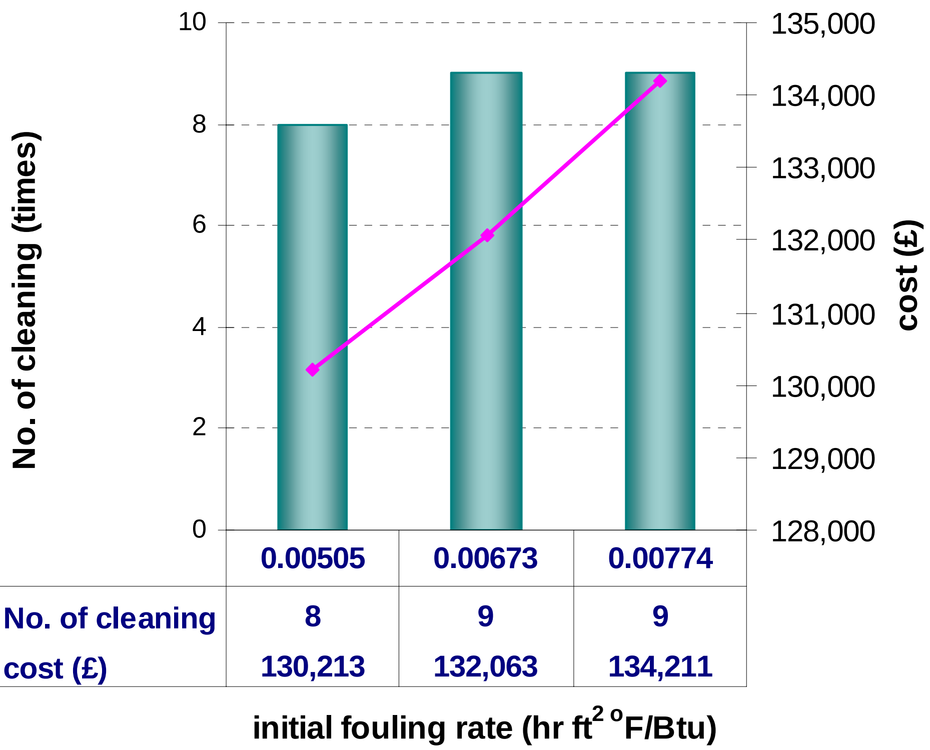
5.2.2 The influence of initial fouling

The simulation of the variation of outlet temperature of cold stream under initial fouling is presented in previous section (Chapter IV). It is observed that the larger initial fouling rate for asymptotic fouling case is result in a rapid decay in heat transfer rate. Therefore, asymptotic fouling model was used in order to studies the influence of initial fouling. This section studied three value of initial fouling: 0.00505 hr ft^2°F/Btu, 0.00673 hr ft^2°F/Btu and 0.00774 hr ft^2°F/Btu. The result of comparison between number of cleaning action and minimize operating cost is shown in Table 5.4 and Figure 5.7.

Table 5.4 Optimal cleaning time with different of initial fouling rate in single heat exchanger.

r (hrft^2°F/Btu)	days of cleaning action (days)									No. of cleaning	cost (£)
	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9		
0.00505	76	158	240	322	404	486	568	650	-	8	130,213
0.00673	69	144	219	294	369	444	519	594	669	9	132,063
0.00774	67	140	213	286	359	432	505	578	651	9	134,211

From Table 5.4, it was observed that the operating cost are 130,213£ and the number of cleaning are 8 times in 0.00505 hr ft^2°F/Btu of initial fouling rate. For 0.00673 hr ft^2°F/Btu of initial fouling rate, the operating cost are 132,063£ and the number of cleaning are 9 times. Lastly of initial fouling rate is 0.00774 hr ft^2°F/Btu, the operating cost are 134,211£ and the number of cleaning are 9 times. The increment in initial fouling rate value is resulting in the decreasing of heat transfer rate. The larger of initial fouling rate is the rapid change in heat transfer rate. Furthermore, the outlet temperature of cold stream is rapid changed in large initial fouling rate which fast reach to minimum temperature as seen in Figure 5.8. Thus, the large initial fouling rate is also resulting in number of cleaning events which more than small initial fouling. Similarly, the operating cost of large initial fouling rate is more than small initial fouling rate. Because large initial fouling rate of loss in heat transfer rate due to fouling, which is main factor of objective function, is more than small initial fouling rate. Therefore, the operating cost is increased when initial fouling rate is increased.



	0.00505	0.00673	0.00774
No. of cleaning	8	9	9
cost (£)	130,213	132,063	134,211

Figure 5.7 The comparison of number of cleaning and operating cost in different initial fouling rate

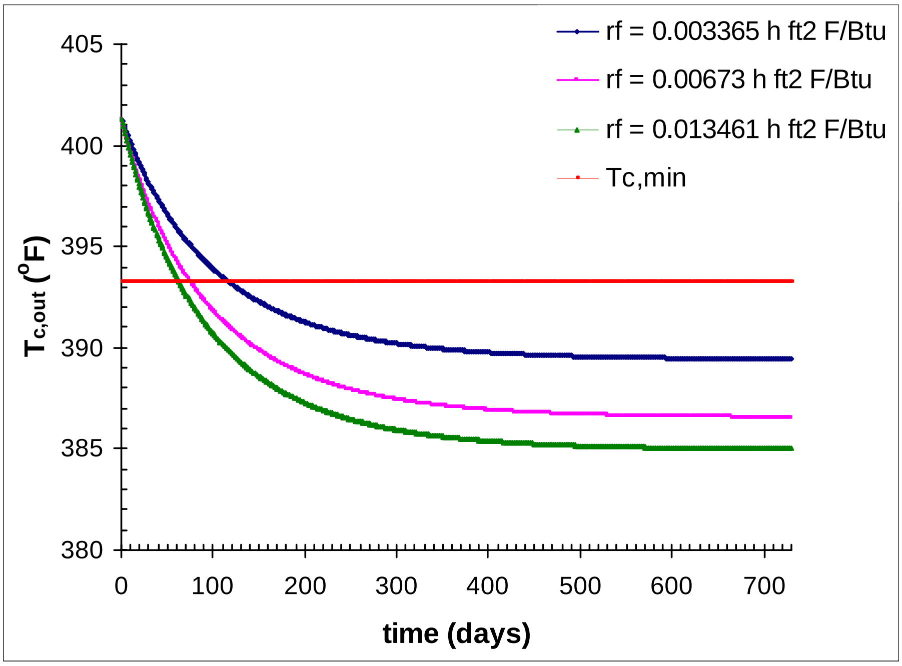


Figure 5.8 The comparison of outlet temperature of cold stream profile with time of variation of initial fouling rate formation and minimum temperature.

5.2.3 The influence of time decay of fouling formation (τ)

Reduction of the time decay of fouling formation increase heat transfer rate. The simulation of the variation of outlet temperature of cold stream under time decay of fouling formation can be seen in previous section (Chapter IV). It was observed that the larger time decay for asymptotic fouling case result in a slowly decay heat transfer rate. Therefore, asymptotic fouling model was also used in order to studies the influence of time decay of fouling formation. This section studied three value of time decay of fouling formation: 90 days, 120 days and 210 days. The result of comparison between number of cleaning action and minimize operating cost were shown in Table 5.5 and Figure 5.9.

Table 5.5 Optimal cleaning time with different of time decay of fouling formation in single heat exchanger.

time (days)	**days of cleaning action (days)**											**# cleans**	**£**
	# 1	**# 2**	**# 3**	**# 4**	**# 5**	**# 6**	**# 7**	**# 8**	**# 9**	**# 10**	**# 11**		
90	59	124	189	254	319	384	449	514	579	644	709	11	151,792
120	69	144	219	294	369	444	519	594	669	-	-	9	132,063
210	99	204	309	414	519	624	-	-	-	-	-	6	122,281

From Table 5.5, it was observed that the operating cost are 151,792£ and the number of cleaning are 11 times in 90 days of time decay of fouling formation. For 120 days of time decay of fouling formation, the operating cost are 132,063£ and the number of cleaning are 9 times. Lastly of initial fouling rate is 210 days, the operating cost are 122,281£, and the number of cleaning are 6 times. These results were observed that the number of cleaning events is reduced when time decay of fouling formation is increased. On account of the increment in time decay of fouling formation is resulting in the decreasing in heat transfer rate. The large time decay of fouling formation provides less fouling value. Therefore, the increment of time decay of fouling formation is resulting of reducing on formation of deposits. The large time decay of fouling formation is resulting slowly reduction of the outlet temperature of cold stream as seen in Figure 5.10. Thus, the outlet temperature of cold stream is slowly changed to target temperature of cold stream. As a result, The number of cleaning events of large time decay of fouling formation is less than small time decay of fouling formation and the first day of cleaning events of large time decay of fouling formation is slower than small time decay of fouling formation.

Similarly, the operating cost of large time decay of fouling formation is less than small time decay of fouling formation. On account of large time decay of fouling formation is resulting increment of loss in heat transfer rate due to fouling, which is main factor of objective function. Therefore, the operating cost is reduced when initial fouling rate is increased.

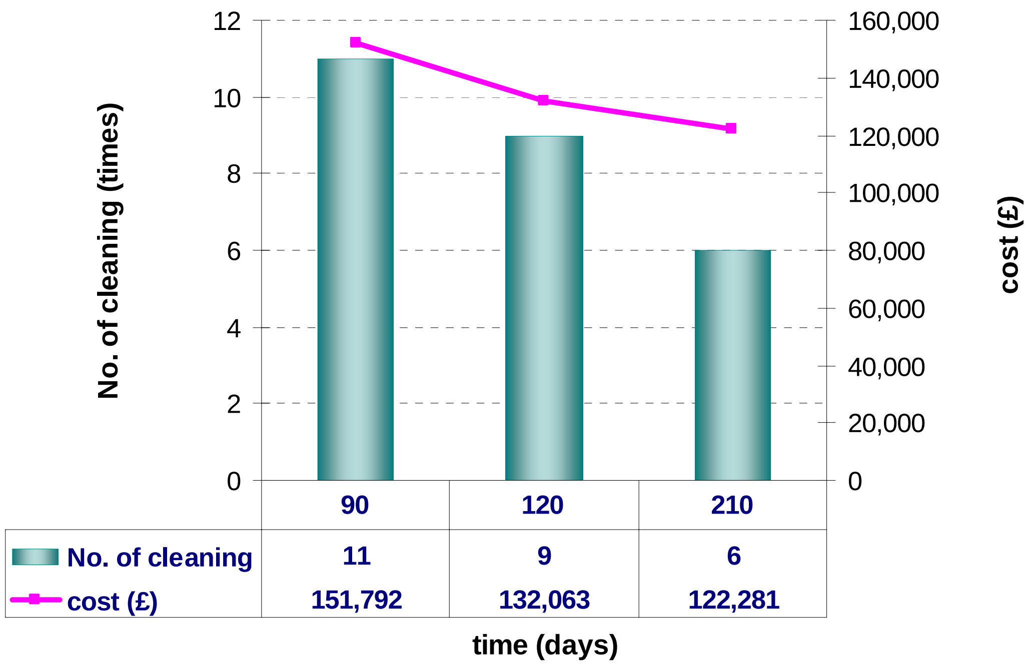


Figure 5.9 The comparison of number of cleaning and operating cost in different time decay of fouling formation.

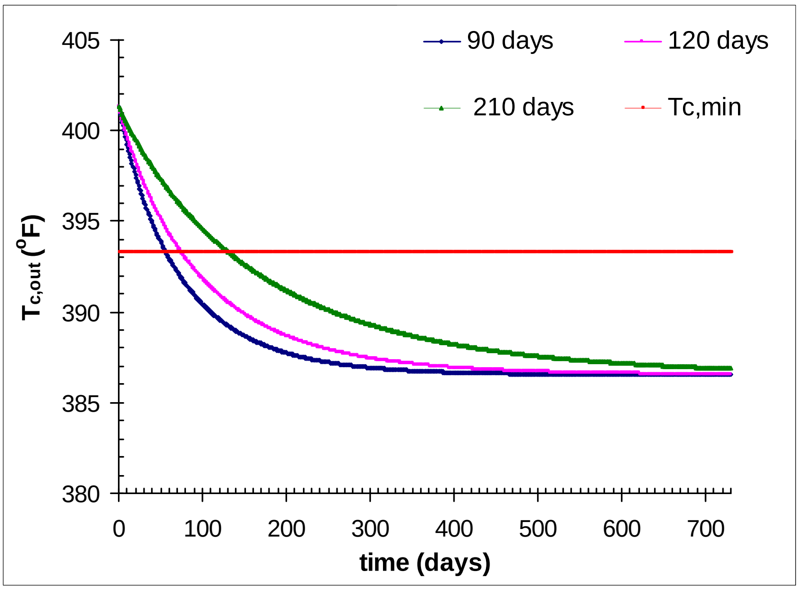


Figure 5.10 The comparison of outlet temperature of cold stream profile with time of variation of time decay and minimum temperature.

5.3 Optimization of heat exchanger network cleaning

This section considers scheduling in heat exchanger network based on a crude oil preheating unit. Figure 5.11 present the layout of 10-exchanger network. In this heat exchanger network, there are 3 cold streams and 6 hot streams. The cold streams are the crude stream from storage tank, after the desalter and flash. The temperatures of the cold streams at the desalter are decreased 50 °F. The temperature change across the flash is taken to be negligible. Each heat exchanger is subject to fouling and may be cleaned if required. The parameters of this heat exchanger network are shown in Table 5.6. In this work, we considered the effects of fouling model on optimal cleaning time. The operating times are 540 days.

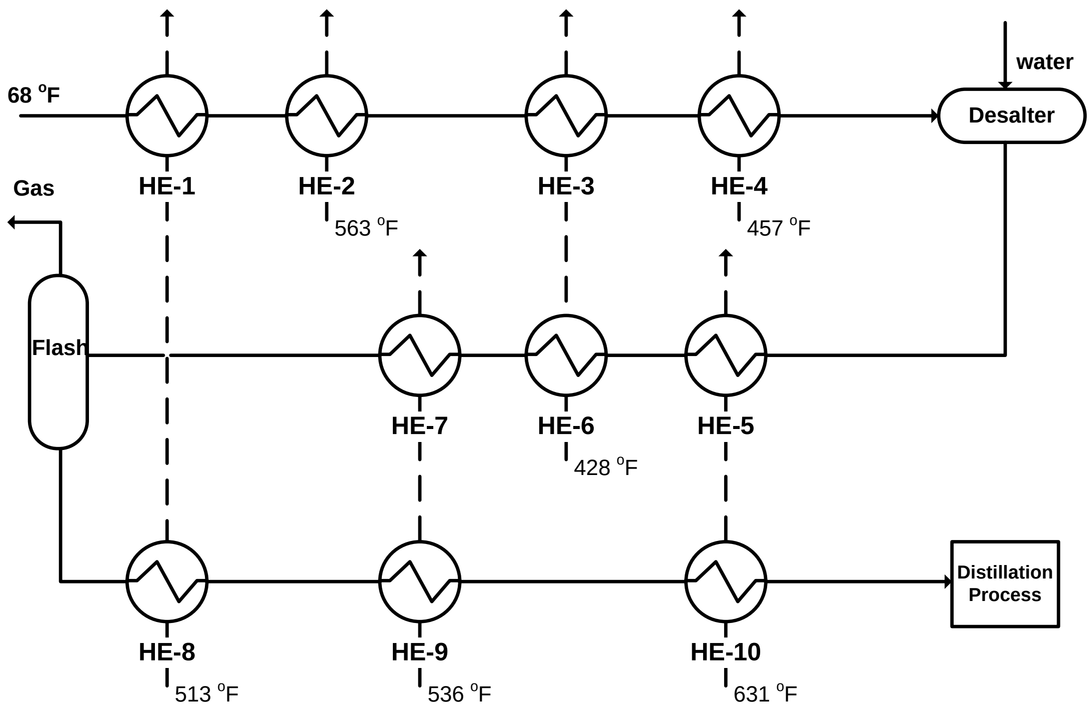


Figure 5.11 The schematic diagram of heat exchanger network. Solid lines: cold streams; dotted lines: hot streams.

Table 5.6 Data for the heat exchanger network case

Heat exchanger	**$T_{h,in}$ (°F)**	**$T_{c,in}$ (°F)**	**F_h (lb/hr)**	**F_c (lb/hr)**	**$C_{p,h}$ (Btu/lb °F)**	**$C_{p,c}$ (Btu/lb °F)**	**U_{clean} (Btu/hr ft^2 °F)**	**A (ft^2)**	**R_f^{∞} (hr ft^2 °F/ Btu)**	**R (linear) (hr ft^2 °F/ Btu)**
1	442	68	141272	721441	0.67	0.46	88.1	465	1.61E-03	1.23E-04
2	563		73811	721441	0.7	0.46	88.1	287.4	2.41E-03	1.84E-04
3	401		423023	721441	0.62	0.46	88.1	1192	1.61E-03	1.23E-04
4	457		428579	721441	0.62	0.46	88.1	1488	2.14E-03	1.64E-04
5	487		207940	721441	0.67	0.55	88.1	183	4.02E-03	3.07E-04
6	428		423023	721441	0.62	0.55	88.1	545.7	2.95E-03	2.25E-04
7	466		210321	721441	0.69	0.55	88.1	491.9	4.02E-03	3.07E-04
8	513		141272	649217	0.67	0.57	88.1	437	4.29E-03	3.27E-04
9	536		282544	649217	0.69	0.57	88.1	884.8	4.82E-03	3.68E-04
10	631		207940	649217	0.67	0.57	88.1	1257	5.09E-03	3.88E-04

In this studied, we considered the effect of fouling model: linear fouling and asymptotic fouling, on no minimum temperature. Table 5.7 and Table 5.8 present the optimal cleaning time schedule of heat exchanger network for linear fouling and asymptotic fouling, respectively. Figure 5.12 and Figure 5.14 have shown Gantt chart for optimal cleaning heat exchanger network of linear fouling and asymptotic fouling. Figure 5.13 and Figure 5.15 have shown outlet temperature of cold stream profile of linear fouling and asymptotic fouling, respectively. In addition, the optimal results are summarized in Table 5.9.

Table 5.7 Optimal cleaning time schedule of heat exchanger network on linear fouling

unit	**days of cleaning action (days)**				**times**
	# 1	**# 2**	**# 3**	**# 4**	
1	-	-	-	-	0
2	251	-	-	-	1
3	281	-	-	-	1
4	275	-	-	-	1
5	262	-	-	-	1
6	180	365	-	-	2
7	257	-	-	-	1
8	174	359	-	-	2
9	131	269	405	-	3
10	101	210	319	429	4
total					16

Table 5.8 Optimal cleaning time schedule of heat exchanger network on asymptotic fouling

unit	**days of cleaning action (days)**								**times**
	# 1	**# 2**	**# 3**	**# 4**	**# 5**	**# 6**	**# 7**	**# 8**	
1	-	-	-	-	-	-	-	-	0
2	-	-	-	-	-	-	-	-	0
3	-	-	-	-	-	-	-	-	0
4	-	-	-	-	-	-	-	-	0
5	262	-	-	-	-	-	-	-	1
6	128	263	397	-	-	-	-	-	3
7	-	-	-	-	-	-	-	-	0
8	128	263	397	-	-	-	-	-	3
9	128	262	396	530	-	-	-	-	4
10	51	110	169	231	292	354	417	480	8
total									19

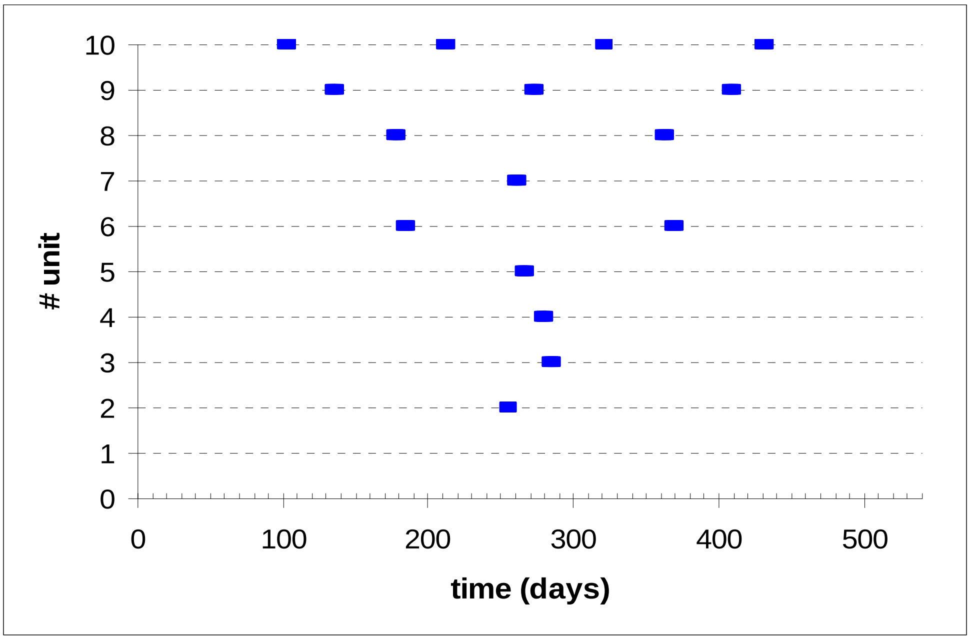


Figure 5.12 Gantt chart for optimal cleaning heat exchanger network of linear fouling; dot line: operating time, black line: cleaning time.

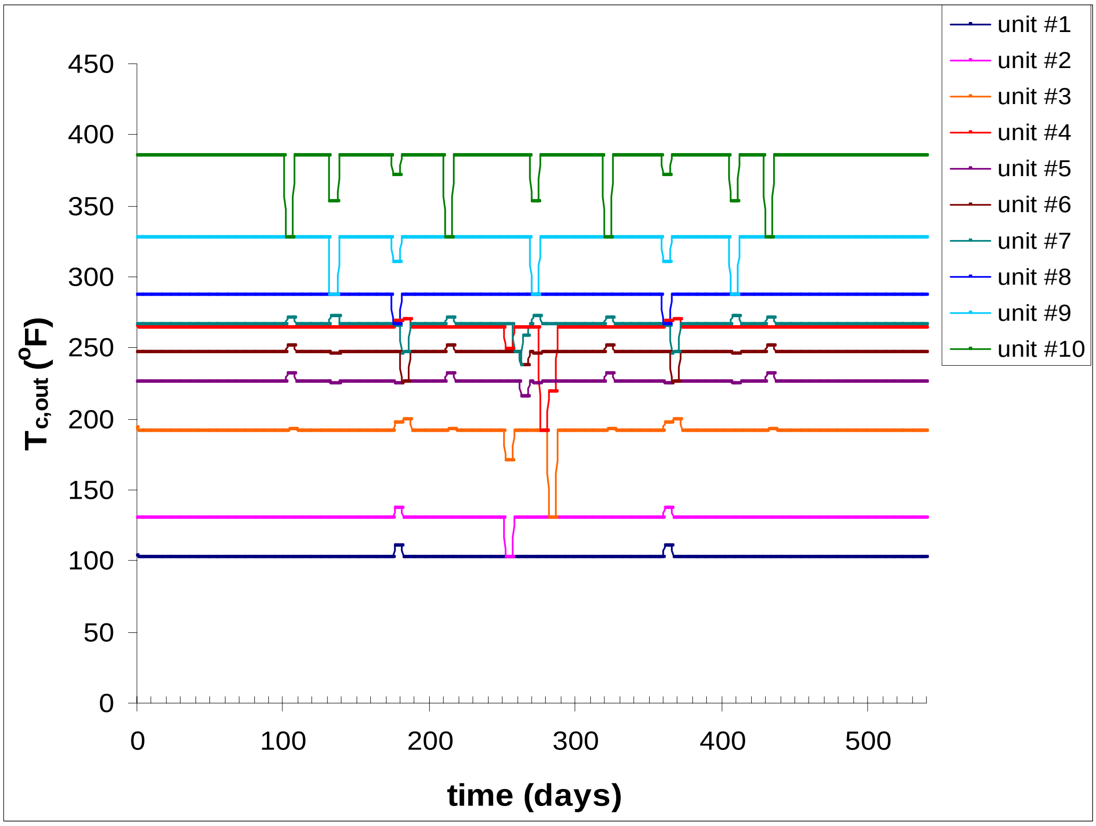


Figure 5.13 Variation of outlet temperature of cold stream of linear fouling case.

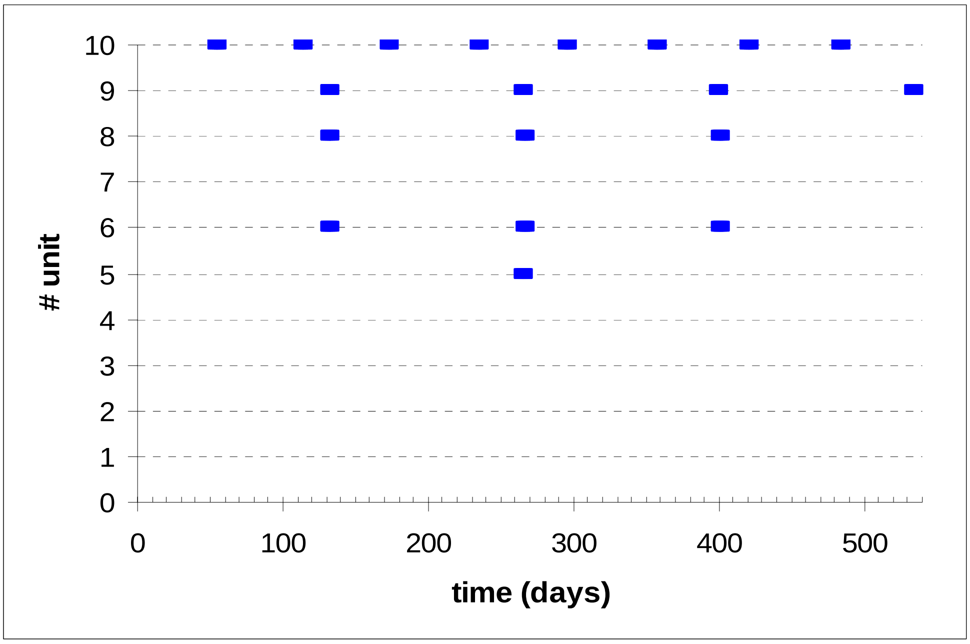


Figure 5.14 Gantt chart for optimal cleaning heat exchanger network of asymptotic fouling; dot line: operating time, black line: cleaning time.

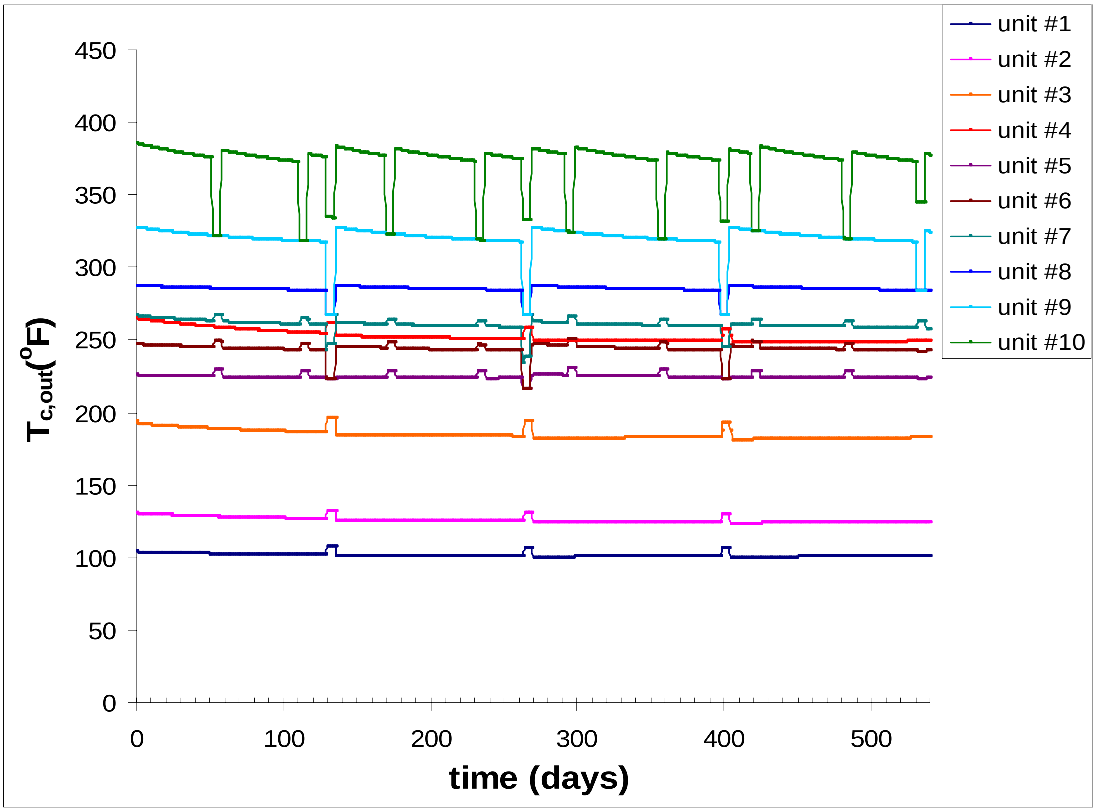


Figure 5.15 Variation of outlet temperature of cold stream of asymptotic fouling case.

The results of optimal cleaning time schedule of heat exchanger network were shown in Table 5.7, Figure 5.12 and Figure 5.13 for linear fouling, and Table 5.8, Figure 5.14 and Figure 5.15 for asymptotic fouling. The total number of cleaning events of linear fouling is 16 times and 19 times for asymptotic fouling. The total number of cleaning events of linear fouling case is less often than asymptotic case. Because all initial fouling rate of linear fouling case is lower than all initial fouling of asymptotic fouling, the linear fouling case is slowly fouling formation. This is reason for the variation of slowly heat transfer rate. These results were observed that heat exchanger unit 10 is often cleaned both linear fouling and asymptotic fouling. On account of the initial fouling rate of unit 10 is largest.

For linear fouling, from Figure 5.12 was observed that the heat exchanger unit 10 is cleaned most often than other unit. On account of the initial fouling rate of heat exchanger unit 10 is most. The cleaning of heat exchanger unit 1 is not occurred because it can be obtained heat from the heat exchanger unit 8 which connected to unit 1. Figure 5.13 show variation of outlet temperature of cold stream of linear fouling case. However, there is increasing of outlet temperature of cold stream of unit 1 because cleaning of unit 8 is occurred. This result is due to connection of unit 1 and unit 8. Thus, outlet temperature of cold stream of unit1 is increased. In addition, while cleanings of unit 2 to 10 are occurred, the outlet temperatures of cold stream of these units are decreased. The reductions of outlet temperature of cold stream of these units as cleaning are equal to the outlet temperature of cold stream of previous unit.

For asymptotic fouling, the cleaning of heat exchanger unit 5 is least occurred of all unit. This result was observed that unit 5 is connected to heat exchanger unit 10 which is most often cleaned. Therefore, the heat exchanger unit 5 can be obtained heat from the heat exchanger unit 10. Similarly, the heat exchanger unit 7 is not cleaned because the heat exchanger unit 9 is cleaned four times which rather often cleaning. From Figure 5.14 which is Gantt chart for optimal cleaning heat exchanger network of asymptotic fouling can be seen that cleaning heat exchanger are occurred in unit 5, 6 and 8 to 10. The cleaning heat exchangers are not occurred in unit 1 to 4 and 7 because these units can be obtained heat from the heat exchanger unit 5, 6 and 8 to 10. Figure 5.15 show variation of outlet temperature of cold stream of asymptotic fouling case. When cleaning of heat exchanger unit 10 are occurred, the reduction of outlet temperature of cold stream are equal to the outlet temperature of cold stream of unit 9. Moreover , there are the reduction of outlet temperature of cold stream of unit 10 because cleaning of other unit are occurred which cold stream send last outlet temperature to unit 10. Therefore, the outlet temperature of cold stream of unit 10 is reduced because cleaning of unit 10 and other unit are occurred. In addition, while cleaning of heat exchanger unit 10 is occurred, the outlet temperature of cold stream of unit 5, 6 and 7 are increased as seen in Figure 5.15. On account of unit 5 is connected to unit 10 which unit 5 can be obtained heat from unit 10 as the cleaning. Unit 6 and 7 can be obtained also heat from unit 5 because cold stream connected unit 6 and 7 with unit 5. Similarly, the outlet temperature of cold stream of unit 1 to 3 are increased as seen in Figure 5.15 because cleaning of unit 6. Because unit 3 is connected to unit 6, it can be obtained heat from unit 6.

In conclusion, if the one of units are cleaning, outlet temperature of cold stream will be decreased. However, there are some unit is increased. Because of interaction of each unit, the cold stream or hot stream connected one of units to another unit. Therefore, heat exchanger network cleaning on no minimum temperature constraint are occurred in order to obtain minimum total operating cost.

Table 5.9 Summary optimal result of heat exchanger network

(a) linear fouling

Cleaning cost (£)	**Linear fouling**			
	Discrete time		**This work**	
	£	**% saving**	**£**	**% saving**
No cleaned	381,000	-	381,000	-
Cleaning	221,867	41.77	177,521	53.41

(b) asymptotic fouling

Cleaning cost (£)	**Asymptotic fouling**			
	Discrete time		**This work**	
	£	**% saving**	**£**	**% saving**
No cleaned	577,000	-	577,000	-
Cleaning	221,933	61.54	185,832	67.79

The minimum operating cost in relaxation constraint cases has shown in Table 5.9(a) and 5.9(b) for linear fouling and asymptotic fouling, respectively. In this study, the operating cost of cleaning is 4,000£ both linear fouling case and asymptotic fouling case. The minimum operating cost is 185,832£ that can be saving cost is 67.79% for asymptotic fouling. Similarly, the minimum operating cost of linear fouling is 177,521£ that can be saving cost is 53.41%. The percent saving of asymptotic fouling is more than linear fouling. On account of fouling formation of asymptotic fouling behavior is faster than linear fouling behavior. Therefore, the reduction of heat transfer rate of asymptotic fouling behavior faster than linear fouling behavior. This result is affect to loss in heat transfer rate due to fouling of asymptotic fouling more than linear fouling. This is the main factor in objective function. Therefore, the total operating cost of asymptotic fouling behavior is more than linear fouling behavior.

To study new algorithm of formulation, the discrete time approach are compared with this work, which is continuous time approach. Both this approach and discrete time approach of the results were obtained by differential evolution. The minimum operating cost were compared in the Table 5.9(a) and Table 5.9(b) for linear fouling and asymptotic fouling, respectively. These results are observed that operating costs in this work are less than discrete time both linear fouling case and asymptotic fouling case. Because in this work considered in every time which is fine interval time. Therefore, the results obtained from this work can be saving cost more than discrete time approach.

5.4 The realistic optimization of cleaning schedule for heat exchanger network

From previous section, the objective function was minimum operating cost that tradeoff between furnace extra fuel costs due to fouling and heat exchanger cleaning costs in every unit of heat exchanger network. In this section, we proposed the realistic model for optimization the cleaning time schedule. The cold stream passes through heat exchanger unit 1, 2, 3 and 4 that the heat is decreased with time. This stream is not equal to the specification heat at desalter. The crude oil from this desalter to flash that passes through heat exchanger unit 5, 6 and 7. The heat at heat exchanger unit 7 is not equal to the specification heat of flash. Moreover, the heat at heat exchanger unit 10 is not equal to the specification heat of distillation. Thus, heat exchanger network (Figure 5.16) has added exchanger (E1, E2 and E3) prior to desalter, flash and distillation in order to repair inlet temperature of desalter, flash and distillation process. Therefore, the objective function should be equation 5.7.

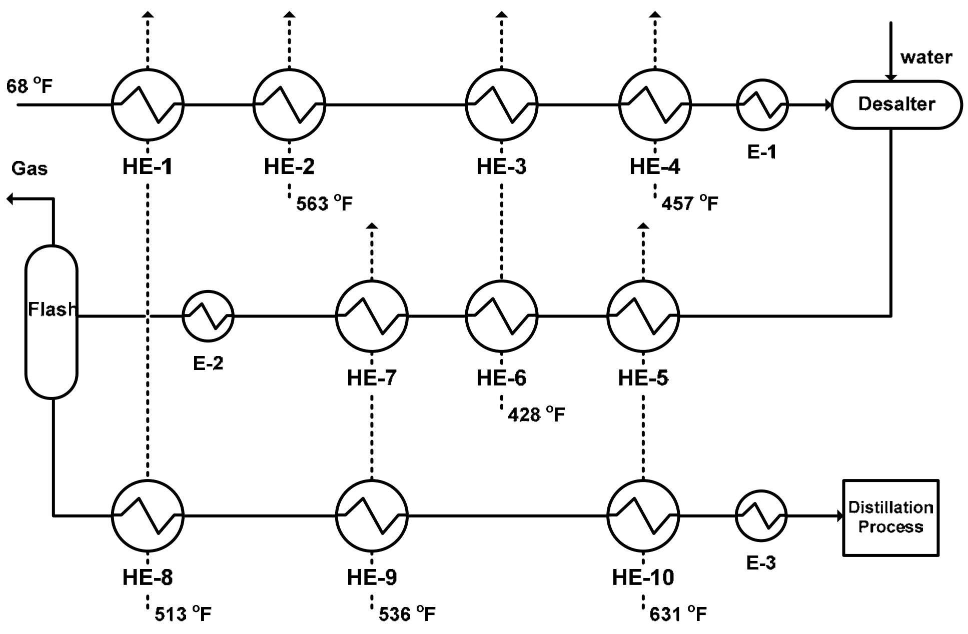


Figure 5.16 The schematic diagram of heat exchanger network. Solid lines: cold streams; dotted lines: hot streams.

$$
\begin{aligned}
Min._{\cos t} = & \int_0^{t_F} (FC_p[T_{desalter} - T(t)_4])dt \\
& + \int_0^{t_F} (FC_p[T_{flash} - T(t)_7])dt \\
& + \int_0^{t_F} (FC_p[T_{distillation} - T(t)_{10}])dt \\
& + \sum_j^{N_c} C_{c,j}
\end{aligned} \tag{5.7}
$$

This model, the objective function is tradeoff between furnace extra fuel costs due to fouling and heat exchanger cleaning cost at heat exchanger unit 4, 7 and 10. In this section studied the optimal cleaning schedule of heat exchanger network under fouling condition by using continuous time approach. The operating time horizon is 540 days. This section divided into two cases: the first case focuses on the optimization of cleaning time schedule of heat exchanger network and the second one deals with the optimization of cleaning time schedule of heat exchanger network for no minimum constraint case.

5.4.1. The Realistic optimization of cleaning schedule of heat exchanger network

In this section considered the optimal cleaning time schedule of heat exchanger network for minimum constraints case. The minimum temperature is limited by heat exchanger unit 4, 7 and 10 which are inlet heat before desalter, flash and distillation process, respectively. Table 5.10(a) and 5.10(b) have shown the optimal cleaning time schedule of this heat exchanger network for linear fouling model and asymptotic fouling model, respectively. Figure 5.17 and Figure 5.19 present Gantt chart for realistic optimization of cleaning heat exchanger network of linear fouling and asymptotic fouling. Figure 5.18 and Figure 5.20 shown variation of outlet temperature of cold stream of linear fouling case and asymptotic fouling case, respectively. In addition, the optimal results were summarized in Table 5.11

Table 5.10 Optimal cleaning time schedule of heat exchanger network for realistic case.

(a) linear fouling

unit	days of cleaning action (days)					times
	# 1	# 2	# 3	# 4	# 5	
1	-	-	-	-	-	0
2	-	-	-	-	-	0
3	258	-	-	-	-	1
4	119	252	346	450	-	4
5	-	-	-	-	-	0
6	257	-	-	-	-	1
7	174	352	-	-	-	2
8	-	-	-	-	-	0
9	252	-	-	-	-	1
10	103	199	288	375	461	5
total						**14**

(b) asymptotic fouling

unit	days of cleaning action (days)								times
	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	
1	-	-	-	-	-	-	-	-	0
2	198	404	-	-	-	-	-	-	2
3	-	-	-	-	-	-	-	-	0
4	-	-	-	-	-	-	-	-	0
5	250	-	-	-	-	-	-	-	1
6	200	397	-	-	-	-	-	-	2
7	-	-	-	-	-	-	-	-	0
8	167	357	-	-	-	-	-	-	2
9	155	316	477	-	-	-	-	-	3
10	52	112	178	244	303	365	433	493	8
total									**18**

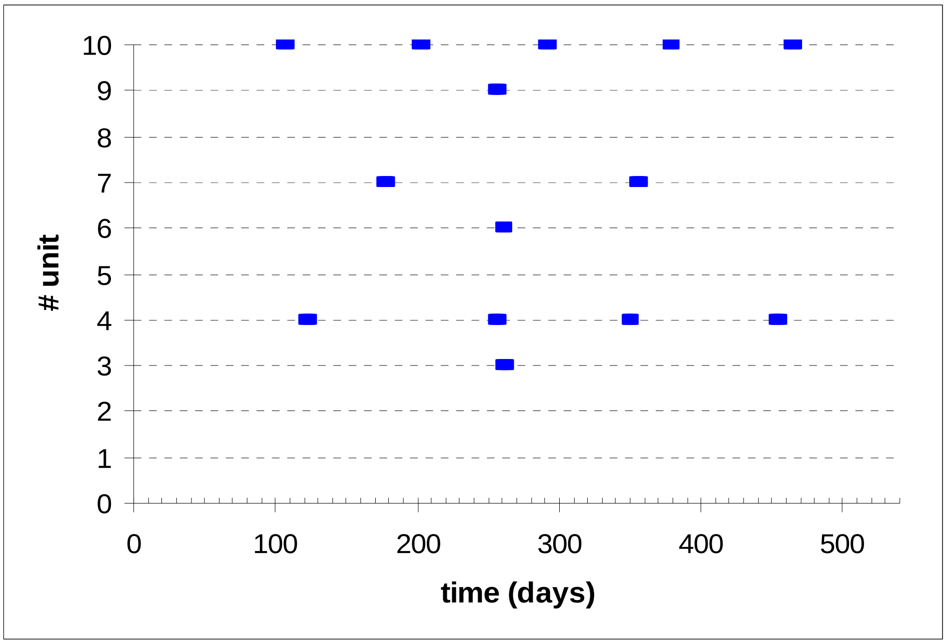


Figure 5.17 Gantt chart for realistic optimization of cleaning heat exchanger network of linear fouling; dot line: operating time, black line: cleaning time.

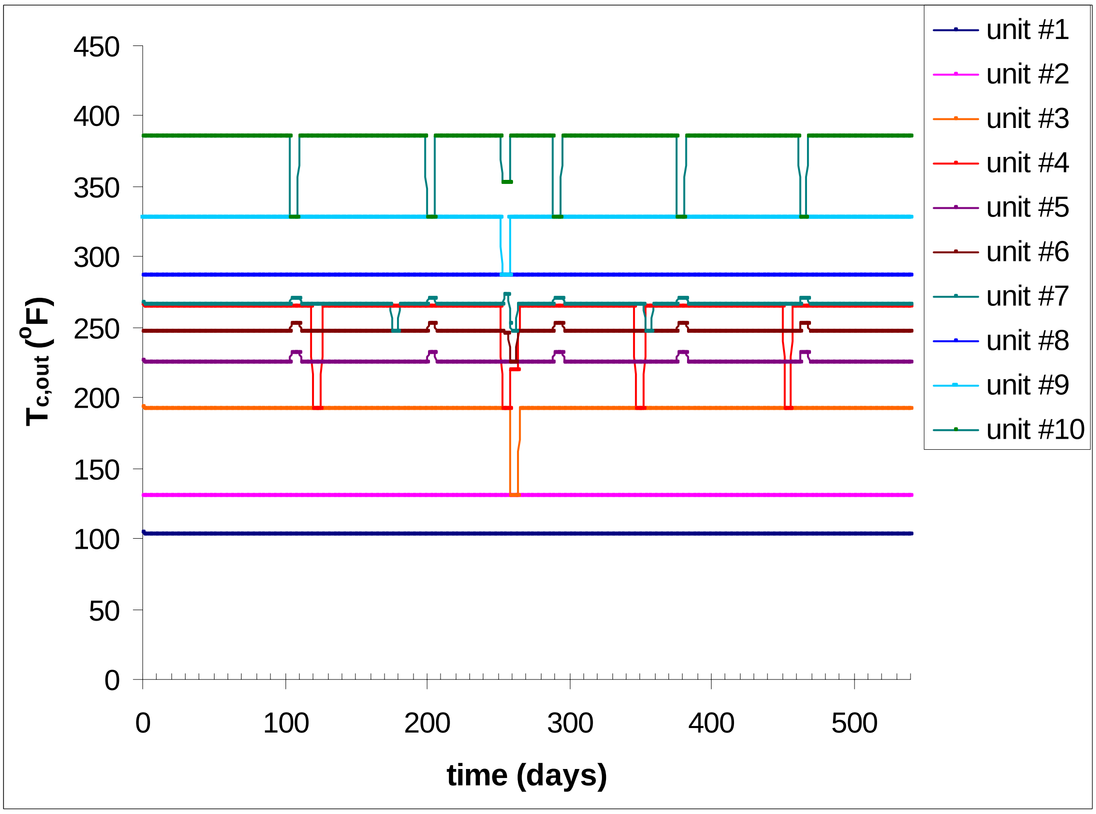


Figure 5.18 Variation of outlet temperature of cold stream of linear fouling case for realistic optimization.

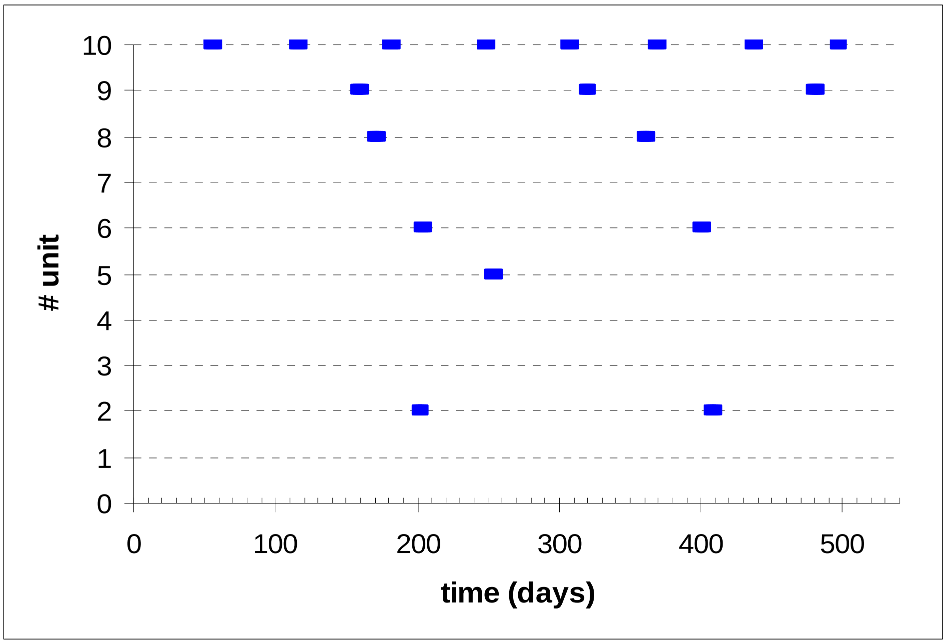


Figure 5.19 Gantt chart for realistic optimization of cleaning heat exchanger network of asymptotic fouling; dot line: operating time, black line: cleaning time.

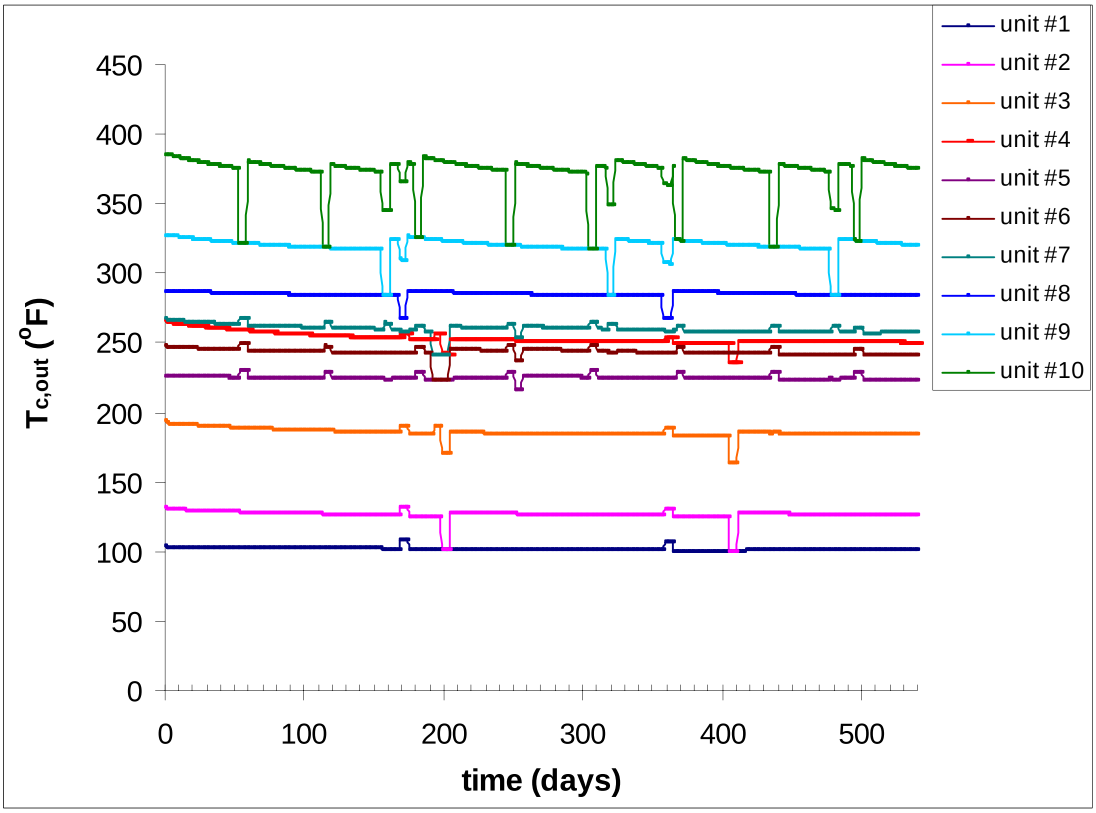


Figure 5.20 Variation of outlet temperature of cold stream of asymptotic fouling case for realistic optimization.

Table 5.10(a) and Table 5.10(b) present the optimal cleaning time schedule of heat exchanger network for linear fouling and asymptotic fouling, respectively. The number of cleaning events of linear fouling is 14 times and the number of cleaning events of asymptotic fouling is 18 times. These results were observed that the number of cleaning events of asymptotic fouling is more often than linear fouling. It is due to all initial fouling rate of linear fouling are lower than asymptotic fouling. The heat exchanger unit 10 is cleaned most often of both linear fouling and asymptotic fouling. Because the heat exchanger unit 10 is largest initial fouling rate, the heat exchanger unit 10 is cleaned most often. From table 5.10(b), the heat exchanger unit 5 is cleaned less than other heat exchanger for asymptotic fouling case. Because of the heat exchanger network connected unit 5 to unit 10, the heat exchanger unit 5 can be obtained heat from the heat exchanger unit 10. Thus, the cleaning of heat exchanger unit 5 is not occurred.

Gantt chart for realistic optimization of heat exchanger network cleaning of linear fouling shown in Figure 5.17 and variation of outlet temperature of cold stream of linear fouling shown in Figure 5.18. While the cleaning of unit 10 is occurred, the reductions of outlet temperature of cold stream are equal to the outlet temperature of cold stream of unit 9. There is reduction of outlet temperature of cold stream of unit 10 on 252 days. Because cold stream connected unit 10 to unit 9, it can be obtained cold temperature from unit 9 as cleaning. Thus, outlet temperature of cold stream of unit 10 is decreased. In addition, outlet temperatures of cold stream of unit 5 to unit 7 are increased in cleaning period of unit 10. Because unit 5 is connected to unit 10, unit 5 can be obtained hot temperature from unit 10 as the cleaning. Thus, unit 6 and 7 can be obtained also heat from unit 5 because cold stream connected unit 6 and 7 with unit 5. Similarly, while the cleaning of unit 4 is occurred, the reductions of outlet temperature of cold stream are equal to the outlet temperature of cold stream of unit 3. However, the reduction of outlet temperature of unit 4 is not effect on other unit because outlet streams are not connected unit 4 to other unit.

For asymptotic fouling case, Gantt chart for realistic optimization of heat exchanger network cleaning and outlet temperature of cold stream profile were shown in Figure 5.19 to 5.20, respectively. It was observed that the cleaning of unit 1 is not occurred because unit 1 is small initial fouling rate. However, there is increasing of outlet temperature of cold stream of unit 1. Because cleaning of unit 8 is occurred and hot stream connected unit 1 to unit 8, the outlet temperature of cold stream of unit 1 is increased. Similarly, the cleaning of unit 3 and unit 4 are not occurred but there are increasing and decreasing of outlet temperature of cold stream. The increasing of outlet temperature of cold stream because cleaning of unit 8 is occurred which hot stream connect to unit 1. The decreasing of outlet temperature of cold stream because cleaning of unit 2 is occurred. Moreover, cleaning of unit 10 are occurred, the decreasing of outlet temperature of cold stream are equal to the outlet temperature of cold stream of unit 9.There are also decreasing of outlet temperature of cold stream because cleaning of unit 8 and unit 9 are occurred.

To sum up, while the one of units has been cleaning, outlet temperature of cold stream will be decreased. However, there are some unit is increased. Because of interaction of each unit, the cold stream or hot stream connected one of units to another unit. Therefore, heat exchanger network cleaning is occurred because minimum temperature. This is the reason for minimum total operating cost.

Table 5.11 Summary of optimal results for realistic.

Cleaning cost (£)	**Discrete time**		**This work**	
	No. of cleaning	**£**	**No. of cleaning**	**£**
Linear fouling	23	94,422	14	82,571
Asymptotic fouling	25	158,403	18	153,808

The operating cost of linear fouling case is 82,571£ and 153,808£ for asymptotic fouling case as shown in Table 5.11. It was observed that the operating cost of linear fouling is less than asymptotic fouling. This is due to fouling formation. The fouling formation of asymptotic fouling is larger than linear fouling. Therefore, the reduction of heat transfer rate is rapidly changed which lead to the increasing of different heat transfer rate from initial heat transfer rate. This is the main factor in objective function. Thus, the operating cost of asymptotic fouling is more than linear fouling. In addition, the results obtained from this technique of this section have lower operating cost than the results obtained using discrete time approach. The discretization is too coarse for time interval but this approach is considered at any point in the continuous domain of time. Therefore, the number of cleaning actions and total operating cost of this technique are less than discrete time approach.

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

The optimal cleaning time schedule of heat exchanger network for no constraints case was considered in this section. Table 5.12(a) and 5.12(b) show the optimal cleaning time schedule of this heat exchanger network for linear fouling model and asymptotic fouling model, respectively. Figure 5.21 and Figure 5.23 present Gantt chart for realistic cleaning heat exchanger network of linear fouling and asymptotic fouling with no constraints. Figure 5.22 and Figure 5.24 show outlet temperature of cold stream profile of linear fouling and asymptotic fouling with no constraint. In addition, the optimal results were summarized in Table 5.13.

The optimal cleaning time schedule of heat exchanger network for realistic case with no constraint were shown in Table 5.12(a) and Figture5.11 (a) for linear fouling case and Table 5.12(b) and Figture5.11(b) for asymptotic fouling case. The number of overall cleaning events of linear fouling is 11 times and the number of overall cleaning events of asymptotic fouling is 16 times. These results were observed that the number of cleaning events of asymptotic fouling is more often than linear fouling. It is due to all initial fouling rate of asymptotic fouling are lower than linear fouling. In addition, it is observed that heat exchanger unit 10 is cleaned more often than other heat exchanger. On account of heat exchanger unit 10 is largest initial fouling rate so it is most often cleaned.

Table 5.12 Optimal cleaning time schedule of heat exchanger network for realistic case with no maximum constraint.

(a) linear fouling

unit	days of cleaning action (days)					times
	# 1	# 2	# 3	# 4	# 5	
1	-	-	-	-	-	0
2	-	-	-	-	-	0
3	-	-	-	-	-	0
4	151	307	454	-	-	3
5	-	-	-	-	-	0
6	-	-	-	-	-	0
7	151	303	455	-	-	3
8	-	-	-	-	-	0
9	-	-	-	-	-	0
10	70	151	267	343	454	5
total						11

(b) asymptotic fouling

unit	days of cleaning action (days)									times
	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	
1	-	-	-	-	-	-	-	-	-	0
2	-	-	-	-	-	-	-	-	-	0
3	-	-	-	-	-	-	-	-	-	0
4	124	254	382	-	-	-	-	-	-	3
5	-	-	-	-	-	-	-	-	-	0
6	-	-	-	-	-	-	-	-	-	0
7	95	199	297	397	-	-	-	-	-	4
8	-	-	-	-	-	-	-	-	-	0
9	-	-	-	-	-	-	-	-	-	0
10	38	91	135	195	264	322	394	461	529	9
total										16

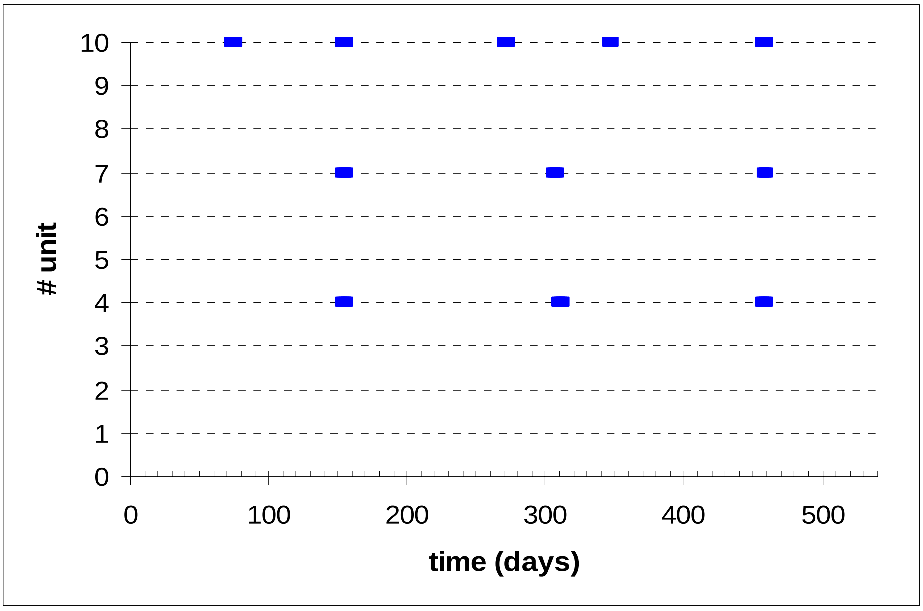


Figure 5.21 Gantt chart for realistic optimization of cleaning heat exchanger network of linear fouling with no constraints; dot line: operating time, black line: cleaning time.

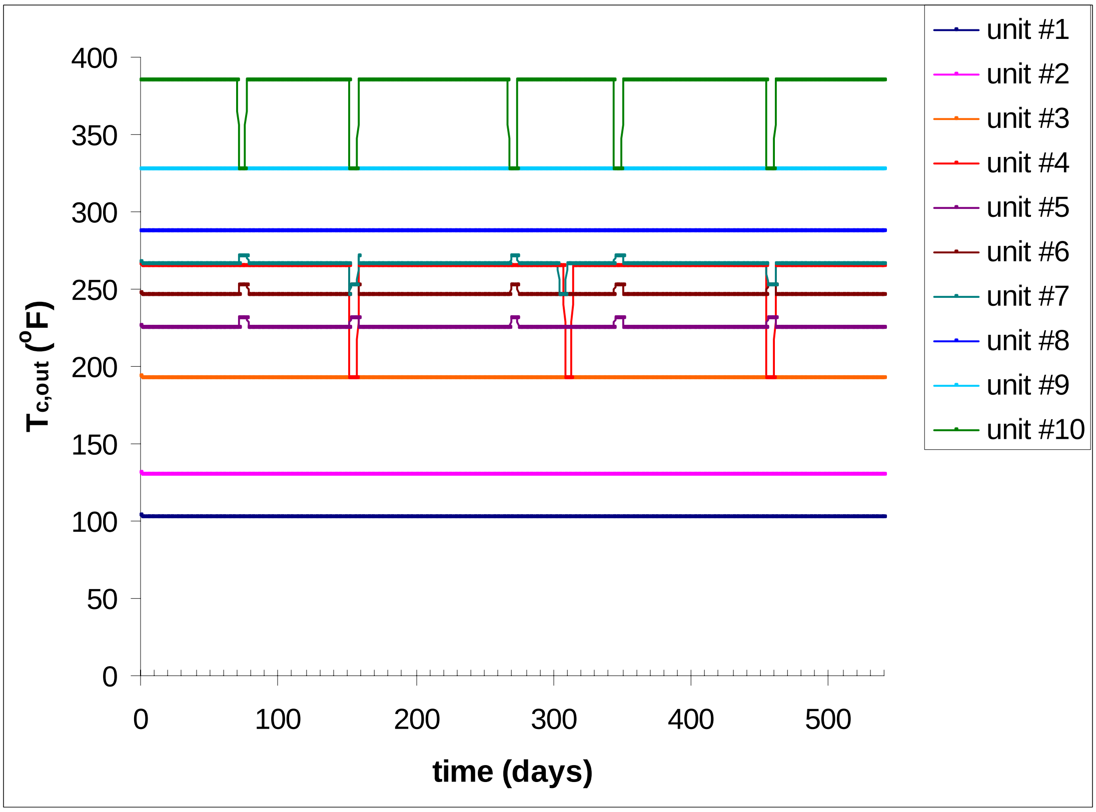


Figure 5.22 Variation of outlet temperature of cold stream of linear fouling case with no constraints.

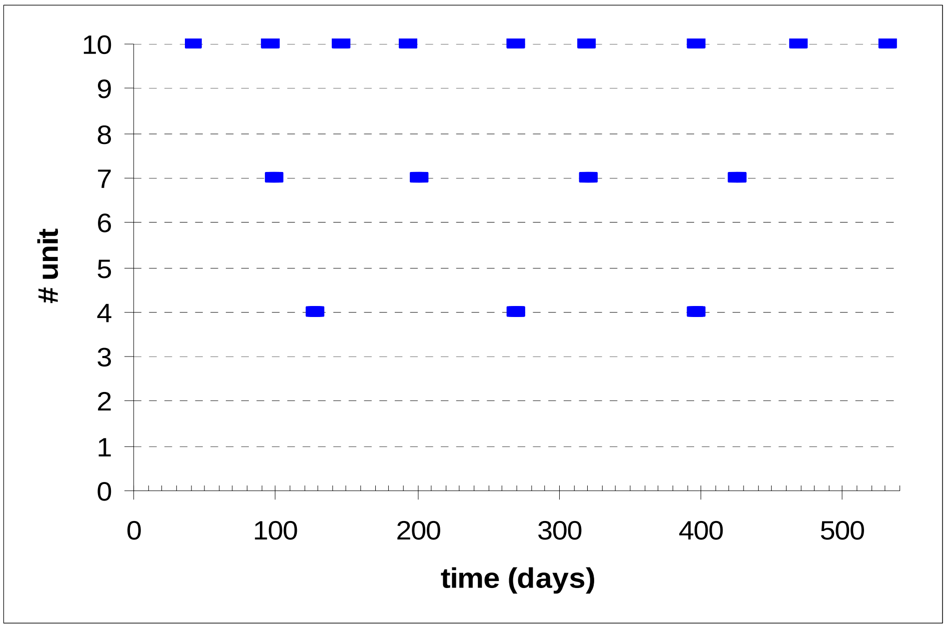


Figure 5.23 Gantt chart for realistic optimization of cleaning heat exchanger network of asymptotic fouling with no constraints; dot line: operating time, black line: cleaning time.

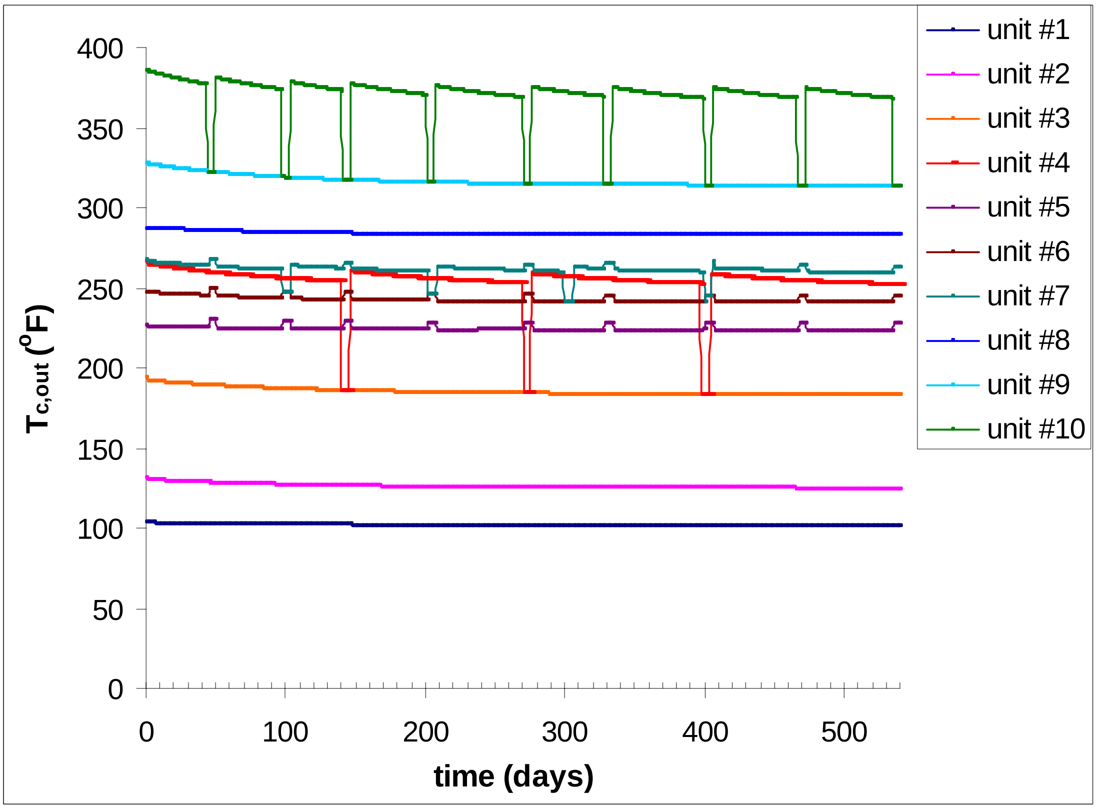


Figure 5.24 Variation of outlet temperature of cold stream of asymptotic fouling case with no constraints.

For realistic optimization of linear fouling case with no constraint show in Figure 5.21 to Figure 5.22. It was observed that while cleaning events of unit 4 are occurred, the reduction of outlet temperature of cold stream is equal to the outlet temperature of cold stream of unit 3. Similarly, cleaning events of unit 7 are occurred. These cleaning caused the decreasing of outlet temperature of cold stream. It is equal to the outlet temperature of cold stream of unit 6. Both cleaning events of unit 4 and unit 7 are not effect on other unit. However, unit 10 is effect on unit 5, unit 6 and unit 7. These results for the increasing of outlet temperature of cold stream of unit 5 to unit 7 as cleaning events of unit 10 are occurred. While cleaning of unit 10 is occurred, the reduction of outlet temperature of cold stream is equal to the outlet temperature of cold stream of unit 9.

For realistic optimization of asymptotic fouling case with no constraint show in Figure 5.23 to Figure 5.24. The increasing and decreasing of outlet temperature of cold stream don’t appear in unit 1 to unit 3. Because unit 8 and unit 6 are not occurred that connected to unit 1 and unit 3, respectively. Furthermore, units 1 to unit 3 are small initial fouling rate. Therefore, the cleaning of unit 1 to unit 3 is not occurred. There are the reductions of outlet temperature of unit 10 as the cleaning of unit 10. This result is the increasing of outlet temperature of unit 5 to unit 7. On account of hot stream connected unit 5 to unit 10. The temperature of unit 5 can be obtained heat from unit 10 as the cleaning. In addition, there are not cleaning of unit 8 and unit 9. Thus, the increasing and decreasing of outlet temperature of cold stream don’t appear in this unit.

In conclusion, while the one of units has been cleaning, outlet temperature of cold stream will be decreased. However, there are some unit which connected it is increased. Because of interaction of each unit, the cold stream or hot stream connected one of units to another unit. Therefore, heat exchanger network cleaning on no minimum temperature constraint are occurred in order to can be obtained minimum total operating cost. Moreover, this section can be seen that cleaning events of unit 4, unit 7 and unit 10 are occurred on both linear fouling case and asymptotic fouling case. Because of cleaning events of unit 4, 7 and 10, an objective function (Equation 5.7) is considered at the heat exchanger unit 4, 7 and 10.

Table 5.13 Summary of optimal results for realistic with no minimum constraints.

Cleaning cost (£)	**Discrete time**		**Continuous time**	
	No. of cleaning	**£**	**No. of cleaning**	**£**
Linear fouling	14	69,694	11	58,830
Asymptotic fouling	22	146,034	16	117,449

Table5.13 shows summary of optimal results for realistic with no minimum constraint. The number of cleaning is 11 times and the operating cost is 58,830£ for linear fouling. For an asymptotic fouling, the number of cleaning is 16 times and the operating cost is 117,449£. The operating cost of asymptotic fouling case is more than linear fouling case. This is due to the fact that the large value of initial fouling rate of asymptotic fouling case. 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 and the operating cost of asymptotic fouling is more than linear fouling.

To study new algorithm of formulation, the discrete time approach were compared with this work, which is continuous time approach. The results of both discrete time approach and this work are obtained by differential evolution. The minimum operating costs were compared in the Table 5.13 for linear fouling and asymptotic fouling. The results of realistic optimization were observed that the operating costs in this work are less than discrete time both linear fouling case and asymptotic fouling case. Because of fine interval time, this work considered at any point in the continuous domain of time. Moreover, this work which is continuous time formulation is not approximations of the actual problem. Therefore, the numbers of cleaning event and total operating cost of this work are less than discrete time approach of both linear fouling and asymptotic fouling case with constraints and no constraints.

5.5 The realistic optimization as decreasing of overall heat transfer coefficient

From previous section, the cleaning of each unit were occurred as minimum temperature constraints and in order to obtained minimum operating cost. However, heat exchangers in network interact to another unit. Thus, the heat exchanger cleaning of one unit is effect on another unit because decreasing or increasing of outlet temperature under fouling of each unit is interaction. Therefore, in this section studied minimum heat transfer coefficient constraint (decreased 80%). The linear fouling model and asymptotic fouling model were considered in this section. The objective function is equation 5.7. The Gantt chart for realistic optimization as decreasing of overall heat transfer coefficient shown in Figure 5.24 to 5.25 for linear fouling and asymptotic fouling, respectively. The total operating costs were shown in Figure 5.14.

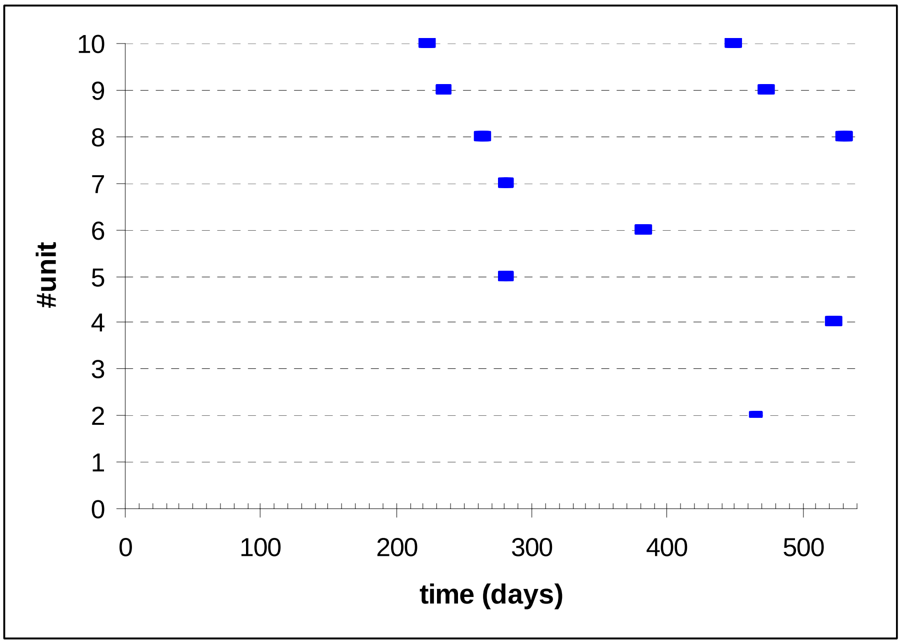


Figure 5.25 Gantt chart for realistic optimization as decreasing of overall heat transfer coefficient of linear fouling with no constraints; dot line: operating time, black line: cleaning time.

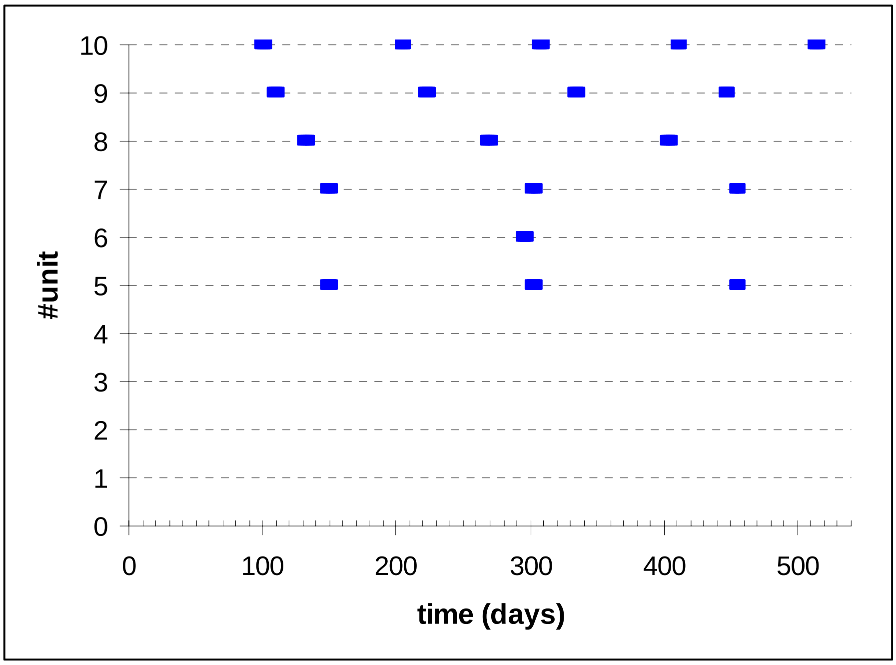


Figure 5.26 Gantt chart for realistic optimization as decreasing of overall heat transfer coefficient of asymptotic fouling with no constraints; dot line: operating time, black line: cleaning time.

From Figure 5.24 and Figure 5.25 shown the Gantt chart for realistic optimization as decreasing of overall heat transfer coefficient of linear fouling and asymptotic fouling. Its were observed that the total number of cleaning events of linear fouling is less than asymptotic fouling. Because overall initial fouling rate of linear fouling is less than asymptotic fouling, the decreasing of overall heat transfer coefficient of linear fouling is slowly down to minimum overall heat transfer coefficient constraint. Therefore, the total number of cleaning events of linear fouling is less than asymptotic fouling. The cleaning of unit 5 and unit 7 are occurred at same time of both linear fouling and asymptotic fouling. Because of cleaning at the same time, an initial fouling rate of unit 5 is equal to unit 7. In addition, the unit 10 is cleaned often than other unit because large initial fouling rate.

From Figure 5.24 can be seen that the cleaning of unit 1 and unit 3 are not occurred because least initial fouling rate. These results are the cause of the decreasing of overall heat transfer coefficient which is not reach down to minimum overall heat transfer coefficient. Thus, unit 1 and unit 3 are not cleaned. Similarly, the initial fouling rates of unit 1 to unit 4 of asymptotic fouling are less than other unit so the cleaning of unit 1 to unit 4 is not also occurred as seen in Figure 5.25. Therefore, if any unit is less initial fouling rate, the decreasing of overall heat transfer coefficient due to fouling will not reach down to minimum overall heat transfer coefficient. This is reason for not cleaning of any unit.

From Table 5.14, the operating cost is 139,518£ and the cost saving is 22.9% for linear fouling. For asymptotic fouling, the operating cost is 223,565£ and the cost saving is 19.04%. This result was observed that the operating cost of linear fouling can be save cost more than the operating cost of asymptotic fouling. Because the loss in heat transfer rate due to asymptotic fouling (Equation 5.7) in first term, which main factor of objective function, is more than the loss in heat transfer rate due to linear fouling. Therefore, the operating cost of asymptotic fouling is more than linear fouling.

Table 5.14 Summary of optimal results for realistic optimization as decreasing of overall heat transfer coefficient.

Cleaning cost (£)	**Linear fouling**			**Asymptotic fouling**		
	No. cleans	**cost(£)**	**%saving**	**No. cleans**	**cost(£)**	**%saving**
No cleaning	-	180,938	-	-	276,134	-
Cleaning	11	139,518	22.9	19	223,565	19.04

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The problem of cleaning time in continuous heat exchanger networks subject to fouling are studied in this work. The crude oil preheat train distillation is chosen as a case study. The aim is to determine the optimal cleaning time schedule as minimize the operating cost of heat exchanger network. In this study, the formulation of optimization problem is solved using continuous time approach. The number of cleaning events is predicted priorly. The optimal solution solved by differential evolution method.

The simulation result of the variations in overall heat transfer coefficient, variations in outlet temperatures of hot and cold streams and variations of heat transfer rate with time are presented in chapter IV. The fouling increases with time which effect on overall heat transfer coefficient reduce with time. While the outlet temperatures of cold stream reduce with time, the outlet temperatures of hot stream increase with time. The heat transfer rates reduce with time. Additionally, comparisons of performance of heat exchanger under fouling are also presented. The different time decay of fouling formation and initial fouling rate effect on the variation in heat transfer rate with time.

Finally, the dynamic optimization of cleaning time for heat exchanger is performed in chapter V which using continuous time approach. The studies are divided into two cases: the first one focuses on single heat exchanger cleaning time schedule and the second one deal with cleaning time schedule of heat exchanger network. The influences of both linear and asymptotic fouling behaviors are compared in optimization. The influences of initial fouling rate and time decay of fouling formation is also studied in first case. These parameters are sensitive to the optimal cleaning time and operating cost. For second case divided into two sections: optimization of heat exchanger network cleaning and the realistic optimization of cleaning schedule for heat exchanger network. The number of cleaning events is predicted in order to the determination of cleaning time schedule. The operating cost of single heat exchanger and heat exchanger network are minimum operating cost. The results obtained from this work compare with discrete time approach. Further, the effect of the prediction of the number of cleaning event under an optimal operating cost has revealed that there is a minimum cleaning time and minimum number of cleaning events for obtaining the minimum operating cost of heat exchanger network.

6.2 Recommendations

Some recommendations for future work are given below. In this research, after the heat exchanger cleaning is restored to initial state 100%. However, the real process can be clean the heat exchanger only reach to 95 to 97%. Therefore, the optimal heat exchanger cleaning problem should be applied to the real process. For the future direction, the multistage optimization of objective function should be studied for continuous time approach in this problem.

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APPENDICES

APPENDIX A

NUMERIC INTEGRATION

Numeric integration means the numeric evaluation of integrals

$$J = \int_a^b f(x)dx \qquad \text{(A-1)}$$

Where a and b are given and f is a function given analytically. Geometrically, J is the area under the curve of f between a and b.

We know that if f is such that we can find a differentiable function F whose derivative is f, then we can evaluate J by applying the familiar formula

$$J = \int_a^b f(x)dx = F(a) - F(b) \qquad \text{(A-2)}$$

Where

$$\left[F'(x) = f(x)\right]$$

Simpson's Rule of Integration

Piecewise constant approximation of led to the rectangular rule ,piecewise linear approximation to the trapezoidal rule, and piecewise quadratic approximation will lead to simpson 's rule ,which is of great practical importance because it is sufficiently accurate for most problems, but still sufficiently simple.

To derive simpson's rule, we divide the interval of integration $a \le x \le b$ into an even number of equal subintervals, say, into $n = 2m$ subintervals of length $h = (b-a)/(2m)$, with endpoints x_0 (= a), $x_1,\ldots,x_{2m-1},x_{2m}$ (= b). We now take the first two subintervals and approximate f(x) in the interval $x_0 \le x \le x_2 = x_0 + 2h$ by the Lagrange polynomial $p_2(x)$ through (x_o, f_o), (x_1,f_1), (x_2, f_2), where $f_j = f(x_j)$.from interpolation polynomial we obtain

The denominators in equation () are $2h^2$, $-h^2$, and $2h^2$, respectively. Setting $s = (x - x_1)/h$, we have

$$x-x_1 = sh, \qquad x - x_0 = x - (x_1 - h) = (s + 1)h \qquad \text{(A-3)}$$

$$x - x_2 = x - (x_1 + h) = (s - 1)h \quad \text{(A-4)}$$

and we obtain

$$p_2(x) = \frac{1}{2}s(s-1)f_0 - (s+1)(s-1)f_1 + \frac{1}{2}(s+1)sf_2 \quad \text{(A-5)}$$

We now integrate with respect to x from x_0 to x_2. This corresponds to integrating with respect to s from -1 to 1. Since dx = h ds, the result is

$$\int_{x1}^{x2} f(x)dx \approx \int_{x1}^{x2} p_2(x)dx = h\left(\frac{1}{3}f_0 + \frac{4}{3}f_1 + \frac{1}{3}f_2\right) \quad \text{(A-6)}$$

A similar formula holds for the next two subintervals from x_2 to x_4, and so on. By summing all these m formulas we obtain Simpson's rule

$$\int_{a}^{b} f(x)dx \approx \frac{h}{3}(f_0 + 4f_1 + 2f_2 + 4f_3 + \cdots + 2f_{2m-2} + 4f_{2m-1} + f_{2m}) \quad \text{(A-7)}$$

Where h = (b-a)/2m and $f_j = f(x_j)$

APPENDIX B

OPTIMIZATION RESULTS

This appendix shows operating cost from prediction of number of cleaning events and outlet temperature of cold stream profile of optimization single heat exchanger while the number of cleaning is predicted. The operating time is 540 days.

B.1 Operating cost

Table B.1 Operating cost from prediction of number of cleaning with constraints.

predicted (times)	Linear fouling	Constraint
	Cost	
2	122,000	No violate constraint
3	68,938	No violate constraint
4	61,315	No violate constraint
5	47,596	No violate constraint
6	55,523	No violate constraint
7	55,066	No violate constraint

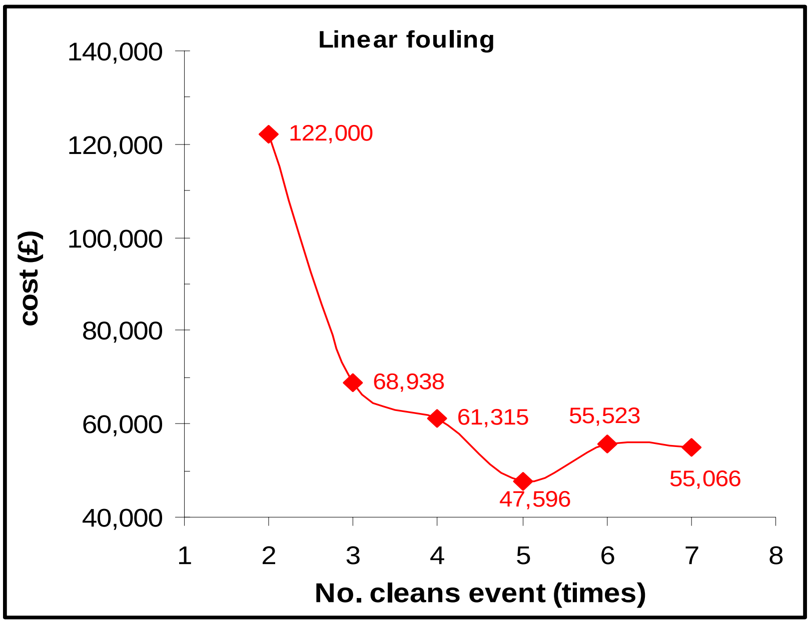

Figure B.1 Operating cost from prediction of number of cleaning for linear fouling.

Table B.2 The operating cost from prediction of number of cleaning events (asymptotic fouling).

predicted (times)	Asymptotic fouling	Constraint
	Cost	
5	169,985	Violate constraint
6	157,652	Violate constraint
7	145,267	Violate constraint
8	139,736	Violate constraint
9	132,062	No violate constraint
10	137,871	No violate constraint

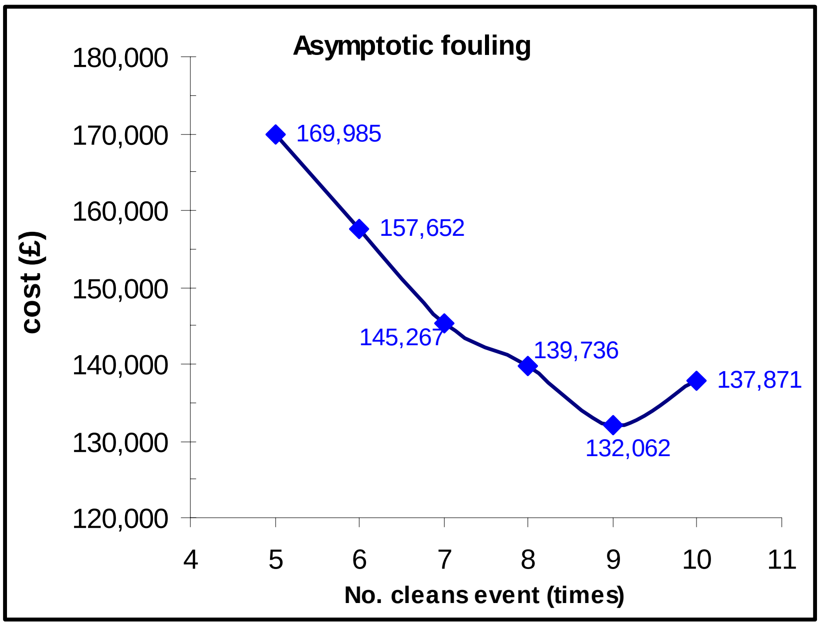

Figure B.2 Operating cost from prediction of number of cleaning for asymptotic fouling.

Therefore, the minimum operating cost case is 47,596£ and the number of cleaning events is 5 times for linear fouling. The minimum operating cost case is 132,062£ and the number of cleaning events is 9 times for linear fouling.

B.2 Temperature profile

This temperatures profile are prediction of number of cleaning events which occurred violate constraints for asymptotic fouling.

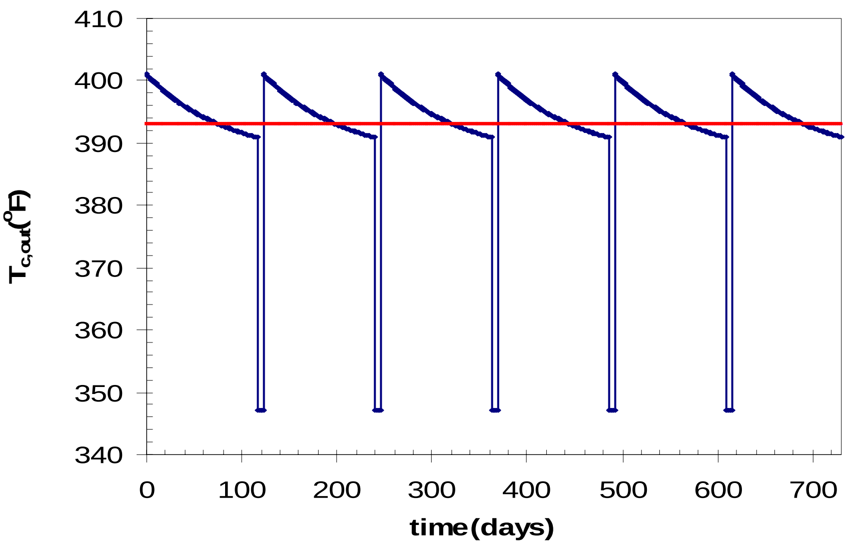

Figure B.3 The cold temperature profile optimization (the number of cleaning events is fixed 5 times).

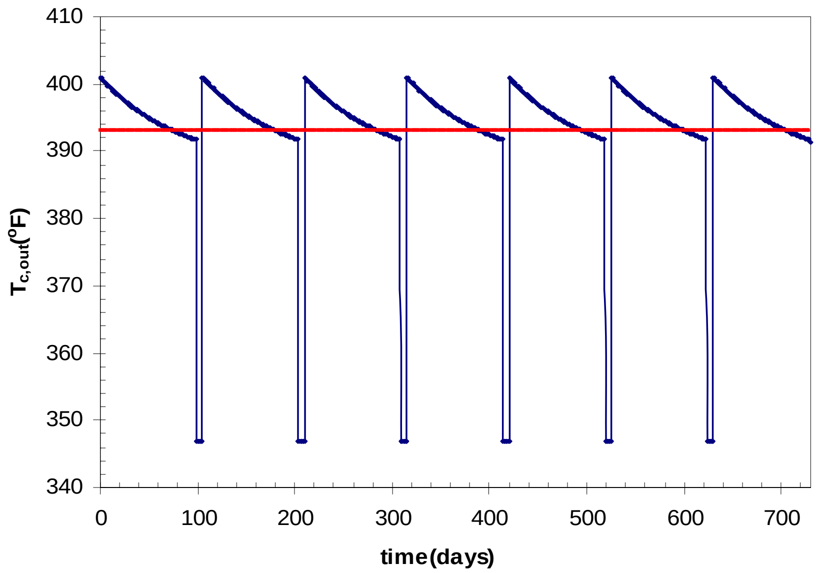

Figure B.4 The cold temperature profile optimization (the number of cleaning events is fixed 6 times).

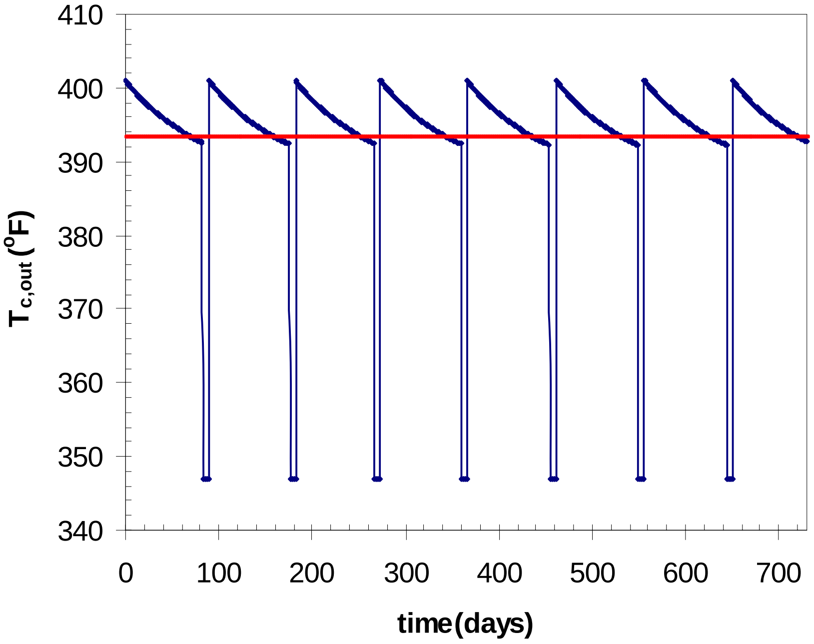

Figure 5.5 The cold temperature profile optimization (the number of cleaning events is fixed 7 times).

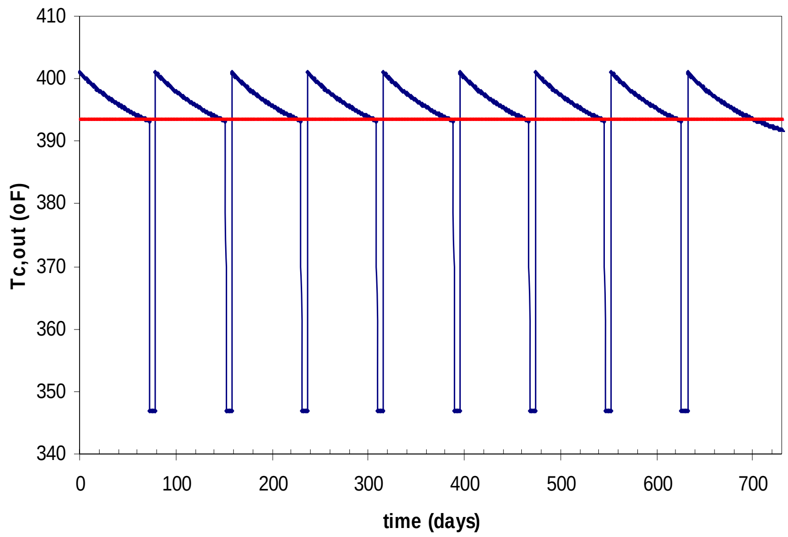

Figure 5.6 The cold temperature profile optimization (the number of cleaning events is fixed 8 times).

APPENDIX C

SIMULATION OF HEAT EXCHANGER NETWORK

This appendix show outlet temperature of cold and hot stream profile for heat exchanger network in linear fouling model and asymptotic fouling model without cleaning. The operating time is 540 days.

C.1 Linear fouling model

$$\dot{R} \equiv \frac{dR_f}{dt} = a$$

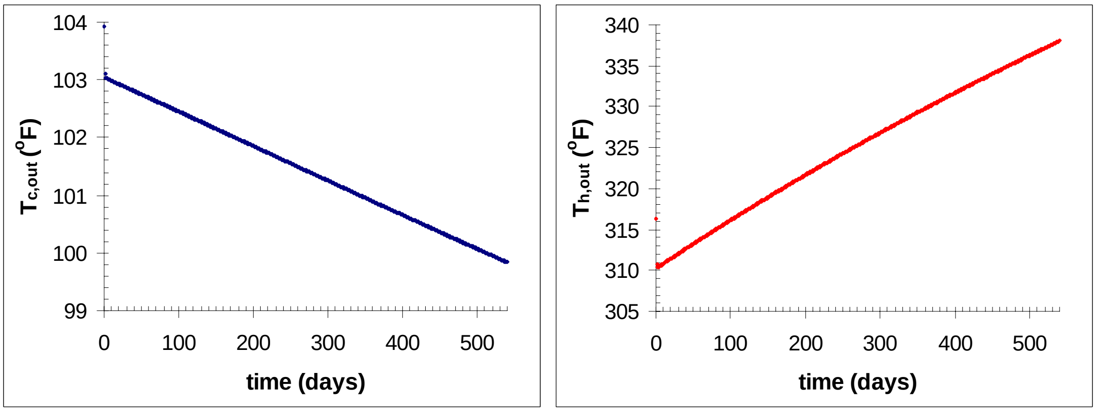

Figure C.1 The schematic diagram of the variations of the outlet temperature in heat exchanger number 1 with time. (linear fouling).

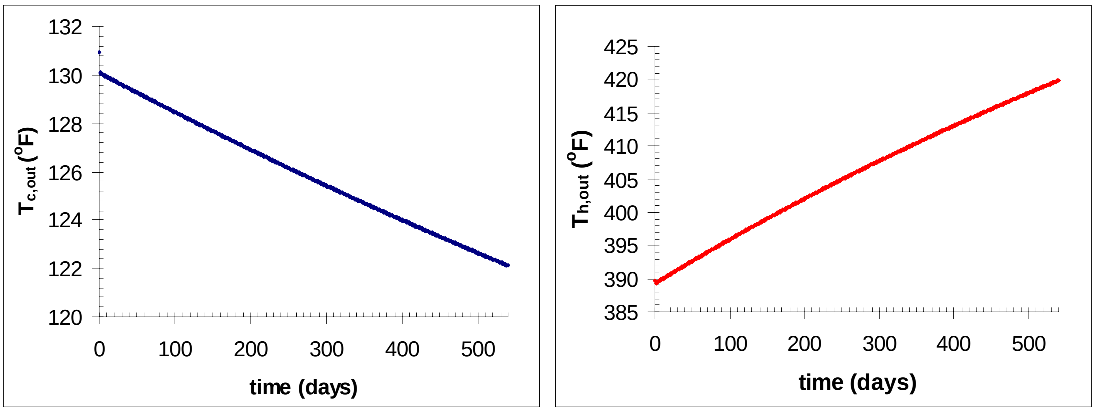

Figure C.2 The schematic diagram of the variations of the outlet temperature in heat exchanger number 2 with time. (linear fouling).

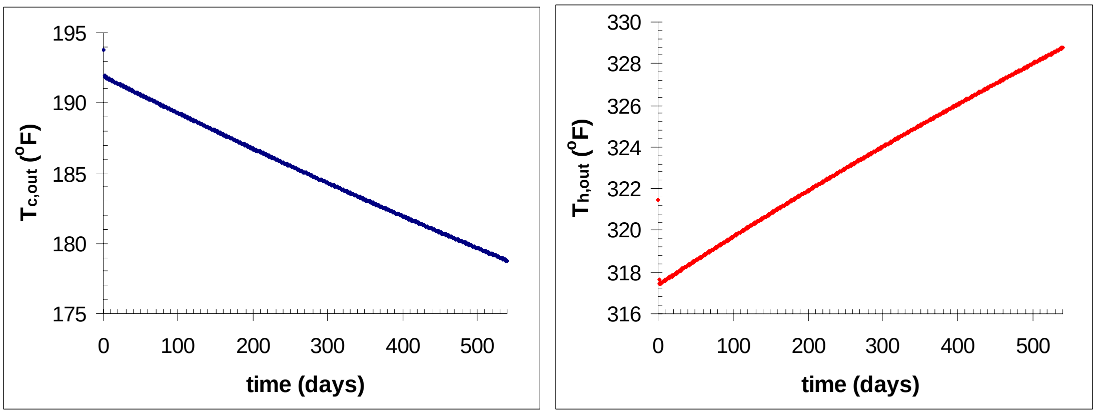

Figure C.3 The schematic diagram of the variations of the outlet temperature in heat exchanger number 3 with time. (linear fouling).

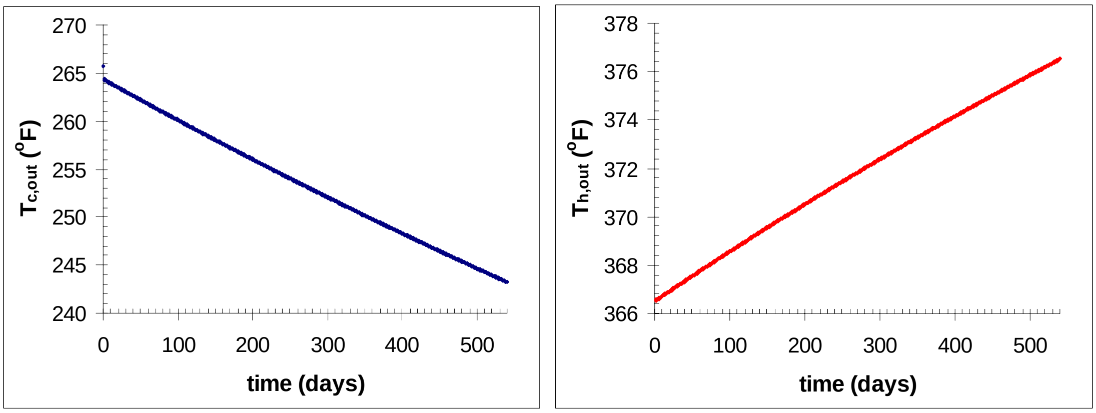

Figure C.4 The schematic diagram of the variations of the outlet temperature in heat exchanger number 4 with time. (linear fouling).

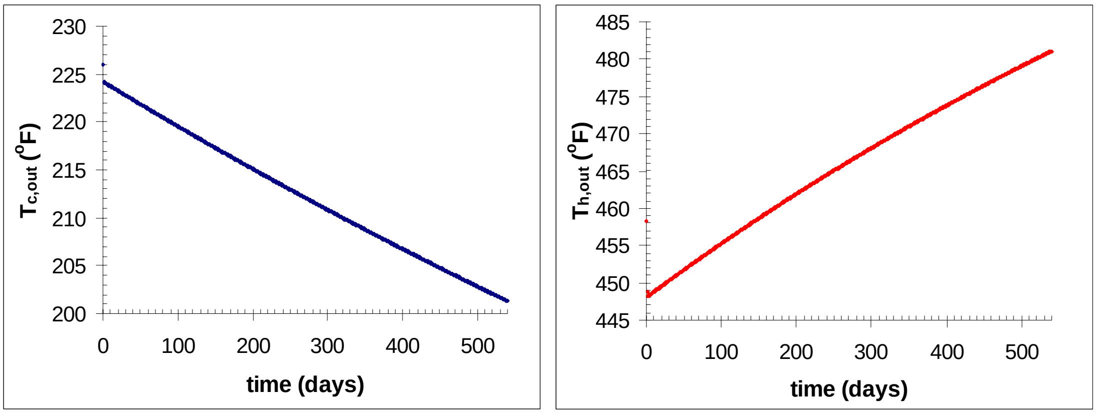

Figure C.5 The schematic diagram of the variations of the outlet temperature in heat exchanger number 5 with time. (linear fouling).

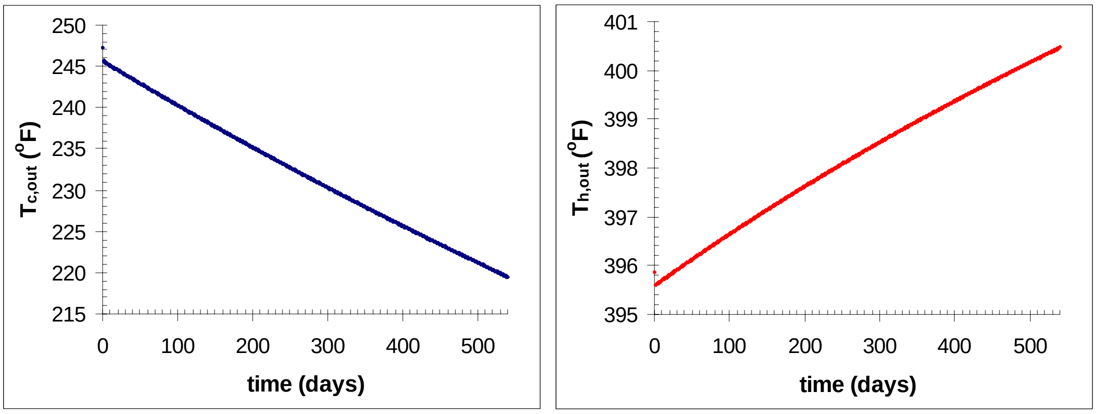

Figure C.6 The schematic diagram of the variations of the outlet temperature in heat exchanger number 6 with time. (linear fouling).

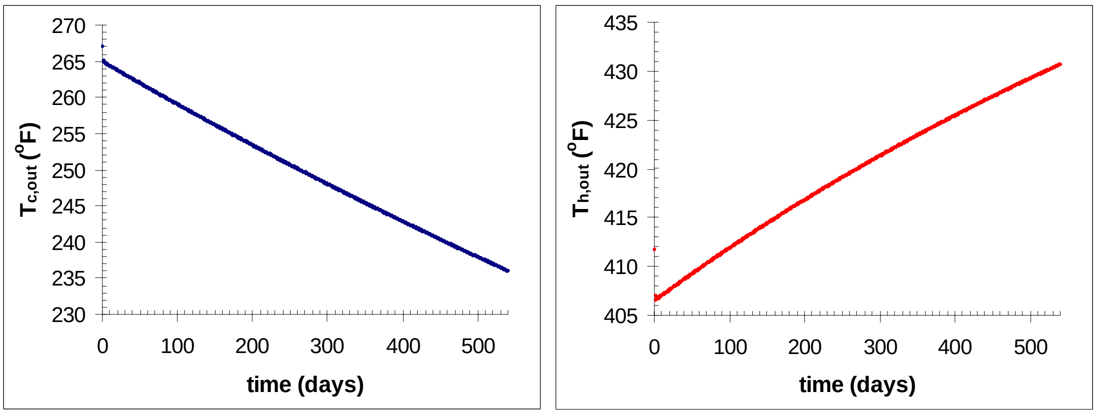

Figure C.7 The schematic diagram of the variations of the outlet temperature in heat exchanger number 7 with time. (linear fouling).

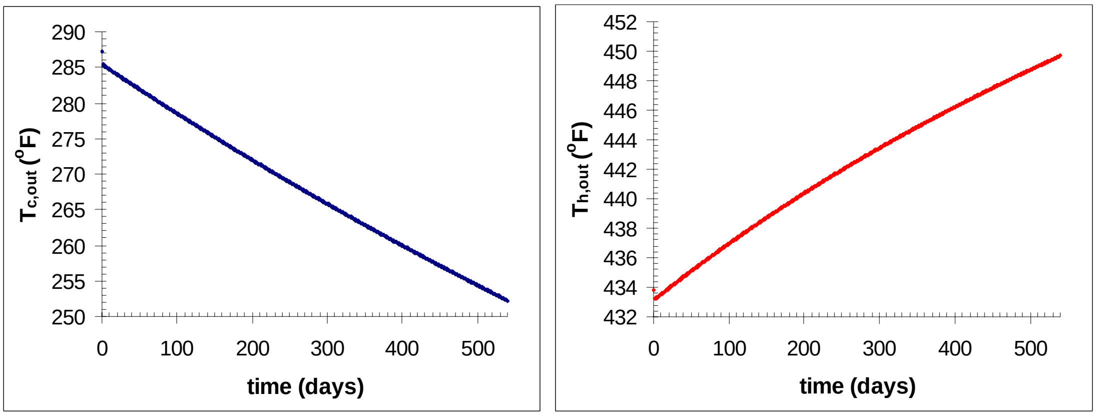

Figure C.8 The schematic diagram of the variations of the outlet temperature in heat exchanger number 8 with time. (linear fouling).

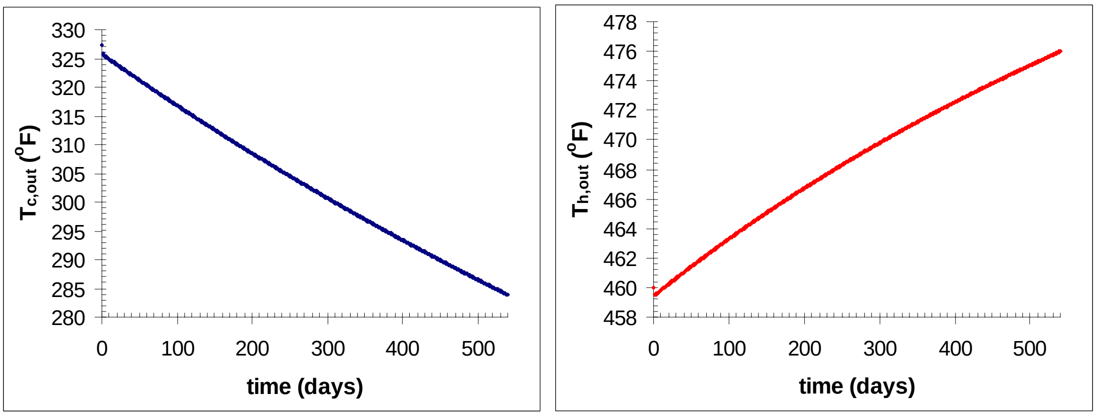

Figure C.9 The schematic diagram of the variations of the outlet temperature in heat exchanger number 9 with time. (linear fouling).

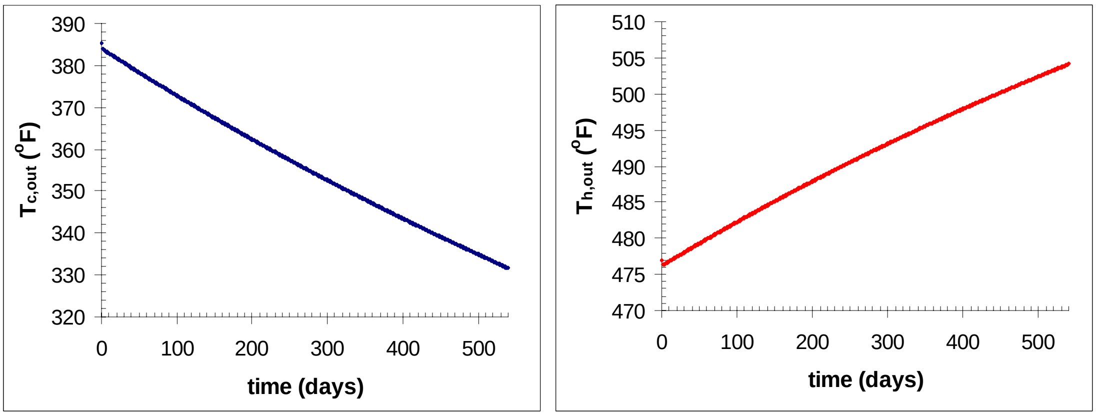

Figure C.10 The schematic diagram of the variations of the outlet temperature in heat exchanger number 10 with time. (linear fouling).

C.2 Asymptotic fouling model

$$R_f(t) = R_f^{\infty}(1 - \exp(-t/\tau))$$

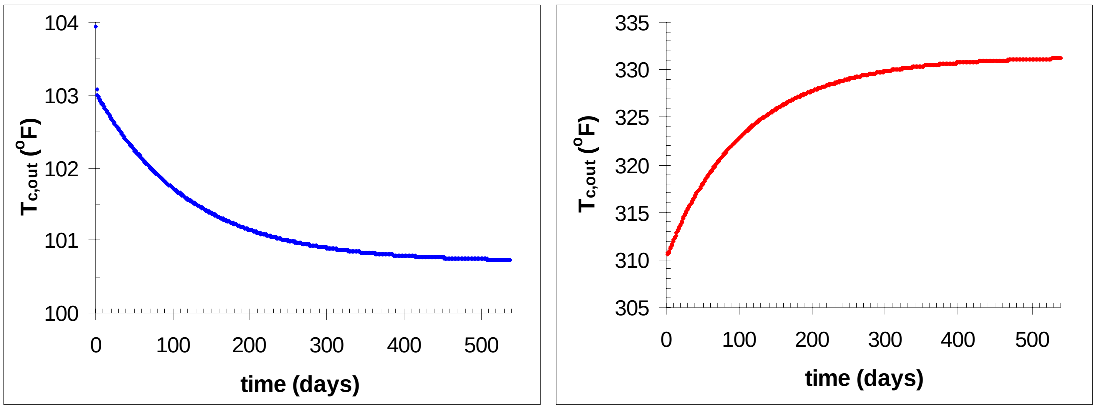

Figure C.11 The schematic diagram of the variations of the outlet temperature in heat exchanger number 1 with time. (asymptotic fouling).

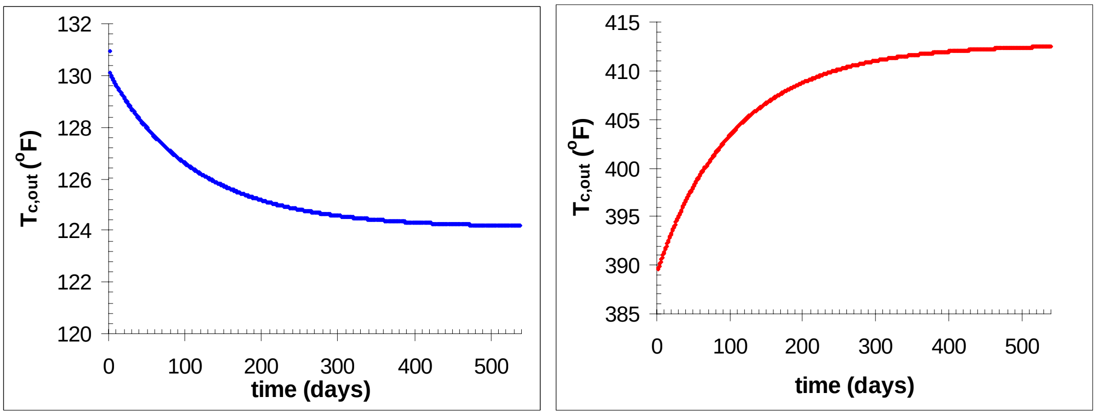

Figure C.12 The schematic diagram of the variations of the outlet temperature in heat exchanger number 2 with time. (asymptotic fouling).

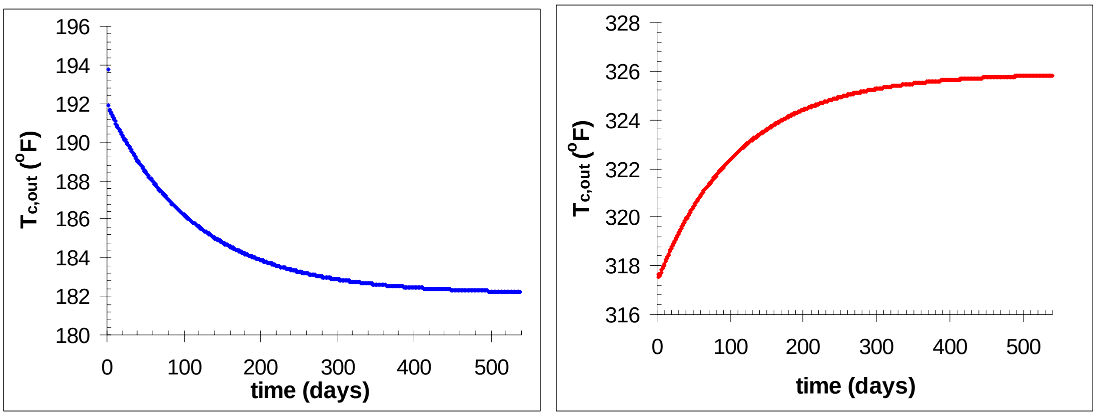

Figure C.13 The schematic diagram of the variations of the outlet temperature in heat exchanger number 3 with time. (asymptotic fouling).

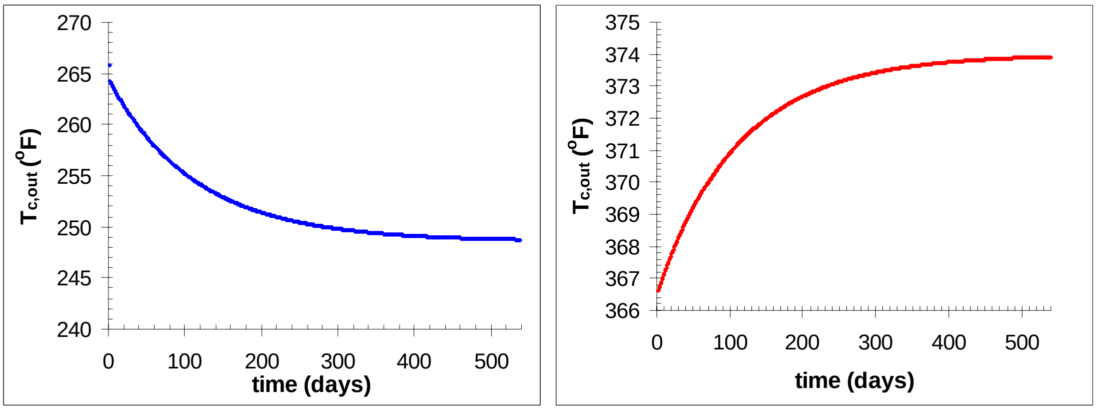

Figure C.14 The schematic diagram of the variations of the outlet temperature in heat exchanger number 4 with time. (asymptotic fouling).

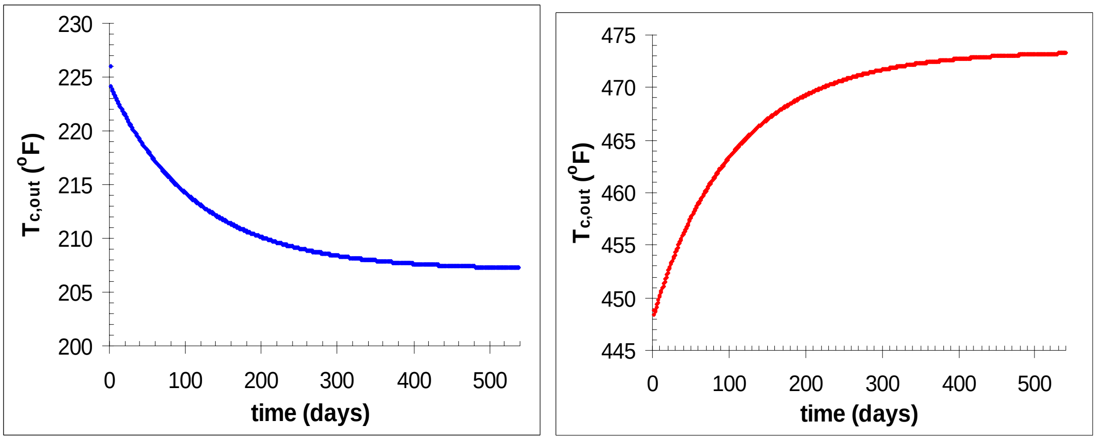

Figure C.15 The schematic diagram of the variations of the outlet temperature in heat exchanger number 5 with time. (asymptotic fouling).

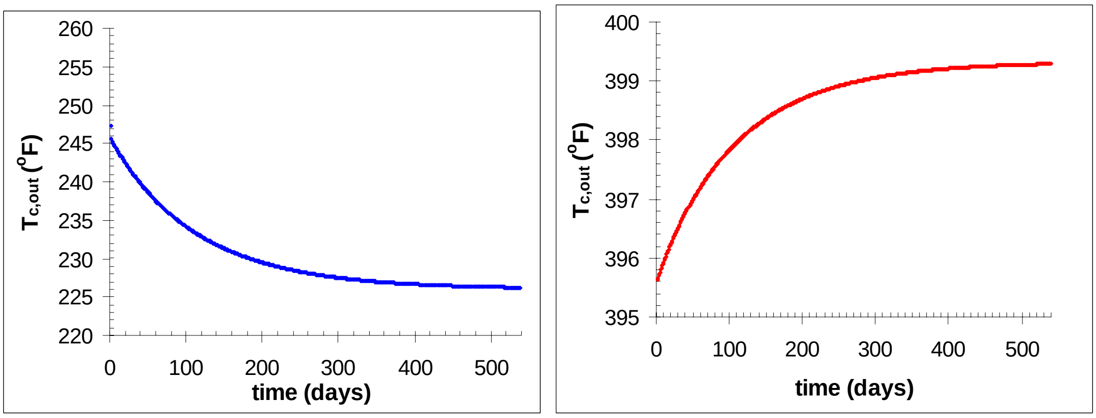

Figure C.16 The schematic diagram of the variations of the outlet temperature in heat exchanger number 6 with time. (asymptotic fouling).

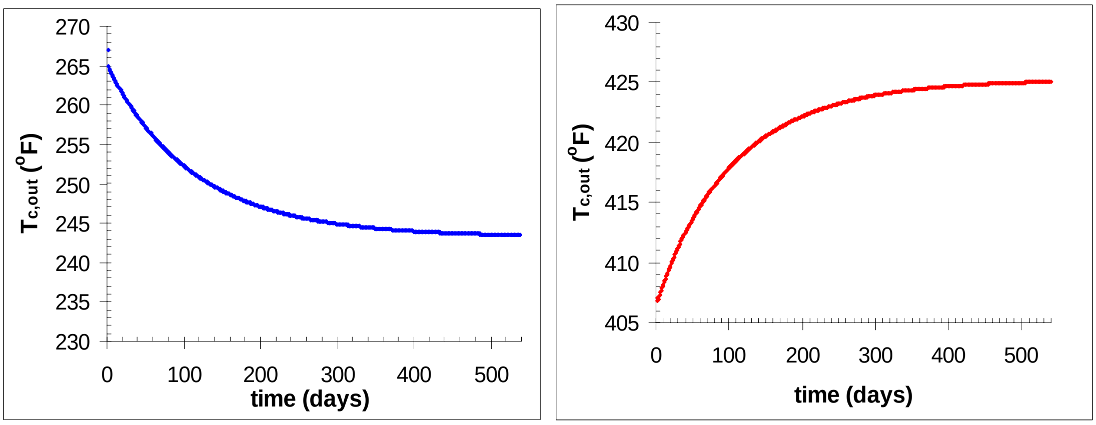

Figure C.17 The schematic diagram of the variations of the outlet temperature in heat exchanger number 7 with time. (asymptotic fouling).

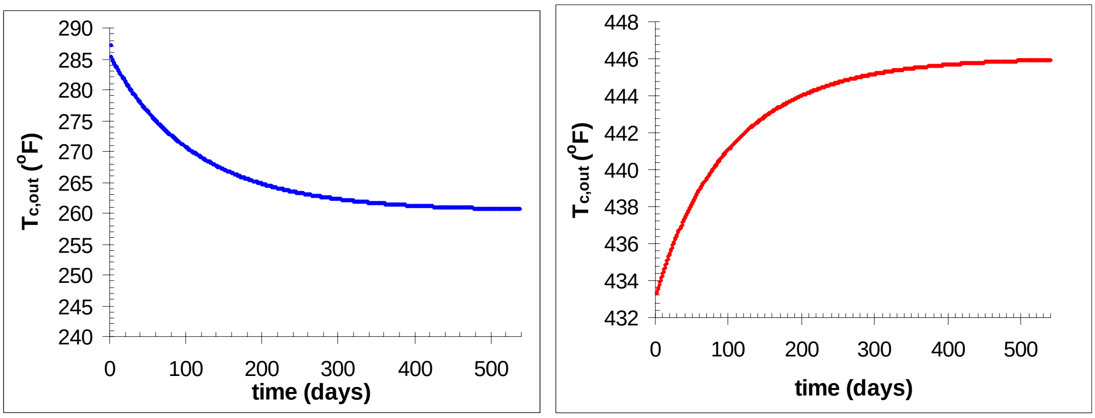

Figure C.18 The schematic diagram of the variations of the outlet temperature in heat exchanger number 8 with time. (asymptotic fouling).

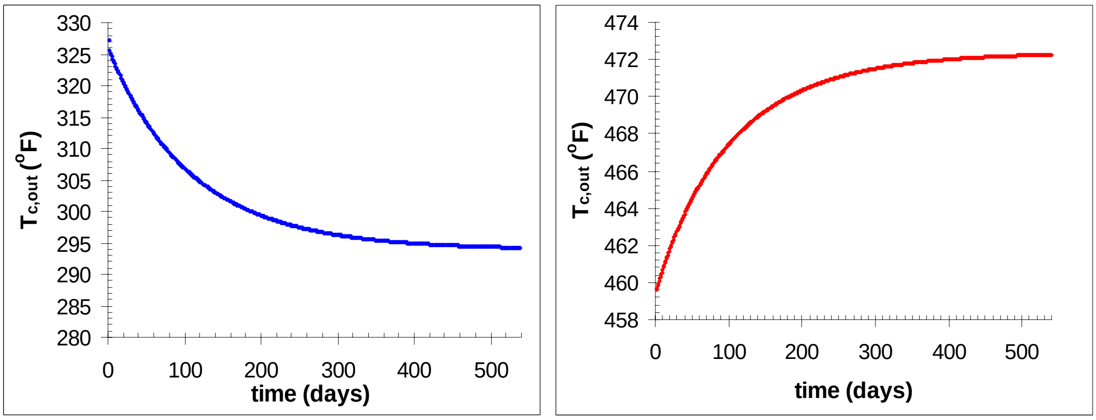

Figure C.19 The schematic diagram of the variations of the outlet temperature in heat exchanger number 9 with time. (asymptotic fouling).

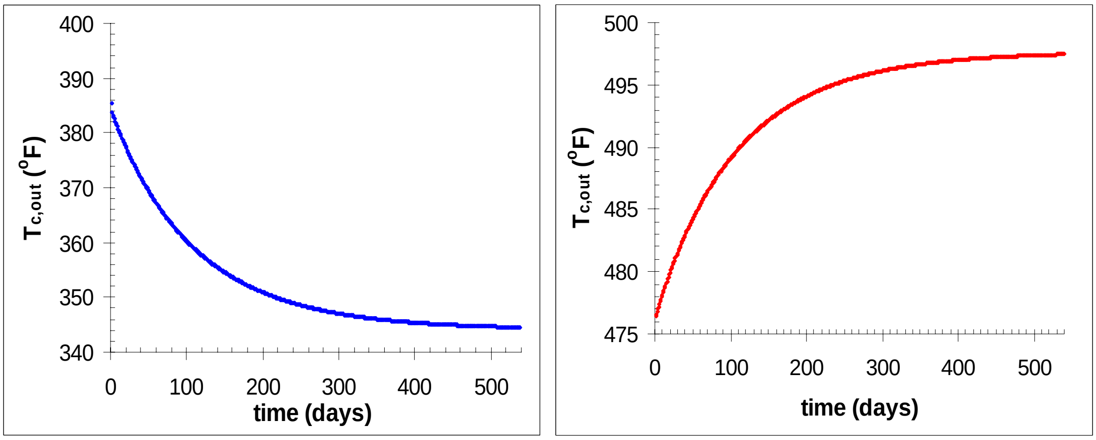

Figure C.20 The schematic diagram of the variations of the outlet temperature in heat exchanger number 10 with time. (asymptotic fouling).

APPENDIX D

LIST OF PUBLICATIONS

National conference

1. Kanyaluk Ao-ekkasit and Surathep Kheawhom. Dynamic optimization of heat exchanger cleaning using continuous time formulation approach. The 6th PSU-Engineering Conference, Songkha, Thailand, May 8-9, 2008: PEC6OR160 (IN THAI)

VITA

Miss Kanyaluk Ao-ekkasit was born in Nakornratchasima, Thailand on November 15, 1982. She finished high school from Suranari Witthaya School, Nakornratchasima. She received the Bachelor Degree of Science from the department of Chemical Science, Faculty of Science, Mahidol University in 2005. After that, she entered the Graduate School of Chulalongkorn University to pursue the Master of Engineering in Chemical Engineering and completed in 2008.