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THE DESIGN AND CONTROL OF RESILIENT HEAT EXCHANGER NETWORK, TARGET TEMPERATURE VARIATION CASE

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A Thesis Submitted in Partial Fulfillment of the Requirements
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บุศรินทร์ ทรัพย์ไสวผล : การออกแบบและควบคุมข่ายงานเครื่องแลกเปลี่ยนความร้อนแบบยืดหยุ่น ในกรณีที่มีการเปลี่ยนแปลงอุณหภูมิเป้าหมาย. (THE DESIGN AND CONTROL OF RESILIENT HEAT EXCHANGER NETWORK, TARGET TEMPERTURE VARIATION CASE) อ. ที่ปรึกษา : ผศ. ดร. มนตรี วงศ์ศรี, 122 หน้า.

ข่ายงานเครื่องแลกเปลี่ยนความร้อนเป็นวิธีการหนึ่งในการนำพลังงานความร้อนกลับมาใช้อย่างมีประสิทธิภาพในอุตสาหกรรมกระบวนการการผลิต อย่างไรก็ตามการแลกเปลี่ยนพลังงานจะทำให้เกิดผลกระทบกับส่วนอื่นภายในกระบวนการ อีกทั้งในบางกรณีอาจมีการเปลี่ยนแปลงอุณหภูมิเป้าหมายเพื่อปรับค่าประสิทธิผลของผลิตภัณฑ์ ทำให้เกิดความยุ่งยากในการควบคุมเพื่อให้ข่ายงานได้การนำกลับคืนพลังงานสูงสุด และได้อุณหภูมิเป้าหมายตามที่กำหนด การออกแบบข่ายงานเครื่องแลกเปลี่ยนความร้อนแบบยืดหยุ่น ซึ่งสามารถจัดการกับความแปรปรวนที่เกิดขึ้นได้จึงเป็นสิ่งสำคัญ

งานวิจัยนี้ได้นำวิธีการออกแบบข่ายงานเครื่องแลกเปลี่ยนความร้อนแบบยืดหยุ่นของ Wongsri (1990) มาดัดแปลงเพื่อให้สามารถรองรับความแปรปรวนของอุณหภูมิเป้าหมายได้ โดยอาศัยแนวทางฮิวริสติกต่าง ๆ ได้แก่ การออกแบบโดยใช้จุดพินช์ กระแสการจับคู่ การจัดการกับความแปรปรวน การเลือกติดตั้งกระแสบายพาส การใช้สัดส่วนการแยกและการสวิตช์ตำแหน่งที่ควบคุม มาประยุกต์ใช้ในการแก้ปัญหาการออกแบบข่ายงานเครื่องแลกเปลี่ยนความร้อน 3 ตัวอย่าง โดยจากงานวิจัยนี้พบว่า วิธีที่ได้ทำการออกแบบนั้นสามารถที่จะรักษาอุณหภูมิเป้าหมาย และยังสามารถที่จะนำกลับคืนพลังงานสูงสุดอีกด้วย ซึ่งข่ายงานเครื่องแลกเปลี่ยนความร้อนนี้ได้นำไปจำลองบนโปรแกรมไฮซิส (HYSYS) เพื่อทดสอบสมรรถนะของโครงสร้างการควบคุมด้วย

ภาควิชา........วิศวกรรมเคมี........ ลายมือชื่อนิสิต บุศรินทร์ ทรัพย์ไสวผล

สาขาวิชา......วิศวกรรมเคมี........ ลายมือชื่ออาจารย์ที่ปรึกษา....................................

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Heat Exchanger Network (HEN) is an effective method to recover the heat energy used in process plants. However, the energy integration causes to the interactions among process units and some cases there are variation in target temperature may cause the process more difficult to maintain the target temperature. Therefore, in order to achieve maximum energy recovery and to track target temperature at changing desirable values, the resilient heat exchangers that can tolerate the varied target temperatures are indeed necessary.

This research, the resilient heat exchanger network design procedure provided by Wongsri (1990) is extended cover the design resilient network in case target temperature variation. We presents procedure for design control structure of heat exchanger network using heuristic approach such as Pinch Design, Match Patterns, Disturbance Directedness, Bypass Setting, Split Ratio and Selector Switch Setting to solve 3 heat exchanger network problems. It has been shown that our procedure is able to maintain target temperatures at specified values. Furthermore, our design does not violate maximum energy recovery. The heat exchanger network with control structures are programmed using HYSYS for control structure performance tests.

Department......Chemical Engineering...
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Academic year.......2007..................

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Finally, I would like to dedicate this dissertation to my family for their edification, support and endless love.

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CHAPTER I

INTRODUCTION

This Chapter is an introduction of this research. It consists of importance and reasons for research, research objective, scope of research, contribution of research and research contents.

1.1 Importance and Reasons for Research

It is now widely recognized that in production processes of the process industry, i.e., petrochemical plant or refinery plant, the process stream temperatures are normally increased or decreased by heat exchange between one stream and other stream or even stream with the utility. In addition to the heat transfer between heat required stream and heat donated stream, it have gained important commercial significance in saving the energy and operating cost.

To reduce the energy consumption in heating and cooling, the energy recovery network or heat exchanger network must be devised. The network designs must not only feature the economic optimum but also the resiliency characteristics namely, the ability to cope with fluctuations in operating conditions while still maintaining acceptable performance. Resiliency is concerned with the problem of insuring feasible steady state operation over a variation of operating conditions.

Heat exchanger network (HEN) is now received more and more attention and is widely used for heat recovery purpose in various kind of industries. Much effort has been devoted by a number of research groups during the past several decades since its discovery in the mid 1970 and sequentially developed to the pinch analysis which can define the maximum energy recovery and minimum utility used in the process. Moreover, the energy integration can cause the interactions and lead the process more difficult to maintain the target temperature. Therefore, in order to achieve objective of procedure and keep target temperature at their desirable range, the resilient heat exchanger network and control efficiency that can tolerate variations are important and indispensable.

This research is aimed to develop the design procedure of resilient heat exchanger networks (RHEN) and their control structures where there are the variations in target temperatures by using Wongsri's RHEN design and control configuration design procedures. The performance of the heat exchanger network designed and their control structures are evaluated via simulation using HYSYS.

1.2 Research Objective

To devise the design procedure for resilient heat exchanger network for the case of target temperatures varied which based on Wongsri (1990).

1.3 Scopes of research

1. No phase changes in all streams.
2. It is assumed that a utility exchanger can handle all variations of heat load.
3. The heat exchanger network with control structures are programmed using HYSYS for control structure performance tests.
4. Any heat exchanger will have enough heat transfer area to accommodate increases in heat loads of disturbed process streams.
5. The target for develop a design procedure resilient heat exchanger network and their control structures where there are variations in target temperatures using network design and control configuration design procedure with 2 independent HEN problems and 1 process related HEN problem.

1.4 Contributions of research

Procedure and method for designing the suitable heat exchanger network and control structure can be achieved and applied with the process in the presence of disturbance from the variation of inlet temperature, outlet temperature and flowrate. It could reduce the expense of energy consumption and keep safety in the operation. Moreover, user can quickly design the suitable control structure and it is more easily for practical purpose.

1.5 Research procedures

1. Study on the past research that involved to heat exchanger network.
2. Study resilience heat exchanger network and concerned information.
3. Design heat exchanger networks of 2 independent HEN problems and 1 process related HEN problem.
4. Steady state modeling and simulation of heat exchanger networks.
5. Dynamic modeling and simulation of heat exchanger networks.
6. Design of control structures for energy - integrated chemical process HEN problem.
7. Dynamic Simulation for the energy - integrated chemical process HEN problem with control structures design.
8. Assessment of the dynamic performance of the control structure.
9. Analysis of the design and simulation results.
10. Conclusion of the thesis.

1.6 Research Framework

This thesis matter is classified into 6 chapters as follows:

Chapter I provides an introduction, motivation, objective, scope, benefit and thesis outline.

Chapter II presents literature reviews related to control and design of heat exchanger network.

Chapter III purposes law of control structure design which was developed from the combination between the considerations of network structure existed and disturbance transfer technique (Wongsri, 1990). This law can be used to develop the procedure to design the suitable control structure as described in chapter IV. Additionally, more description about the approach for selector switch which is the heuristic of selection and manipulation of heat pathway is presented.

Chapter IV shows the selection of manipulated variable and control variable. Procedures of Design the heat exchanger network and control structure by developing theory in chapter 3. This step can be applied with general heat exchanger network in the presence of energy disturbance i.e., the variation of outlet condition but still be operated and also achieved the target required.

Chapter V the last chapter shows overall conclusions of this research and recommendations for future research.

CHAPTER II

LITERATURE REVIEW

2.1 Heat Exchanger Network Design

The objectives of heat exchanger network are reaching the minimum number of matches and also the maximum energy recovery. Several methods have been performed, Graphs or Diagrams (Nishida et al. 1971), Temperature Interval (Linnhoff and Flower (1978a) , Evolutionary Design Methods (Linnhoff and Flower 1978b), Pinch Method (Linnhoff and Hindmarsh 1983) which utilizes design heuristics and insights derived from the previous work (Linnhoff and Flower 1978a). This method has been widely employed because it is simply and can guarantee maximum energy recovery. The problem must be firstly identified whether it is (1) a heating problem or, (2) a cooling problem or, (3) both heating and cooling problem at which the network is separated by pinch. However, it is important to note that the heat must not be allowed to transfer across the pinch. The suggested matching heuristics are start matching from the pinch, do not transfer heat across the pinch, observe the heat capacity flow rate constraints, etc.

Additionally, Saboo and Morari (1983) classified flexible HENs into two classes according to the kind and magnitude of disturbances that affect the pinch location. For the temperature variation, they show that if the MER can be expressed explicitly as a function of the stream supply and target conditions the problem belongs to Class I, i.e. the case where small variations in inlet temperatures do not affect the pinch temperature location. If an explicit function for the minimum utility requirement valid over the whole disturbance range dose not exists, the problem is of Class II, i.e. the case where large changes in inlet temperatures or flow rate variations cause the discrete changes in pinch temperature locations. It is generally believed that Class II problems are more difficult to solve since the network structure has to vary substantially from one point to another. Furthermore a discontinuity in the pinch zone occurs, the so-called "pinch-jump". Cerda and Galli (1990a) termed this type of problem *nonconvex*. As they pointed out, nonconvexities due to flow rate changes are attributed to the fact that some constraints in the corner point feasibility test become nonlinear. The sources of nonconvexity are: (1) the changes in inlet temperature which cause changes in the stream population in the pinch range (2) flowrate variations.

Although, the pinch technology is the proper way to design HEN, it may not achieve maximum energy recovery (MER) in the presence of disturbance. So, the network design must also realize the resilient of network.

The resilient HEN synthesis methods presented by Marselle et al. (1982), identified heuristically the extreme conditions to design a HEN and the net solution is obtained by combining the network designed at the specified extreme conditions. Later on, Wongsri (1990) developed the heuristics and procedures for resilient heat exchanger network synthesis. The heuristics are used to develop basic and derived match patterns and Disturbance Propagation Method. This method will transfer disturbance from one stream to another stream which remain heat. Moreover, this algorithm can find a resiliency network structure directly from the resiliency requirement and also feature minimum number of units (MNU) and maximum energy recovery (MER). And Cerda et al.,(1990) present a direct design procedure by using a multioptimization technique to generate a resilience network structure. After that, Ploypaisansang (2003) presented the resilient heat exchanger network design procedure provided by Wongsri (1990) is use to design resilient network for the Hydrodealkylation process (HDA Process). The match pattern heuristic, shift approach and the heat load propagation technique are essential approach. Six alternatives for the HDA process are redesign to be the resiliency networks for maintaining target temperature and also reaching maximum energy recovery (MER).

2.2 Control Structure Design

The objectives of heat exchanger network control are reaching the target temperature and keeping the minimum utility. There are recently a few research works concerned heat exchanger network control. Marselle et al. (1982) proposed that all heat exchanger in network should be equipped with bypass and alsoall utilities should be considerably settled with control loop. Calandranis and Stephanopoulos (1988) proposed an approach to design the control loops for a HEN and to order the control actions of the loops in order to accommodate setpoint change and reject load disturbances.

From the prccess design point of view, Mathisen et al. (1992) provided a heuristic method for bypass placement. The resultant HEN is supposedly satisfactory in rejecting disturbances over a moderate range of operating conditions. Aruilera and Marchetti (1998) proposed optimizing and controlling the operation of heat exchange networks. It was divided into two kinds as controlling target temperature and optimization of utility for achieving maximum energy recovery. This finding suggested that bypass selection should be used at control side. Later on, Kunlaniteewat (2001) designed the heat exchanger network structure based on heuristic approach including match pattern, control loop, bypass setting and split ratio. The main purpose was to reach maximum heat recovery and maintain target temperature in the presence of small disturbances (Class1 Problem). After that Leonardo et al. (2003) proposed the design control systems capable of efficiently handling constraints on the manipulated variables of heat exchanger networks (HENs). Flexible-structure refers to the capability of the resulting control system to switch from one closed-loop structure to another that is by switching control structures when the main control signals in order to keep regulation.

Montree Wongsri and Yulius Deddy Hermawan (2004) proposed an appropriate heat pathway, which is selected by means of a selective controller with low selector switch (LSS) to direct the disturbance load to a heating or cooling utility unit in order to achieve dynamic maximum energy recovery (DMER). A selective controller i.e. a low override switch (LOS) was employed in order to select an appropriate heat pathway through the process to carry the associated load to a utility unit. In order to evaluate the dynamic performance of the control system, some disturbances were made. The results revealed that the complex energy integration deteriorated the dynamic performances of the process. The new designed plantwide control structure for HDA process was also compared with the earlier work given by Luyben et al. (1999). In general, better responses of the furnace and cooler utility consumptions were achieved compare to the Luyben's control structure. Both furnace and cooler duties could be decreased according to the input disturbance load, since the HPH was applied in the current work. Therefore, the proposed HPH was proven to be useful as in the illustration of the HDA process to achieve DMER.

CHAPTER III

THEORY

3.1 Introduction

This chapter is aimed to summarize heuristic approach from the previous researches and this approach in heat pathway view point which was developed by Wongsri and Hermawan (2004). It is eventually concluded in law of network design and design control structure when the disturbance from flowrate, supply temperature and target temperature occurred.

3.2 Basic Knowledge for Pinch Technology

3.2.1 Pinch Technology

Pinch technology has been developed for more than two decades and now provides a systematic methodology for analysis chemical processes and surrounding utility systems. The concept was first developed by two independent research groups (Flower and Linnhoff, 1978; Umeda et al., 1979), based on an applied thermodynamics point of view.

3.2.2 Basic Pinch Analysis Concept

The pinch analysis concept is originated to design the heat recovery in network for a specified design task. Starting with do calculate heat and material balance of the process obtained after the core process, i.e. reaction and separation system, has been designed. By using thermal data from the process, we can set the target for energy saving prior to the design of the heat exchanger networks. The necessary thermal data is source, target temperature and heat capacity flow rate for each stream as shown in Table 3.1.

Table 3.1 Thermal data for process streams (Linnhoff and Hindmarsh, 1983).

Stream No.	Stream type	Start Temperature (Ts), °C	Target Temperature (Tt), °C	Heat capacity flow rate (CP), kW/°C
1	Hot	150	60	2
2	Hot	90	60	8
3	Cold	20	125	2.5
4	Cold	25	100	3

Here the hot streams are referred to the streams that required cooling, i.e. the source temperature is higher than that of the target. While the cold streams are referred to those required heating, i.e. the target temperature is higher than the supply. Heat Capacity flow rate is defined as the multiple between specific heat capacity and mass flow rate as shown below.

$$CP = Cp * F \qquad (3.1)$$

Where CP = heat capacity flow rate (kW/°C)

Cp = Specific heat capacity of the stream (kJ/ °C.kg)

F = mass flow rate of the stream (kg/s)

The data used here is based on the assumption that the heat capacity flow rate is constant. In practice, this assumption is valid because every streams with or without phase change can easily be described in terms of linearization temperature-enthalpy data (i.e. CP is constant). The location of pinch and the minimum utility requirement can be calculated by using the problem table algorithm (Linnhoff and Flower, 1979) for a specified minimum temperature different, ΔT_{min}. In the case of $\Delta T_{min} = 20^{o}C$, the results obtained from this method are shown in Table 3.2.

Table 3.2 The problem table for data given in Table 3.1

W				T hot (°C)	T cold (°C)	ΣW (kW/C)	ΔT (°C)	Required Heat (kW)	Interval (kW)	Cascade Heat (kW)	Sum Interval (kW)
H1	H2	C1	C2								
0	0	0	0	150	130	0		Qh		-105	
2	0	0	0	145	125	2	5	107.5	10	2.5	10
2	0	2.5	0	120	100	-0.5	25	117.5	-12.5	12.5	-2.5
2	0	2.5	3	90	70	-3.5	30	105	-105	0	-107.5
2	8	2.5	3	60	40	4.5	30	0	135	-105	27.5
0	0	2.5	3	45	25	-5.5	15	135	-82.5	30	-55
0	0	2.5	0	40	20	-2.5	5	52.5	-12.5	-52.5	-67.5
										Qc	

The pinch separates the problem into 2 thermodynamic regions, namely, hot end and cold end. The hot end is the region comprising all streams or part of stream above the pinch temperature. Only hot utility is required in this region but not cold utility. In contrast to the hot end, the cold end is the region comprising all streams or part of stream below the pinch temperature and only cold utility is instead desired regardless the hot utility. It is important to note that there is no heat transfer across the pinch therefore the minimum utility requirement is achieved.

Additionally, Saboo and Morari (1983) classified flexible HENs into two classes according to the kind and magnitude of disturbances that affect the pinch location. For the temperature variation, they show that if the MER can be expressed explicitly as a function of the stream supply and target conditions the problem belongs to Class I, i.e. the case where small variations in inlet temperatures do not affect the pinch temperature location. If the explicit function for the minimum utility requirement valid over the whole disturbance range dose not exists, the problem is of Class II, i.e. the case where large changes in inlet temperatures or flow rate variations cause the discrete changes in pinch temperature locations.

3.3 Heat Exchanger network

It is generally accepted that an optimal network must feature a minimum number of units that reflects on a capital cost and minimum utility consumption that reflects on operating costs. A good engineering design must exhibit minimum capital and operating costs. For Heat Exchanger Network (HEN) synthesis, other features that are usually considered in design are operability, reliability, safety, etc. in recent years the attention in HEN synthesis has been focused on the operability features of a HEN, e.g. the ability of a HEN to tolerate unwanted changes in operating conditions. It has been learned that considering only a cost objective in synthesis may lead to a worse network, i.e. a minimum cost network may not be operable at some neighboring operating conditions. The design must not only feature minimum cost, but also be able cope with a fluctuation or changes in operating conditions. The ability of a HEN to tolerate unwanted changes is called *resiliency*. It should be note that the ability of a HEN to tolerate wanted changes is called *flexibility*.

The resiliency property of a design becomes an important feature to be accounted for when the extent of integration of a design introduces significant interactions among process components. The energy integration of a HEN generates a quite complex interaction of process streams, despite the fact that transfer of heat from hot to cold process streams is the only activity of the network. The goal of a network is to deliver the process streams to their target temperatures by using most of their heating and cooling availability and a minimum of heating and cooling utilities. The process streams are coupled through a net of heat exchangers. Changing in conditions of one stream in the network may affect the performances of many heat exchanges and the conditions of several process streams. Since resiliency is a property of a network structure.

3.3.1 Definition of HEN Resiliency

In the literature, resiliency and flexibility have been used synonymously to describe the property of HEN to satisfactorily handle variations in operating conditions. These two terms have difference in meaning.

The resiliency of a HEN is defined as the ability of a network to tolerate or remain feasible for disturbances in operating conditions (e.g. fluctuations of input temperatures, heat capacity flowrate, etc.). As mentioned before, HEN flexibility is closed in meaning to HEN resiliency, but HEN flexibility usually refers to the wanted changes of process conditions, e.g. different nominal operating conditions, different feed stocks, etc. That is, HEN flexibility refers to the preservation of satisfactory performance despite varying conditions, while flexibility is the capability to handle alternate (desirable) operating conditions.

A further distinction between resiliency and flexibility is suggested by Colberg el al. (1989). Flexibility deals with planed, desirable changes that often have a discrete set of values; resilience deal with unplanned, undesirable changes that naturally are continuous values. Thus a flexibility is a 'multiple period' type of problem. A resilience problem should be a problem with a continuous range of operating conditions in the neighborhood of nominal operating points.

In order to make Alternative 6 of HDA plant more economically appealing, the minimum number of auxiliary utilities is identified using the proposed design scheme adapted from Wongsri's RHEN (for resilient heat exchanger network) design method.

3.3.2 Heuristics

The heuristics approach is based on the use of rules of thumb to provide a plausible direction in the solution of the problem. There are a number of design procedures using heuristic in structuring an optimal network featuring minimum number of matches and maximum energy recovery (Nishida et al.,1981, Linnhoff and Hindmarsh, 1963); however, there are to be the best of our knowledge that use heuristics to structure a resilient network.

The following are heuristics from the literature classified according to the design criteria.

The heuristics to minimize the capital cost (the number of heat exchangers):

Heuristic C.1 To generate a heat exchanger network featuring the minimum number of heat transfer units, let is match eliminate at least one of the two streams – a 'tick-off' rule (Hohmann, 1971).

Heuristic C.2 Prefer the matches that will leave a residual stream at its cold end if a problem is a heating problem, and at its hot end if a problem is a cooling problem. Obviously, a match of this type will feature the maximum temperature difference.[1]

Heuristic C.3 Prefer matching large heat load streams together. The significance of this rule is that the control problem (a capital cost) of a match of this type(whether it is implemented by one or many heat exchangers) should be less than that of heating or cooling a large stream with many small streams.

The heuristics to minimize the energy cost (the minimum utility requirement):

Heuristic E.1 Divide the problem at the pinch into subproblems and solve them separately (Linnhoff and Hindmarsh, 1983). This is followed by the next three heuristics.

Heuristic E.2 Do not transfer heat across the pinch.

Heuristic E.3 Do not cool above the pinch.

Heuristic E.4 Do not heat below the pinch.

The laws of thermodynamics:

Rule T.1 In a heating problem, if a supply temperature of a cold stream is less than a target temperature of a hot stream by the minimum approach temperature (ΔT_{min}) or more and the heat capacity flowrate of a hot stream is less than or equal to the heat capacity of flowrate of cold stream, the match between these two streams is feasible. (Immediately above the pinch temperature, the heat capacity flow rate of a cold stream must be greater than or equal to that of a hot stream.)

Rule T.2 In a cooling problem, if a supply temperature of a hot stream is greater than a target temperature of a cold stream by minimum approach temperature, ΔT_{min}, or more and the heat capacity of flowrate of a cold stream, the match between these two streams is certainly feasible. (Immediately below the pinch temperature, the heat capacity flow rate of the hot stream must be greater than or equal to that of a cold stream.)

Rule T.1 and T.2 can be used as a quick checks in match feasibility tests.

Rule T.3 For a situation different from the above rules, a match feasibility must be determined by checking whether the minimum temperature difference of a match violates the minimum approach temperature, ΔT_{min}, specifed by the design.

The heuristics that concern heat load state that one must match a large heat load hot and cold streams first. However, we want to propose two heuristics:

Heuristic N.1 We propose that for a heating subproblem, a match where the heat load of a cold stream is greater than of a hot stream should be given higher priority than the other. The reason is that the net heat load in a heating subproblem is a deficit. The sum of heat loads of cold streams is greater than that of hot streams. The proposed match will likely be present in a solution.

Heuristic N.2 Conversely, we prefer a match where the heat load of a hot stream is greater than that of a cold stream in a cooling subproblem.

3.3.3 Physical Approach

In this section a physical or heuristic approach to synthesize a resilient HEN is discussed. By a physical approach we mean the use of the principal knowledge of the HEN and the synthesis heuristics. We believe that this approach will give, not only an understanding of the design, but also an insight to the problem of control and operation as well. The match pattern and the heat load propagation concepts will be explained. The match pattern representation and the heat load propagation method will be used extensively in the resilient HEN design.

The following definitions are for clarity and identifying the scope of the terms that will be used in this research.

Definition 3.1 Heat Exchanger Load (L_{E_i}): Heat exchanger load is a load of heat exchanger, E_i at the design condition.

Definition 3.2 Process Stream Load (L_{S_i}): Process stream load is a load of process stream, S_i at the design condition.

Definition 3.3 **Heat Capacity Flowrate** *(W_i)*: The heat capacity flowrate of stream i for design is the minimum value in its range.

Definition 3.4 **Stream Resiliency Parameter** *(S)*: The stream resiliency parameter is a measure of the difference in the heat load of a stream i from its current value to when its heat capacity flowrate equals the heat capacity flowrate of stream j, W_j.

$$S_i = (W_j - W_i)(T_i^1 - T_i^2) \tag{3.2}$$

Where *(i,j)* is a pair of hot and cold streams $L_j \geq L_i, T^1$ is a hot end temperature and T^2 is a cold end temperature of a process stream. If $W_i > W_j, S_i$ will have a negative value.

***Definition 3.5 Heat Exchanger Resilience Parameter** (E):* Heat exchanger resilience parameter is the measure of how far ΔT_s, is from ΔT_{min}.

$$E_{i,j} = W_j(\Delta T_s - \Delta T_{min}) \tag{3.3}$$

where *(i, j)* is a pair of matched streams. $L_j > L_i$. When $\Delta T_s = \Delta T_{min}$, $E_i = 0$.

***Definition 3.6 Heat Exchanger Resiliency** ($R_{i,j}$):* Heat exchanger resilience of a specified stream *i* (which matched to a larger stream *j*) is the value of the extra heat load that can be shifted from a stream *i* to a stream *j* via such a heat exchanger. The value depends on the particular match pattern of the heat exchanger. In general,

$R_{i,j}$ can be the value of $E_{i,j}$ or R_j whichever is less, R_j where is the resiliency of a residual stream *j* matched to a stream *i*.

Definition 3.7 Original Disturbance *(D)*: The original disturbance now includes the heat capacity flowrate disturbance. See Figure 6.2.

$$D_i = D_i^{\theta} + D_i^{w} + D_i^{t} \tag{3.4}$$

Definition 3.8 Pinch Induced Disturbance *(D^P)*: The pinch-induced disturbance is a disturbance caused by pinch variation. The pinch-induced disturbances are not independent from each other so, they are not additive as ordinary disturbance but deductive. The pinch-induced disturbance is:

Definition 3.9 Supply Temperature Disturbance (D_i^{θ}): The original disturbance of a stream is the disturbance entered at the supply temperature.

$$D_i^{\theta} = \left(T_{i,\max}^{supply} - T_{i,\min}^{supply}\right) \times W_i \tag{3.5}$$

Definition 3.10 Target Temperature Disturbance (D^t_i): The original disturbance of a stream is the disturbance at the target temperature.

$$D^t_i = \left(T_{i,\max}^{target} - T_{i,\min}^{target}\right) \times W_i \tag{3.6}$$

Definition 3.11 Flowrate Disturbance (D^{ω}_i): The flowrate disturbance is the increased heat load due to an increase of heat capacity flowrate from its minimum (design) value to its maximum value over the maximum temperature range of such a stream. See Figure 6.1.

$$D_i^{\omega} = (W_{i,\max} - W_{i,\min})(T_{i,\max}^{1} - T_{i,\min}^{2}) \tag{3.7}$$

3.2.4 Propagated Disturbance

Wongsri (1990) developed the disturbance propagation design (DPD) based on the shift approach. In order to a stream to be resilient with a specified disturbance load, the disturbance load must be transferred to heat sinks or heat sources within the network.

There several design conditions, and usually, these are specified at extreme operating conditions as follows:

1. Nominal operating condition

This is an operating condition that is obtained from a steady state heat and mass balance of a process. In a good design, a network must be operated at this condition most of the time. In general, a fluctuation in operating condition is plus and minus from this point.

2. *Maximum heat load condition.*

This is a condition where all process streams at their maximum heat loads. For example, input temperatures of hot streams are the highest and of cold streams are the lowest. This is also known as the largest maximum energy recovery condition.

3. *Minimum heat load condition*

This is a condition where all process streams at their minimum heat loads. For example, input temperatures of hot streams are the lowest and of cold streams are the highest. This is also known as the lowest maximum energy recovery condition.

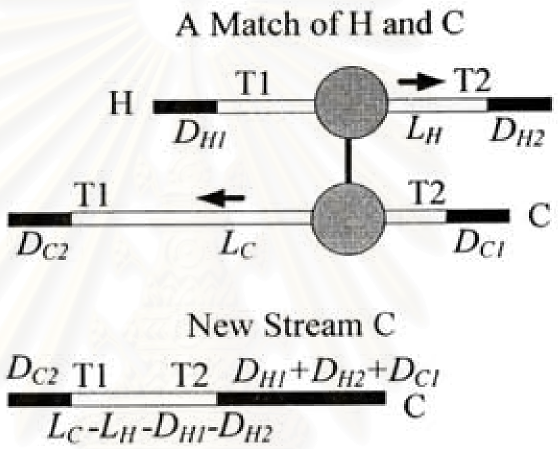
The variations of supply temperature, target temperature and heat capacity flowrate can be viewed as a heat packet that can be shifted through the streams and heat exchangers to dissipate in heat sinks (coolers) or heat sources (heater) of a network. In this approach, there are two cases to be considered as follows:

1. The disturbance load is shifted to a utility exchanger within its network, where it does not across the pinch temperature.
2. The disturbance load is shifted across the pinch temperature to a utility exchanger within its network.

The principles of the DPD can be summarized as follows:

1. The disturbance load of a smaller stream will be shifted to a larger stream. The propagated disturbance of a process stream is the disturbance caused by a variation in heat load of process stream to which such a stream is matched. Only a residual stream will have a propagated disturbance. The new disturbance load of a residual stream will be the sum of its own disturbance (if any) and the propagated disturbance (see Figure 3.1).

2. The design condition was selected to be the minimum heat load condition. This is a condition where all process streams are at their minimum heat loads. For example the input temperatures of hot streams are the lowest and those of cold stream are the highest.
3. Then only the positive disturbance loads of process streams were considered. Thus, the positive disturbance load originating from the hot stream is shifted to heater, and the positive disturbance load originating from the cold stream is shifted to the cooler.



Note:

D_{H1} : The original disturbance of hot stream from supply temperature
D_{H2} : The original disturbance of hot stream from target temperature
D_{C1} : The original disturbance of cold stream from supply temperature
D_{C2} : The original disturbance of cold stream from target temperature
L_H : The Load of hot stream
L_H : The Load of cold stream
T1: The inlet temperature of hot or cold stream at the lowest
T2: The inlet temperature of hot or cold stream at the highest

Design condition was selected to be the minimum heat load condition. Thus, only positive disturbances were considered.

Figure 3.1 A concept of propagated disturbance

For a pinch problem, the process streams are partitioned into heating and cooling subproblems. The pinch temperature for the resilient HENS problem is no longer a fixed point but is defined by a region determined by one or more pinch determining streams. The pinch range can be a single continuous range or two or more disjointed pinch continuous ranges.

A new procedure for stream partitioning must be developed for the disturbance propagation technique. Maintaining MER means that the balance of the heat load of process streams above the pinch point must be transferred to heaters and the balance of heat load of parts of process streams below the pinch point must be transferred to coolers.

The provision for pinch variation is made in our synthesis procedure:

1. The inlet and outlet temperatures of the partitioned process streams, by our convention, are subjected to modification within the range of the pinch region. The partition point for a hot end is the lowest pinch temperature in the pinch region and that of a cold end the highest pinch temperature.
2. The minimum cold end temperature, T2 (the target temperature for a hot stream, the supply temperature for a cold stream) for process streams in a heating subproblem is the highest pinch temperature and the minimum hot end temperature, T1 for process streams in a cooling subproblem is the lowest pinch temperature.
3. The pseudo or pinch-induced disturbances are created to account for the pinch temperature variation.

3.4 Match Pattern

A heuristic approach to design or synthesize a resilient HEN has been presented by Wongsri (1990). A resilient network is defined as a network that provides a down path for variable process streams so that their specified input heat load disturbances can be shifted to the heaters or coolers in their network without violation in the specified target temperatures and MER. HEN synthesis is usually considered as a combinatorial matching problem. Match patterns are the descriptions of the match configuration of two, and possibly more, process streams and their properties that are thermally connected with the heat exchangers.

3.4.1. Classes of Match Paterns

There are four match patterns for a pair of hot and cold streams according to the match position and the length (heat load) of stream. The four match patterns are considered to be the basic match pattern classes and simply called A, B, C, and D as shown in Figures 3.2 to 3.5. Any eligible match must belong to one of the four match pattern classes.

Class A Match Pattern

The heat load of a cold stream is greater than the heat load of a hot stream in a pattern, i.e. the hot stream is totally serviced. The match is positioned at the cold end of the cold stream. The residual heat load is on the hot portion of the cold stream (Figure 3.2).

Class B Match Pattern

The heat load of a hot stream is greater than the heat load of a cold stream in a pattern, i.e. the cold stream is totally serviced. The match is positioned at the hot end of the hot stream. The residual heat load is on the cold portion of the hot stream (Figure 3.3).

Class C Match Pattern

The heat load of a hot stream is greater than the heat load of a cold stream in a pattern, i.e. the cold stream is totally serviced. The match is positioned at the cold end of the hot stream. The residual heat load is on the hot portion of the hot stream (Figure 3.4).

Class D Match Pattern

The heat load of a cold stream is greater than the heat load of a hot stream in a pattern, i.e. the hot stream is totally serviced. The match is positioned at the hot end of the cold stream. The residual heat load is on the cold portion of the cold stream (Figure 3.5).

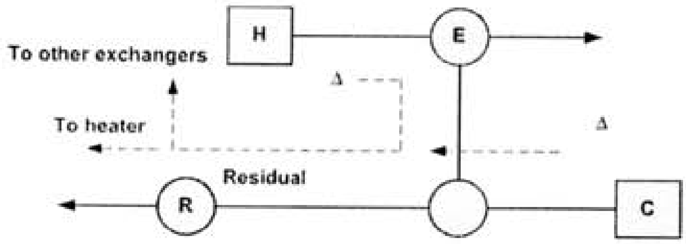


Figure 3.2 Class A Match Pattern.

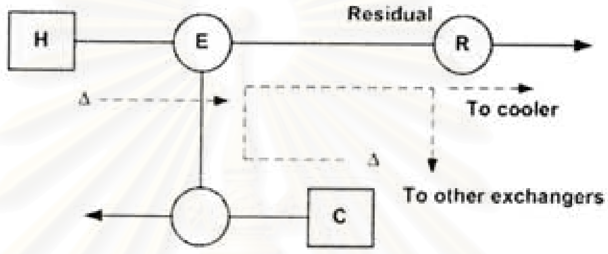


Figure 3.3 Class B Match Pattern.

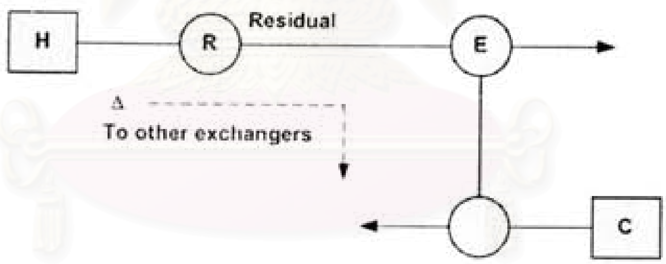


Figure 3.4 Class C Match Pattern.

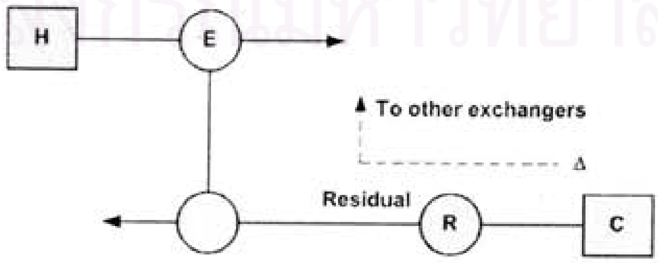
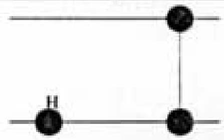
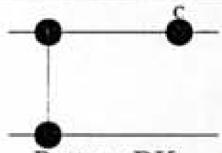
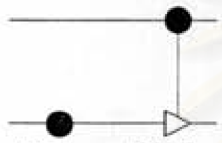
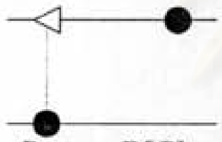
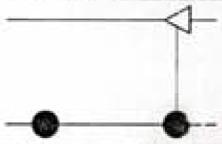
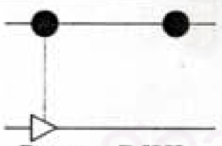


Figure 3.5 Class D Match Pattern

Table 3.3 Match Pattern Operators of Class A and B

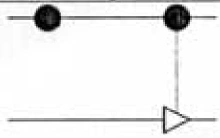
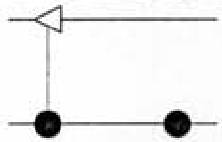
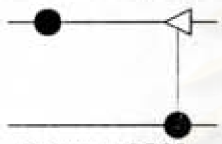
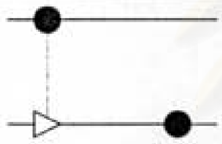
Match Operators	Conditions	Actions
 Pattern AH	$T_H^s * \geq T_C^t **$ $L_H \leq L_C$ $T_H^s \geq T_C^s + L_H W_C^{-1}$ $L_C - L_H \leq Q_{\min}^{heating}$	Match H and C Status of H $\Leftarrow$ Matched*** $T_C^s \Leftarrow T_C^s + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern BK	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $T_C^s \leq T_H^s - L_C W_H^{-1}$ $L_H - L_C \leq Q_{\min}^{cooling}$	Match H and C Status of C $\Leftarrow$ Matched $T_H^s \Leftarrow T_H^s - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$
 Pattern A[H]	$T_H^t \geq T_C^s$ $L_H \leq L_C$ $W_C \geq W_H$	Match H and C Status of H $\Leftarrow$ Matched $T_C^s \Leftarrow T_C^s + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern B[C]	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $W_C \leq W_H$	Match H and C Status of C $\Leftarrow$ Matched $T_H^s \Leftarrow T_H^s - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$
 Pattern A[C]	$T_H^t \geq T_C^s$ $L_H \leq L_C$ $W_C < W_H$ $T_H^s \geq T_C^s + L_H W_C^{-1}$	Match H and C Status of H $\Leftarrow$ Matched $T_C^s \Leftarrow T_C^s + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern B[H]	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $W_H < W_C$ $T_C^s \leq T_H^s - L_C W_H^{-1}$	Match H and C Status of C $\Leftarrow$ Matched $T_H^s \Leftarrow T_H^s - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$

* T^t=target temp, T^s=supply temp, W=heat capacity flowrate, L, Q=heat load.

** Cold stream temperatures are shifted up by ΔT_{min}.

*** There are two statuses of process streams, 'active' and 'matched'. This will exclude this stream from a set of process streams to be selected next.

Table 3.4 Match Pattern Operators of Class C and D

Match Operators	Conditions	Actions
 Pattern C[H]	$T_H^t \ge T_C^s$ $L_H > L_C$ $W_H \le W_C$	Match H and C Status of C $\Leftarrow$ Matched $T_H^t \Leftarrow T_H^t - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$
 Pattern D[C]	$T_H^s \ge T_C^t$ $L_H < L_C$ $W_H \ge W_C$	Match H and C Status of H $\Leftarrow$ Matched $T_C^t \Leftarrow T_C^t + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern C[C]	$T_H^t \ge T_C^s$ $L_H > L_C$ $W_C < W_H$ $T_C^t \le T_H^t + L_C W_H^{-1}$	Match H and C Status of C $\Leftarrow$ Matched $T_H^t \Leftarrow T_H^t - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$
 Pattern D[H]	$T_H^s \ge T_C^t$ $L_H \le L_C$ $W_H < W_C$ $T_H^t \ge T_C^t - L_H W_C^{-1}$	Match H and C Status of H $\Leftarrow$ Matched $T_C^t \Leftarrow T_C^t + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$

3.5 Resilient Match Patterns

When the residual heat load in a match pattern is matched to a utility stream, it is a closed or completed pattern. Otherwise, it is an open or incomplete pattern. It can be seen that if the heat load of the residual stream is less than the minimum heating or cooling requirements (depend on the types of the problems and the match pattern) then the chances that the match pattern will be matched to a utility stream is high. So, we give a match pattern which residual less than the minimum heating or cooling requirement a high priority in match selection. Resiliency of a match pattern can be achieved if the disturbances in input conditions of the hot and cold streams can be transferred to the active stream (a residual portion). For Class A and Class B (Figures 3.2 and 3.3), the disturbance of a member stream can be transferred to the residual. So, they are considered to be potential resilient match pattern.

For Class C and Class D (Figures 3.3 and 3.4), we can see that only the disturbances of a hot stream in Class C and of a cold stream in Class D can be managed but neither a cold stream in Class C nor a hot stream in Class D. Since these two classes cannot handle disturbance of one of their streams, they are considered non-resilient match pattern. Class C and Class D match patterns can be taken into account only when the non-resilient streams in these classes are not subjected to the variations. If the other streams in Class C and Class D must be resilient, its residual stream must be connected to either Class A or Class B match patterns. Hence the only two classes of interests are Class A and Class B

3.6 Resiliency Requirement Test

The test of a resilient match for the flowrate variation case must also test for the resiliency according to temperature and heat capacity flowrate variation.

Two test are required for a specified resiliency for a match with flowrate variation, the first one is the disturbance load as in the temperature disturbance case and the other one is for the heat capacity flowrate constraint.

- Disturbance load constraint. This test is to check whether the given disturbance can pass through a heat exchanger to the residual stream and whether a residual stream can handle the given disturbance.

$$D_i^{\omega} \leq \min\left\{E_{i,j}, R_{j,i}\right\} \tag{3.9}$$

For match patterns A[H] and B[C],

$$D_i^{\omega} \leq R_{j,i} \tag{3.10}$$

- Heat capacity flowrate constraint. This test is to verify whether a match is able to deliver a small heat load process stream to its target temperature.

In general, for a match with both type of disturbance, the resiliency requirements are:

$$D_i^{\omega} + D_i^{\theta} + D_i^{t} \le \min\left\{E_{i,j}, R_{j,i}\right\} \qquad (3.11)$$

$$D_i^{\omega} \le E_{i,j} \qquad (3.12)$$

In shot for the heat capacity flowrate variation case, one more test is required in addition to a temperature variation case:

- Temperature variation case: The propagated disturbance load.
- Heat capacity flowrate variation case: The heat capacity flowrate constraint. Using an equivalent argument, to be resilient a process stream with a lower heat load much match its maximum heat load against the minimum heat load of a larger process stream.

The match test and resiliency test equation of Class A and Class B match patterns are shown in Table 3.6. Those of Class C and Class D are shown in Table 3.7. In the tables, the temperatures of the cold streams and scales up by $\Delta T_{\min}$

Table 3.5 Match Operators I

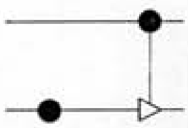
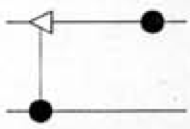
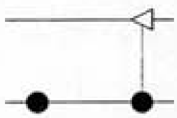
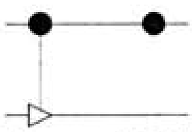
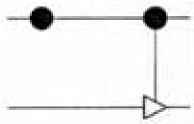
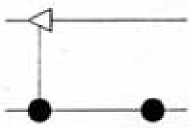
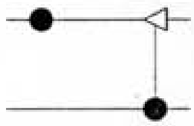
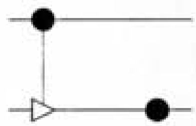
Match Operators	Match Test Equations	Resiliency Test Equations
 Pattern A[H]	$T_H^t \ge T_C^s$ $L_H \le L_C$ $W_C \ge W_H$	$D_H^\theta + D_H^\omega + D_H^t \le R_{C,H}$ $D_H^\omega \le E_{C,H} + S_{C,H}$
 Pattern B[C]	$T_H^s \ge T_C^t$ $L_C \le L_H$ $W_C \le W_H$	$D_C^\theta + D_C^\omega + D_C^t \le R_{H,C}$ $D_C^\omega \le E_{H,C} + S_{H,C}$
 Pattern A[C]	$T_H^t \ge T_C^s$ $L_H \le L_C$ $W_C < W_H$ $T_H^s \ge T_C^s + L_H W_C^{-1}$	$D_H^\theta + D_H^\omega + D_H^t \le \{\min R_{C,H}, E_{C,H}\}$ $D_H^\omega \le E_{C,H} + S_{C,H}$
 Pattern B[H]	$T_H^s \ge T_C^t$ $L_C \le L_H$ $W_H < W_C$ $T_C^s \le T_H^s - L_C W_H^{-1}$	$D_C^\theta + D_C^\omega + D_C^t \le \{\min R_{H,C}, E_{H,C}\}$ $D_C^\omega \le E_{H,C} + S_{H,C}$

Table 3.6 Match Operators II

Match Operators	Match Test Equations	Resiliency Test Equations
 Pattern C[H]	$T_H^t \geq T_C^s$ $L_H > L_C$ $W_H \leq W_C$	$D_C^\theta + D_C^\omega + D_C^t \leq R_{H,C}$ $D_C^\omega \leq E_{H,C} + S_{H,C}$
 Pattern D[C]	$T_H^s \geq T_C^t$ $L_H < L_C$ $W_H \geq W_C$	$D_H^\theta + D_H^\omega + D_H^t \leq R_{C,H}$ $D_H^\omega \leq E_{C,H} + S_{C,H}$
 Pattern C[C]	$T_H^t \geq T_C^s$ $L_H > L_C$ $W_C < W_H$ $T_C^t \leq T_H^t + L_C W_H^{-1}$	$D_C^\theta + D_C^\omega + D_C^t \leq \{\min R_{H,C}, E_{H,C}\}$ $D_C^\omega \leq E_{H,C} + S_{H,C}$
 Pattern D[H]	$T_H^s \geq T_C^t$ $L_H \leq L_C$ $W_H < W_C$ $T_H^t \geq T_C^t - L_H W_C^{-1}$	$D_H^\theta + D_H^\omega + D_H^t \leq \{\min R_{C,H}, E_{C,H}\}$ $D_H^\omega \leq E_{C,H} + S_{C,H}$

3.7 Design of Heat Pathways for Dynamic MER

For the plantwide energy management, the heat pathways through the network are designed so that the dynamic MER can always be achieved. In this work, the heat pathways are designed based on the match patterns design and disturbance propagation technique (Wongsri, 1990)

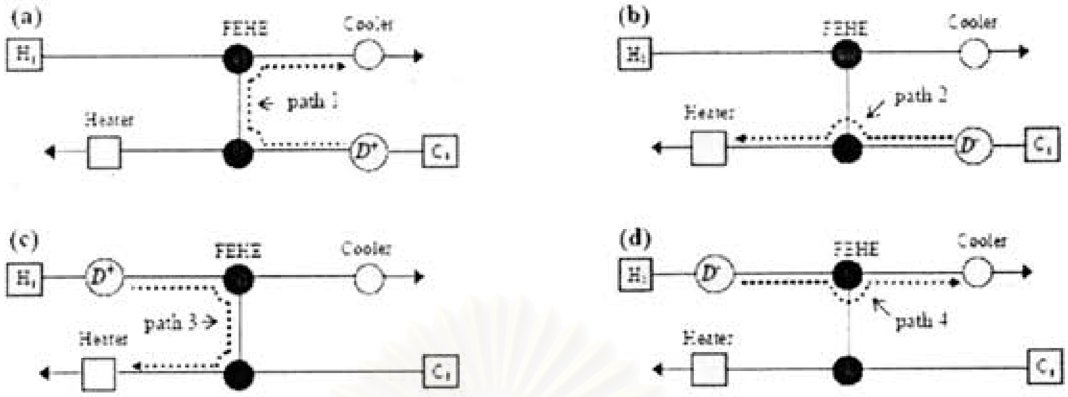


Figure 3.6 Heat pathways in the simplified HEN to achieve the highest possible dynamic MER, where: (a) path 1 is used to shift the positive disturbance load of the cold stream C1 to the cooler, (b) path 2 is used to shift the negative disturbance load of the cold stream C1 to the heater, (c) path 3 is used to shift the positive disturbance load of the hot stream H1 to the heater, and (d) path 4 is used to shift the negative disturbance load of the hot stream H1 to the cooler.

A simplified HEN as shown in Figure 3.6 is used to explain how an appropriate heat pathway should be activated to carry associated load to the utility unit. For instance, when the inlet temperature of a disturbed cold stream decreases, path 1 (Figure 3.6a) should be activated by controlling the cold outlet temperature of FEHE. This will have the effect of shifting the positive disturbance load to the cooler. Thus, the positive disturbance load of a cold stream will result in decrease of the cooler duty. Conside: the case when the inlet temperature of a disturbed cold stream increases, path 2 (Figure 3.6b) should be activated by controlling the hot outlet temperature of FEHE to shift its negative disturbance load to heater. Thus, the negative disturbance load of a cold stream will result in decrease of the heater duty.

On the other hand, when the inlet temperature of a disturbed hot stream increases, path 3 (Figure 3.6c) should be activated by controlling the hot outlet temperature of FEHE to shift its positive disturbance load to heater. As a result, the heater duty will be decreased. Consider the case when the inlet temperature of a disturbed hot stream decreases, path 4 (Figure 3.6d) should be activated by controlling the cold outlet temperature of FEHE to shift its negative disturbance load to cooler. As a result, the cooler duty will be decreased.

3.8 Control Structure of Heat Exchanger Networks

1. Control loop must be settled for reducing the disturbance load path. Calandranis and Stephanopoulos (1988) claimed that it should select the disturbance load path related to the least number of heat exchanger namely the shortest path way in order to reduce the effect of disturbance on another part of network.

2. Bypass Settings

2.1 Reason for Setting Bypass Stream

Bypass stream is the division of stream before exchanging energy in the heat exchanger. This part has no energy exchange. The purpose for setting bypass stream can be divided into two topics as follows (Mathisen et al. 1992)

- To reduce exchanger area.
- To increase degree of freedom in the presence of disturbance in which it acts as manipulated variable.

2.2 Setting of Bypass Stream for Controlling

There are many ways of using bypass stream for a controlling purpose to set its stream and the controller location as can be seen from figure 3.7. Lyben et al. (1998) said that for the design consideration, the bypass stream should be settled on the cold side because it would be safer to equip measure equipment and control valve on the hot side. On the other hand, it should settle bypass stream on the controlling side regardless whether it is hot or cold stream as shown in figure 3.7a and 3.7c. However, the selection must bring about the best performance of control system. Calandranis and Stephanopoulos (1988) attributed that the effect of bypass at steady state regardless the hot side or cold side cause the same result. That is to say it can result in a similar load but different in dynamic result. Marselle et al. (1982), Calandranis and Stephanopoulos (1988), Mathisen et al. (1992), Aguiler and Marchetti (1998) proposed that it should settle bypass stream on the temperature controlling side. For example, bypass stream should be settled on the hot side if hot stream temperature is expected to control.

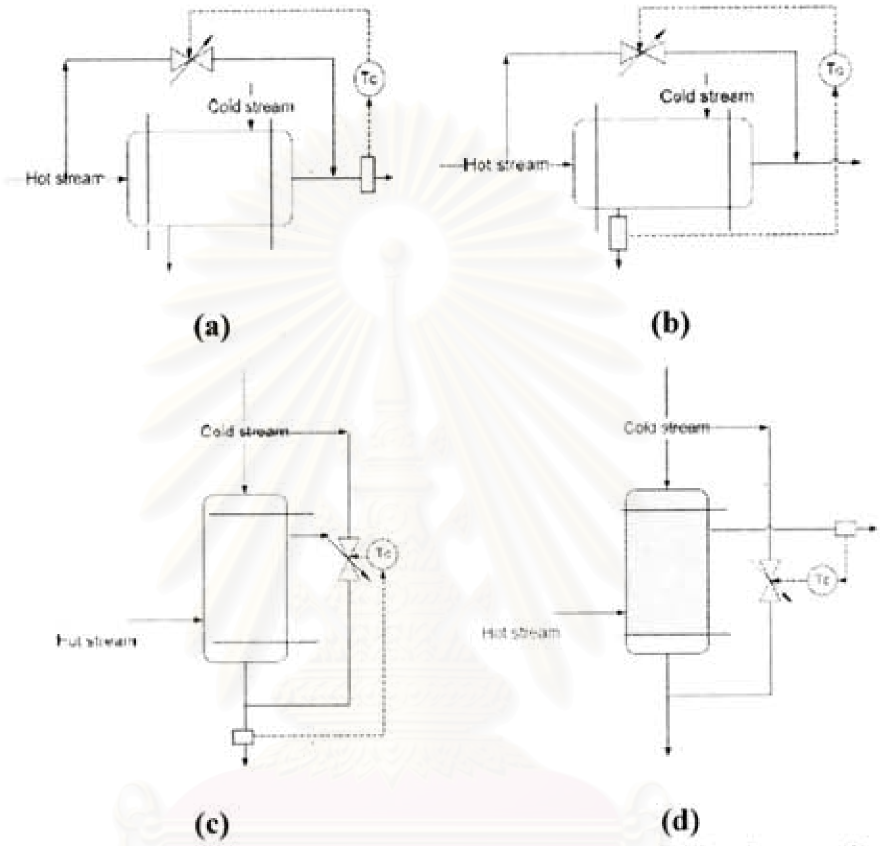


Figure 3.7 The alternation of choosing bypass for controlling heat exchanger.

3. Split Ratio

In network which comprises of split stream, it can adjust the split ratio instead of settling bypass stream for controlling temperature of the exchanged stream. If the controlling temperature is the temperature of aggregated stream, bypass should be settled on heat exchanger at split stream to control that temperature.

For example, figure 3.8, when inlet temperature of stream H2 changes, split ratio can be adjusted to propagate disturbance to utility and the target temperature of stream H2 can be controlled regardless the bypass setting at unit E2 which lower the investment cost of setting bypass and controlled valve as well. If the controlling temperature is the temperature of aggregated stream, which is the outlet temperature of stream C2. The temperature control of C2 can be performed in 3 ways: 1. bypass on E1, 2. bypass on E2 3. adjusting split ratio. In addition to control H2 temperature, it can be performed in 2 ways: bypass on E2 and adjusting split ratio. It is on considering that only bypass on E1 has no effect on temperature of H2. Mathisen et al. (1992) proposed the selection of bypass on unit affected the unity manipulated variable. Thus it should control stream C2 by using bypass E1 and control temperature H2 by using split ratio.

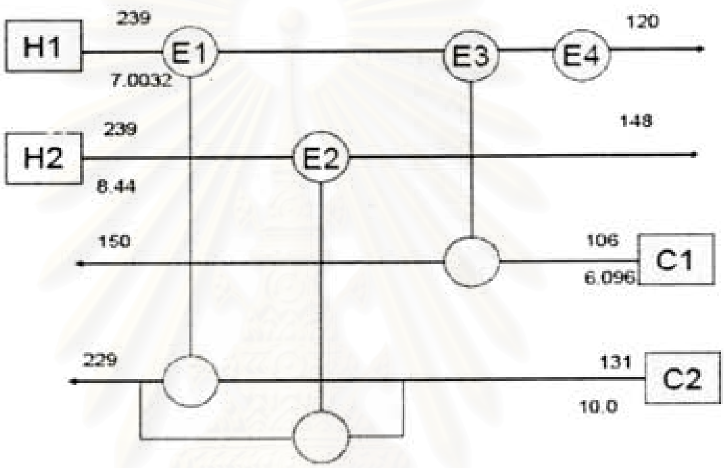


Figure 3.8 Heat exchanger network consist spilt stream.

CHAPTER IV

PROCESS AND DESIGN

4.1 Introduction

As discussed in the previous chapter, a network will be resilient if disturbance loads can be transferred to heaters or coolers in order to maintain target temperatures at specified values. Furthermore, this action

4.2 The Synthesis Procedure

The synthesis of a resilient heat exchanger network by using (1) match pattern as operators in mapping one design state to the next and (2) heat load propagation technique can be done by the following systematic sequence:

1. Choose the minimum heat load condition in order to make the disturbance positive and guarantee the network.
2. Pop a match pattern operator from the ordered stack of match patterns. If all the patterns are chosen, backtrack to the parent design state and repeat the procedure.
3. Choose a pair of hot and cold streams from the set of unmatched process streams. If all streams have been chosen and none were satisfied, go back to the first step to try a new pattern.
4. Apply the match pattern to the selected pair of streams. If the streams satisfy the pattern test and the resiliency requirement, go to the next step. Otherwise go back to the previous step to select a new pair of streams.

   Match pattern test: Check whether the heat load, input temperature and heat flow rate capacity satisfy the match pattern description.

Resiliency test: Check whether the disturbance load of the smaller heat load stream can be shifted to the larger heat load stream.

5. Create a new state to support the new fact. A new state is a descendant of a current one. Change the parameters of the larger heat load stream: the supply or target temperature, the heat load and the disturbance load.

The new supply or target temperature will be adjusted according to the regular heat load and the disturbance heat load of the matched stream. The new heat load of the residual stream is the value between the supply and target temperature at the design condition.

The new disturbance load is the sum of the disturbance load from supply temperature of both matched streams and target temperature of stream which smaller heat load. A special treatment is needed for a pinch match or the match starts off from the pinch point. The new disturbance will be the sum of the upstream disturbance of a stream in the match pair and the difference between the pinch induced disturbance of the two streams. See Figure 4.1.

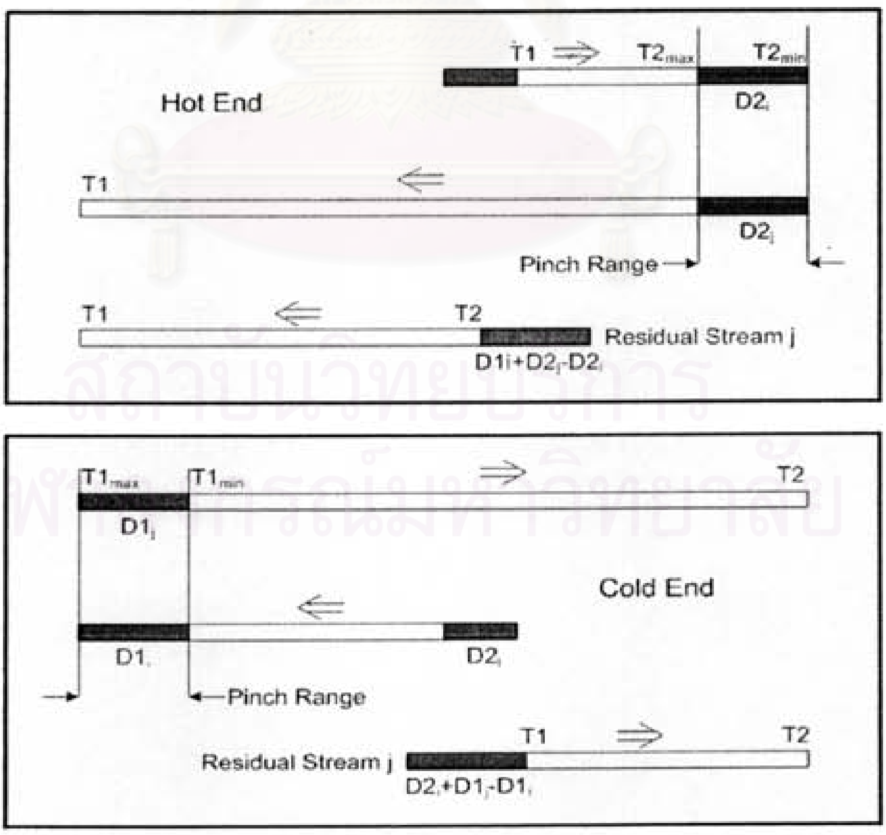


Figure 4.1 A Pinch Match on the Propagated Disturbance Concept

6. For a pinch match of stream i and j for which Wj > Wi and Lj > Li, the disturbance of a residual stream j:

$$D_j = D_i + \left(D_{j,pinch} - D_{i,pinch}\right)$$

The disturbance at the pinch of the two streams must be deductive instead of being additive as in general case. Since the variations of the inlet temperature of stream j and outlet temperature of stream i are not independently varied but tied to the pinch temperature.

The disturbance at outlet stream position induced by the pinch variation has no net effect to the other streams since:

- By the deductive effect described above. It should be denote here that by considering only match pattern Class A and Class B, only a larger heat load and heat capacity flow rate stream can be matched to such a stream. Therefore its downstream disturbance will be engulfed by a larger stream to which such a stream is matched. Only the remaining upstream disturbance of a larger stream (and don't forget the upstream disturbance of a small stream, if there is any) will be propagated to its own residual stream.
- No none-pinched stream can be matched to such stream because of the temperature constraint.

7. If there are unmatched hot and cold streams, go to the second step. Otherwise go to the next step.
8. Match the only hot or cold streams with the utility streams.
9. If there are other unused match patterns go to the first step. This is equivalent to saying that there might be other solutions available, continue.

4.3 The New Heuristic Design Procedure for HEN Control Configuration and Operation

For any HEN configurations, based on the method developed for the above models, we propose the outline for the design of control configuration for heat pathways management to achieve DMER as follows:

1. The heat exchanger network for a particular processing plant should be designed as a resilient HEN following the match pattern proposed by Wongsri (1990)
   1.1 Design the match pattern in HEN as Class A or Class B so that they are considered to be potential resilient match pattern.
   1.2 If there is the match pattern in HEN as Class C or Class D, they are considered as non-resilient match pattern. For the remedy, any Class C or Class D in the match pattern should be redesigned so that its residual stream must be connected to either Class A or Class B. Hence the only two classes of interests are Class A and Class B.
2. Control loop must be settled for reducing the disturbance load path. Calandranis and Stephanopoulos (1988) claimed that it should select the disturbance load path related to the least number of heat exchanger namely the shortest path way in order to reduce the effect of disturbance on another part of network.
3. Use Bypass stream for controlling. The bypass stream should be settled on the cold side because it would be safer to equip measure equipment and control valve on the hot side. On the other hand, it should settle bypass stream on the controlling side regardless whether it is hot or cold stream. However, the selection must bring about the best performance of control system.
4. In network which comprises of split stream, it can adjust the split ratio instead of settling bypass stream for controlling temperature of the exchanged stream. If the controlling temperature is the temperature of aggregated stream, bypass should be settled on heat exchanger at split stream to control that temperature.
5. From the economic point of view, we strongly suggest to:
   (5.1) shift D^+ of cold stream or D^- of the hot stream to the cooler utility, thus its duty will be decreased.
   (5.2) shift D^- of cold stream or D^+ of the hot stream to the heater utility, thus its duty will be decreased.
6. A selective controller with low selector switch (LSS) should be employed to select an appropriate heat pathway through the network to carry the associated load to the utility unit.
7. A selective controller with low selector switch (LSS) should be employed to select an appropriate heat pathway through the network to carry the associated load to the utility unit.

8. The number of LSS to be used in a particular case can be determined as follows:

(7.1) Identify the heat pathway of disturbance

(7.2) If there is only one heat pathway (see Figure 4.2), it do not need to be set the LSS.

(7.3) If there are more than one heat pathway, it need to be set the LSS (see Figures 4.3):

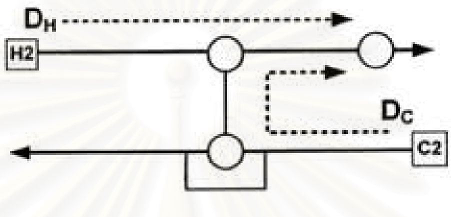


Figure 4.2 One heat pathway

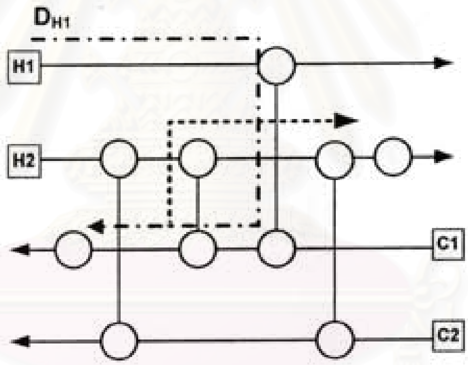


Figure 4.3 More than one heat pathway

4.4 The Hydrodealkylation Process, (HDA Process)

In this section, we presented the process for the Hydrodealkylation (HDA) which converts toluene to produced benzene. Figure 4.4 shows nine basic unit operations: reactor, furnace, vapor-liquid separator, recycle compressor, two heat exchangers, and three distillation columns. Two raw materials, hydrogen, and toluene, are converted into the benzene product, with methane and diphenyl produced as byproducts. The two vapor-phase reactions are

$$C_7H_8(Toluene) + H_2(Hydrogen) \longrightarrow C_6H_6(Benzene) + CH_4(Methane)$$

$$2C_6H_6(Benzene) \rightleftharpoons C_{12}H_{10}(Diphenyl) + H_2(Hydrogen)$$

The kinetic rate expressions are functions of the partial pressure (in psia) of toluene p_T , hydrogen p_H, benzene p_B, and diphenyl p_D, with an Arrhenius temperature dependence. Zimmerman and York (1964) provide the following rate expression.

$$r_1 = 3.6858\times10^6 \exp(\frac{-25616}{T})p_T p_H^{1/2}$$

$$r_2 = 5.987\times10^4 \exp(\frac{-25616}{T})p_B^2 - 2.553\times10^5 \exp(\frac{25616}{T})p_D p_H$$

where r_1 and r_2 have units of lb-mol/(min.ft^3) and T is the absolute temperature in Kelvin. The heats of reaction given by Douglas (1988) are -21500 Btu/lb-mol of toluene for r_1 and 0 Btu/lb-mol for r_2.

The effluent from the adiabatic reactor is quenched with liquid from the separator. This quenched stream is the hot-side feed to the process-to-process heat exchanger, where the cold stream is the reactor feed stream prior to the furnace. The reactor effluent is then cooled with cooling water and the vapor (hydrogen, methane) and liquid (benzene, toluene, diphenyl) are separated. The vapor stream from the separator is split and the remainder is sent to the compressor for recycle back to the reactor.

The liquid stream from the separator (after part is taken for the quench) is fed to the stabilizer column, which has a partial condenser component. The bottoms stream from the stabilizer is fed to the product column, where the distillate is the benzene product from the process and the bottoms is toluene and diphenyl fed to the recycle column. The distillate from the recycle column is toluene that is recycled back to the reactor and the bottom is the diphenyl byproduct.

Makeup toluene liquid and hydrogen gas are added to both the gas and toluene recycle streams. This combined stream is the cold-side feed to the process-to-process heat exchanger. The cold-side exit stream is then heated further up to the required reactor inlet temperature in the furnace, where heat is supplied via combustion of fuel. Tables 4.1 to 4.4 contain data for selected process streams, Table 4.5 presents equipment data and Table 4.6 compiles the heat transfer rates within process equipment.

Table 4.1 Process Stream Data, Part 1

	Fresh toluene	Fresh hydrogen	Purge gas	Stabilizer gas	Benzene product	Diphenyl Product
Stream number	1	2	3	4	5	6
Flow (lb mol/h)	290.86	490.38	480.88	21.05	272.5	6.759
Temperature (°F)	86	86	115	113	211	559
Pressure (psia)	575	575	480	480	30	31
H_2, mole fraction	0	0.97	0.3992	0	0	0
CH_4	0	0.03	0.5937	0.9349	0	0
C_6H_6	0	0	0.0065	0.0651	0.9997	0
C_7H_8	1	0	0.0006	0	0.0003	0.00026
$C_{12}H_{10}$	0	0	0	0	0	0.99974

Table 4.2 Process Stream Data, Part 2

	Gas recycle	Toluene recycle	Furnace inlet	Reactor inlet	Reactor effluent	Quench
Stream number	7	8	9	10	11	12
Flow (lb mol/h)	3519.2	82.14	4382.5	4382.5	4382.5	156.02
Temperature (°F)	115	272	1106	1150	1263.2	113
Pressure (psia)	513	30	513	503	486	486
H_2, mole fraction	0.3992	0	0.4291	0.4291	0.3644	0
CH_4	0.5937	0	0.4800	0.4800	0.5463	0.0515
C_6H_6	0.0065	0.00061	0.0053	0.0053	0.0685	0.7159
C_7H_8	0.0006	0.00037	0.0856	0.0856	0.0193	0.2149
$C_{12}H_{10}$	0	0.00002	0	0	0.0015	0.0177

Table 4.3 Process Stream Data, Part 3

	FEHE Hot in	FEHE Hot out	Separator Gas out	Stabilizer feed	Stabilizer bottoms	Product bottoms
Stream number	13	14	15	16	17	18
Flow (lb.mol/h)	4538.5	4538.5	4156	382.5	361.4	88.91
Temperature (°F)	1150	337	113	113	200	283
Pressure (psia)	486	480	486	480	480	33
H_2, mole fraction	0.3518	0.3518	0.3992	0	0	0
CH_4	0.5294	0.5294	0.5397	0.0515	0	0
C_6H_6	0.0907	0.0907	0.0065	0.7159	0.7538	0.0006
C_7H_8	0.0260	0.0260	0.0006	0.2149	0.2275	0.9234
$C_{12}H_{10}$	0.0021	0.0021	0	0.0177	0.0187	0.0760

Table 4.4 Process Stream Data, Part 4

	Product column reflux	Recycle column reflux
Stream number	19	20
Flow (lb.mol/h)	300	12
Temperature (°F)	211	272
Pressure (psia)	30	30
H_2, mole fraction	0	0
CH_4	0	0
C_6H_6	0.9997	0.00061
C_7H_8	0.0003	0.99937
$C_{12}H_{10}$	0	0.00002

Table 4.5 Equipment Data and Specification

Unit operation	Property	Size
Reactor	Diameter	9.53 ft
	Length	57 ft
FEHE	Area	30000 ft^2
	Shell volume	500 ft^3
	Tube volume	500 ft^3
Furnace	Tube volume	300 ft^3
Separator	Liquid volume	40 ft^3
Stabilizer column	Total theoretical trays	6
	Feed tray	3
	Diameter	4.3 ft
	Reflux drum liquid holdup	7 ft^3
	Column base liquid holdup	250 ft^3
Product column	Total theoretical trays	27
	Feed tray	15
	Diameter	5 ft
	Theoretical tray holdup	2.1 lb mol
	Efficiency	50%
	Reflux drum liquid holdup	25 ft^3
	Column base liquid holdup	30 ft^3
Recycle column	Total theoretical trays	7
	Feed tray	5
	Diameter	3 ft
	Theoretical tray holdup	1 lb mol
	Efficiency	30%
	Reflux drum liquid holdup	100 ft^3
	Column base liquid holdup	15 ft^3

Table 4.6 Heat Transfer Rates

Unit Operation	Power (MW)
FEHE	19.400
Furnace	0.984
Separator condenser	5.470
Product reboiler	2.180
Product condenser	2.050
Recycle reboiler	0.439
Recycle condenser	0.405
Reactor heat generation	1.830

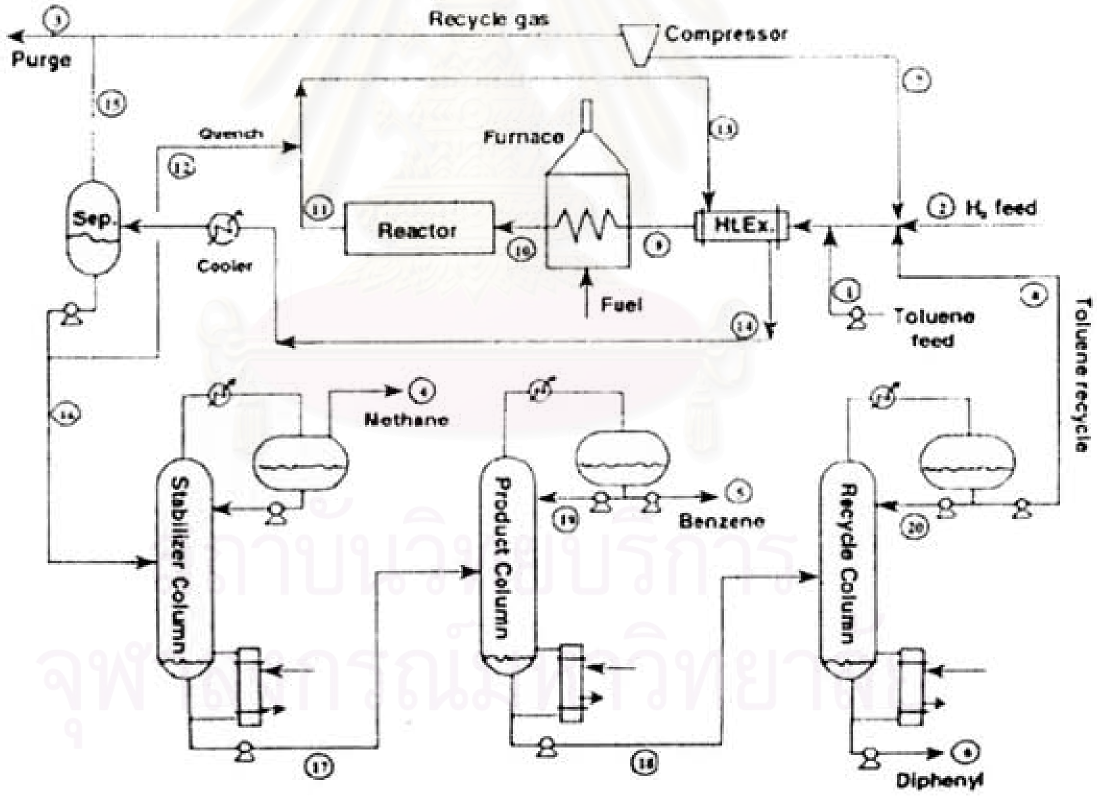


Figure 4.4 Hydrodealkylation HDA of toluene process.

CHAPTER V

RESULT

5.1 Introduction

In this chapter, we give the examples for design and control the resilience heat exchanger network. The design procedures and definitions from previous chapters will be an accessory to design. The Problem Table Method is applied to find pinch temperature and reach maximum energy recovery (MER). The network resiliency, dynamic simulation result and Integral absolute error (IAE) will be consequence to compare and choose the best network.

5.2 Example 1

The data of the synthesis problem is adapted from Tankim (2006) as shown in Table 5.1. The ınlet temperature variations are $\Delta T = \pm 10^{o}C$. The design condition is selected to be the minimum hot and maximum cold streams input temperatures.

5.2.1 Design Heat Exchanger network

With considering the problem from Table 5.1, it could generate problem table as shown in Table 5.2. The pinch is at 100 °C and at this condition the minimum cooling requirement is 115.0 kW and the minimum heating requirement is 124.0 kW.

Table 5.1 Inlet and outlet condition of network in Example 1

Stream No.	Stream Type	W (kW/°C)			Start Temperature (°C)			Target Temperature (°C)		
		Max	Nom	Min	Max	Nom	Min	Max	Nom	Min
1	Hot	1.6	1.5	1.4	145	140	135	115	110	105
2	Hot	-	4.5	-	165	160	155	25	20	15
1	Cold	8.9	8.8	8.7	-	90	-	125	120	115
2	Cold	-	3.5	-	25	20	15	145	140	135

Table 5.2 Problem table for Example 1

W				T hot	T cold	ΣW	ΔT	Required Heat	Interval	Cascade Heat	Sum Interval
H1	H2	C1	C2								
0	0	0	0	160	150	0		Qh			
0	4.5	0	0	150	140	4.5	10	124	45	0	45
0	4.5	0	3.5	140	130	1	10	169	10	179	55
1.5	4.5	0	3.5	130	120	2.5	10	179	25	204	80
1.5	4.5	8.8	3.5	110	100	-6.3	20	204	-126	78	-46
0	4.5	8.8	3.5	100	90	-7.8	10	78	-78	0	-124
0	4.5	0	3.5	30	20	1	70	0	70	70	-54
0	4.5	0	0	20	10	4.5	10	70	45	115	-9
										Qc	

A simple table called *the synthesis table* is constructed to facilitate the match pattern selection. The synthesis table is shown in Table 5.3. The displayed items are ordered for convenience in browsing. The heat load in the second column and temperatures T1 and T2 tell us whether a selected pair belongs to Class A or B. T1 is a higher value of temperature of a stream, e.g. an inlet temperature of a hot stream, and T2 is a lower one, e.g. an inlet temperature of a cold stream. The next column displays values of heat capacity flowrates, whose relationship between a hot and a cold stream tell us whether a selected pair belongs to the H or C category.

The synthesis is carried out stepwise as follows:

1. The starting condition of the process streams in the hot end is shown in Table 5.3 (a)
2. The match pattern A[H] is selected first. A match is found between H1 and C1 since the following conditions satisfy the match pattern A[H].

$$L_{H1} \le L_{C1}$$

$$W_{H1} \le W_{C1}$$

$$T2_{C1} + \Delta T_{\min} \le T2_{H1}$$

The resiliency requirement is that the disturbance of H1 must be less than the difference of the heat loads of the two streams.

$$D_{H1} \le R_{C1,H1}$$

$$D_{H1} \le L_{C1} - L_{H1}$$

This is the only requirement for the pattern A[H] (and also B[C]). In other words, the minimum heat load of the residual C1 (the value after the disturbance is shifted in) must be greater than zero.

The new process stream data in State 2 are shown in Table 5.3 (b). Notice that the new T2 temperature of C1 is the highest value of the range determined by using the propagation concept. So, the temperature variation range of the residual C1 is increased to 3.22 *°C*. The new disturbance load of C1 is 8+14+9 = 31 *kW*. The disturbance at target temperate of C1 is the same.

3. By just browsing over the table we can see that the match pattern A[H] cannot be satisfied further by the new set of streams since none of the cold streams has a higher heat load value than of the hot stream.
4. The next operator is the match pattern B[C] and there are three active streams -- H2, C1 and C2 to be considered. H2 and C2 satisfy the pattern and the resiliency tests.
5. C2 is match to H2 – State 2.
6. In State 3, C1 is matched to H2. Then there is only one pair of streams left – H2 and C1. They can be matched together by the pattern A[H]. See Table 5.3 (c). The disturbance load of C1 is less than the residual heat load of H2 or the minimum cooling load so the resiliency requirement is satisfied.

From this particular problem in which there is only one cooler, it can be seen that a resilient network structure solution can be found if the *propagated* heat load is less than a minimum utility requirement.

7. State 4. Table 5.3 (d). Match the residual C1 to a heating utility stream.
8. In the cold end, the starting condition of the process streams is shown in Table 5.4 (a)
9. There is only one pair of streams left so it is satisfied the match pattern B[C]. The new process stream data show in Table 5.4 (b) and match the residual H2 to cooling utility stream.

Table 5.3 Synthesis Table for Hot End of example 1

Hot end

Stream	Load	W	T1	T2	Ds	Dt	Dw	Action
(a) State 1								
H1	28.00	1.40	135.00	115.00	14	14	8	Selected
H2	247.50	4.50	155.00	100.00	45	0	0	
C1	217.50	8.70	115.00	90.00	0	87	7	Selected A[H]
C2	157.50	3.50	135.00	90.00	0	35	0	
(b) State 2								
H1								Matched to C1
H2	247.50	4.50	155.00	100.00	45	0	0	Selected
C1	154.50	8.70	115.00	93.22	0	87	43	
C2	157.50	3.50	135.00	90.00	0	35	0	Selected B[C]
(c) State 3								
H1								Matched to C1
H2	55.00	4.50	120.00	100.00	80	0	0	Selected
C1	154.50	8.70	115.00	93.22	0	87	43	Selected A[H]
C2								Matched to C2
(d) State 2								
H1								Matched to C1
H2								Matched to C2
C1	19.50	8.70	115.00	99.54	115	87	0	to heater
C2								Match to H2

Table 5.4 Synthesis Table for Cold End of example 1

Cold end

Stream	Load	W	T1	T2	Ds	Dt	Dw	Action
(a) State 1								
H1								
H2	360.00	4.50	100.00	20.00	0.00	0.00	0.00	Selected
C1								
C2	227.50	3.50	90.00	25.00	0.00	35.00	0.00	Selected B[C]
(b) State 2								
H1								
H2	97.50	3.50	49.44	20.00	35.00	0.00	0.00	to cooler
C1								
C2								

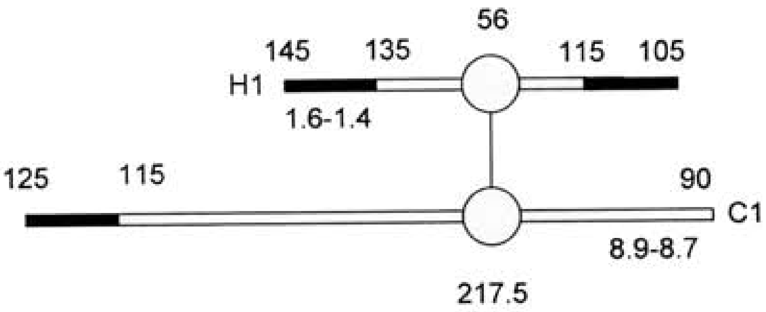


Figure 5.1 The Stream H1 and C1 of Example1

The test procedures for the match of

1. Match test. From the table we see that In Figure 5.1 the T2 temp of H1 and C1 different 10 °C= ΔT_{min} , so it is satisfied the requirement. Next, we must look at the Heat capacity flowrate constraint, since the match is class A[H], $L_{H1} \le L_{C1}$ and $W_{H1} \le W_{C1}$.
2. Resiliency test. The resiliency is required because both H1 and C1 are variable stream. The load of H1 will be use up. The residual load of C1 is 217.5 - 56 = 161.5 or $R_{C1,H1} = 161.5$

$$D_{H1}^{\theta} = 1.4(145-135) = 14$$

$$D_{H1}^{t} = 1.4(115-105) = 14$$

$$D_{H1}^{\omega} = (1.6-1.4)(145-105) = 8$$

$$D_{H1}^{\theta} + D_{H1}^{t} + D_{H1}^{\omega} = 35 \le R_{C1,H1}$$

The disturbance load is satisfied, the next test is feasibility of a match on the extra heat capacity flowrate. In this test we see whether the exchanger resilience parameter or the stream resiliency parameter can handle an extra load due to the heat capacity flowrate disturbance. Since the heat capacity flowrate of H1 is less than C1, the stream resiliency parameter is negated by definition.

$$E_{C1,H1} = 8.7(110-90-10) = 87$$
$$S_{C1,H1} = (8.7-1.4)(145-110) = 182.5$$
$$D_{H1}^{\omega} = 7 \le E_{C1,H1} + S_{C1,H1}$$

The match of H1 and C1 passes the match and resiliency test.

The network solution for cold end is shown in Figure 5.2

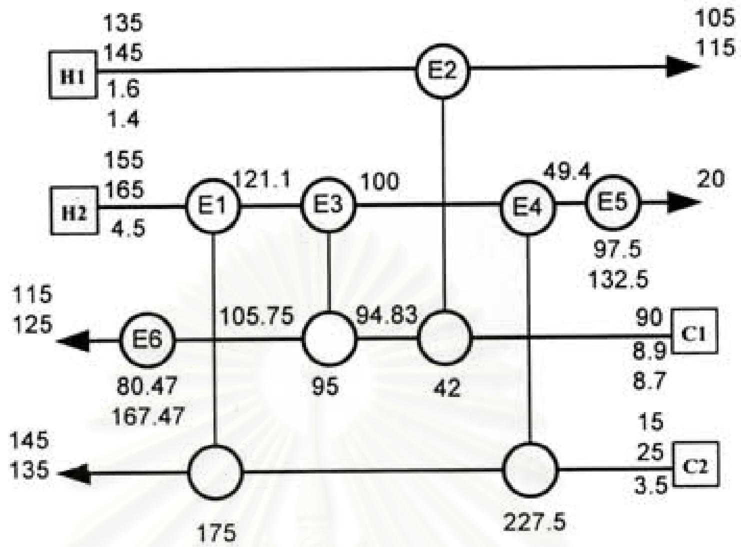


Figure 5.2 A network solution of Example1

5.2.2 Design Control Structure

From the procedure, it can be used to design control structure as follows:

Step 1. Design control structure. We consider the maintenance target temperature and heat pathway of disturbance simultaneously.

Network at cold end side (Figure 5.3)

Beginning with determination of set up control loop at utility of any stream in order to maintain target temperature. Then equip bypass at hot stream of HE 1 and at cold stream of HE1 to control H1 and C1 outlet temperature because they are the end of the stream. H2 should be settled bypass and control loop for control the pinch temperature. Actually we have elected to install the bypass valves on the cold side to lower the investment cost but for facilitate maintenance we have chosen to install the bypass valves on the same side that we control.

Network at hot end side (Figure 5.4)

C2 should be settled bypass and control loop for control the pinch temperature.

Step 2. Set up LSS in the network based on the heat path way heuristic approach.

Considering Figure 5.5, dash lines show the pathway of disturbance, there are 2 ways at HE4 and HE1. Then, settle up cascade in order to calculate new setpoint temperature of hot stream and cold stream of HE4 and HE1 which provide no increase in cooler duty and heater duty (Figure 5.6).

In Figure 5.7 and 5.8 show the heat pathway of positive and negative disturbance in Example 1 when settled the control structure and LSS. We see that all disturbances will transfer to the utility. In Figure 5.9 shows the simulation in HYSYS flowsheet.

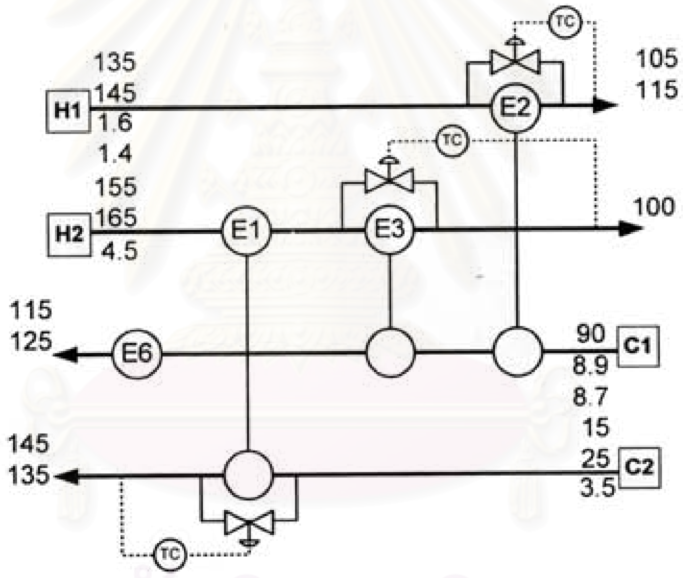


Figure 5.3 Control structure of Cold End side for Example 1

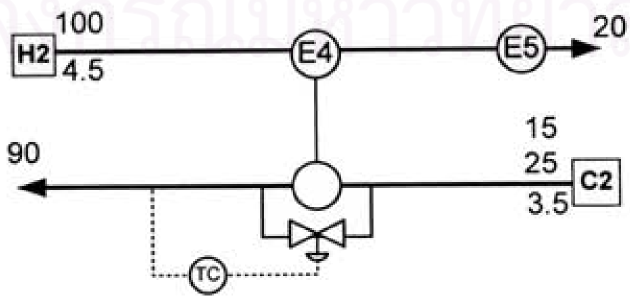


Figure 5.4 Control structure of Hot End side for Example 1

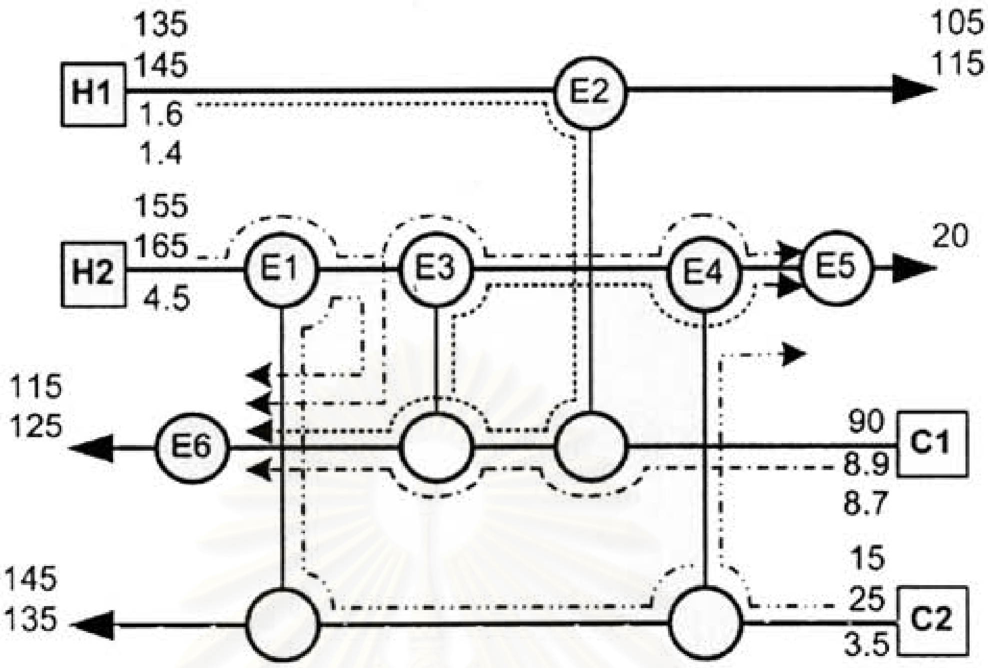


Figure 5.5 Heat pathways of disturbances in each stream for Example 1

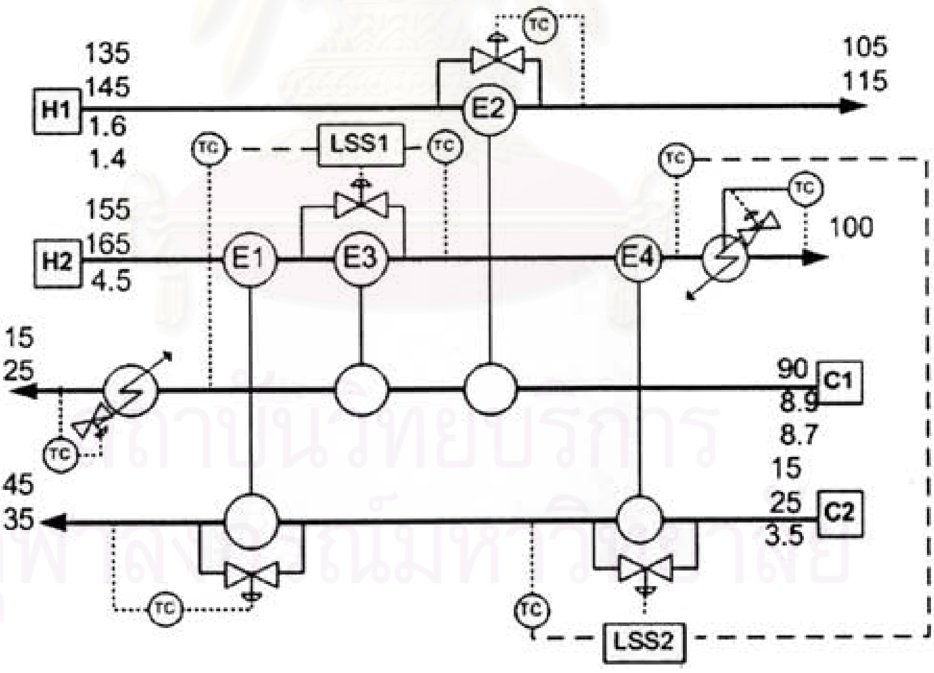


Figure 5.6 Control structure for Example 1 with LSS

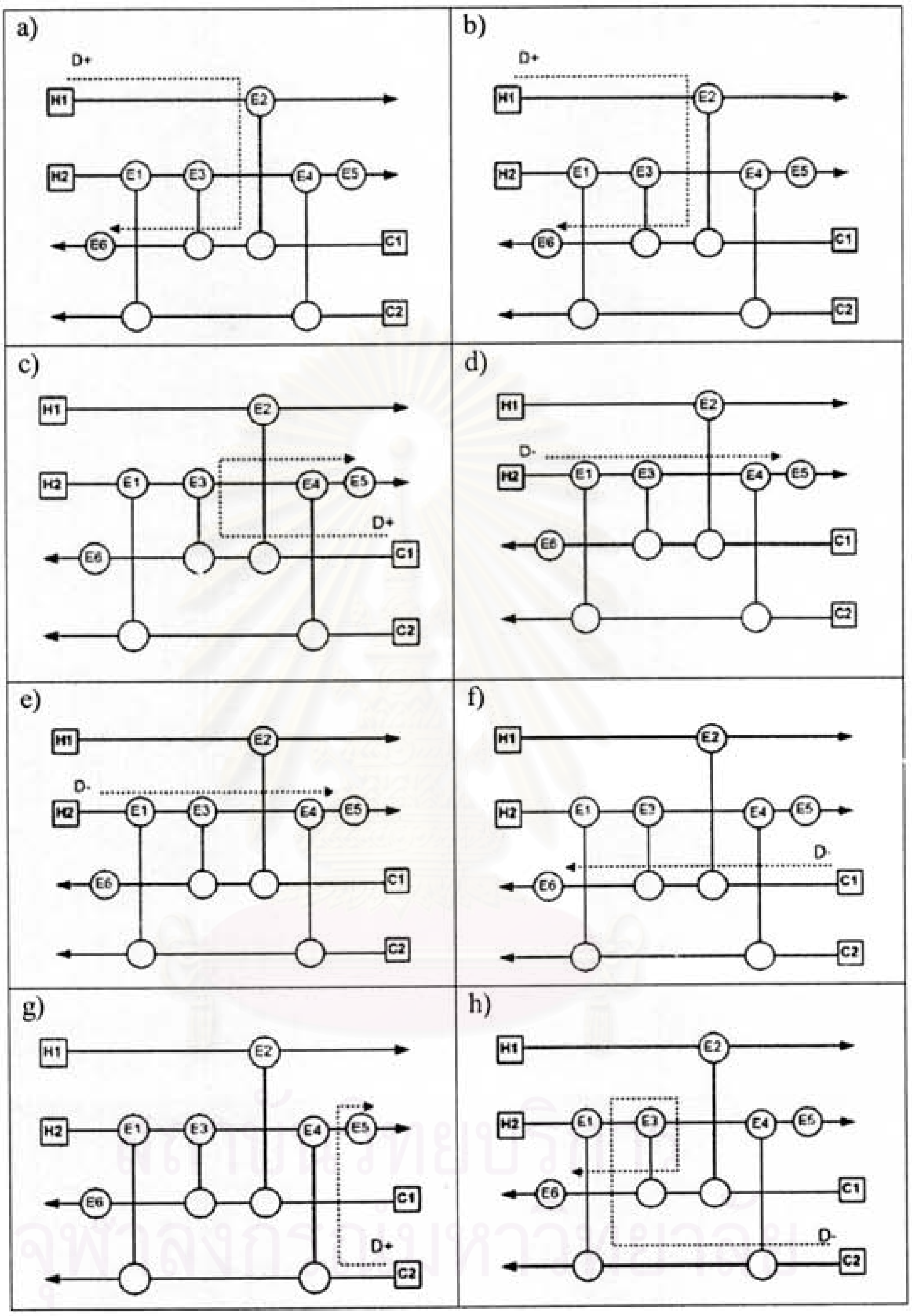


Figure 5.7 Heat pathway of control structure of network equipped with LSS of Example 1 when there is the disturbance at supply temperature a) D+ presented at H1, b) D- presented at H1 c) D+ presented at H2, d) D- presented at H2 e) D+ presented at C1, f) D- presented at C1 g) D+ presented at C2, h) D- presented at C2

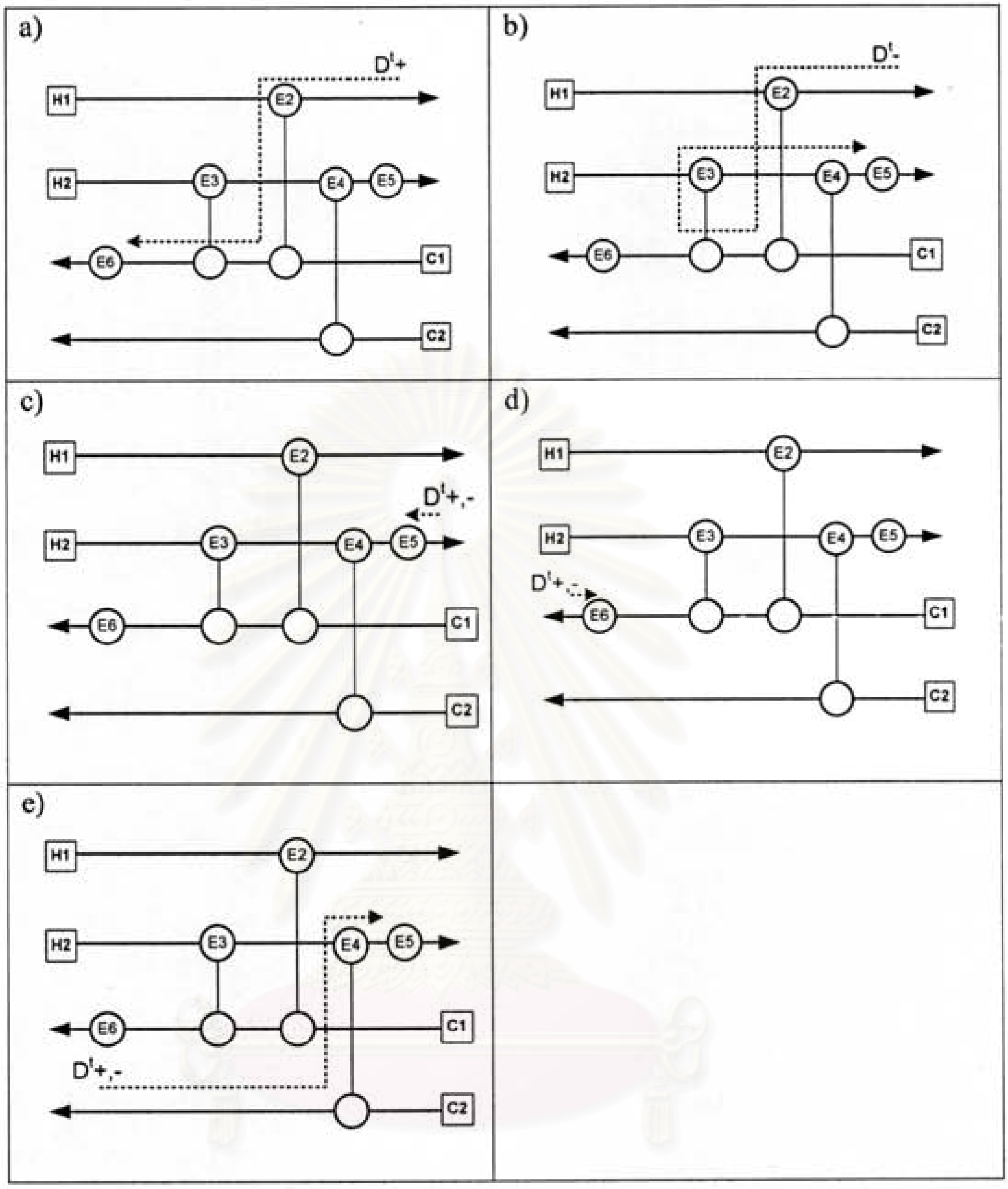


Figure 5.8 Heat pathway of control structure of network equipped with LSS of Example 1 when there is the disturbance at target temperature a) D^t+ presented at H1, b) D^t- presented at H1 c) D^t+, D^t - presented at H2, d) D^t+, D^t - presented at C1 e) D^t+, D^t - presented at C2

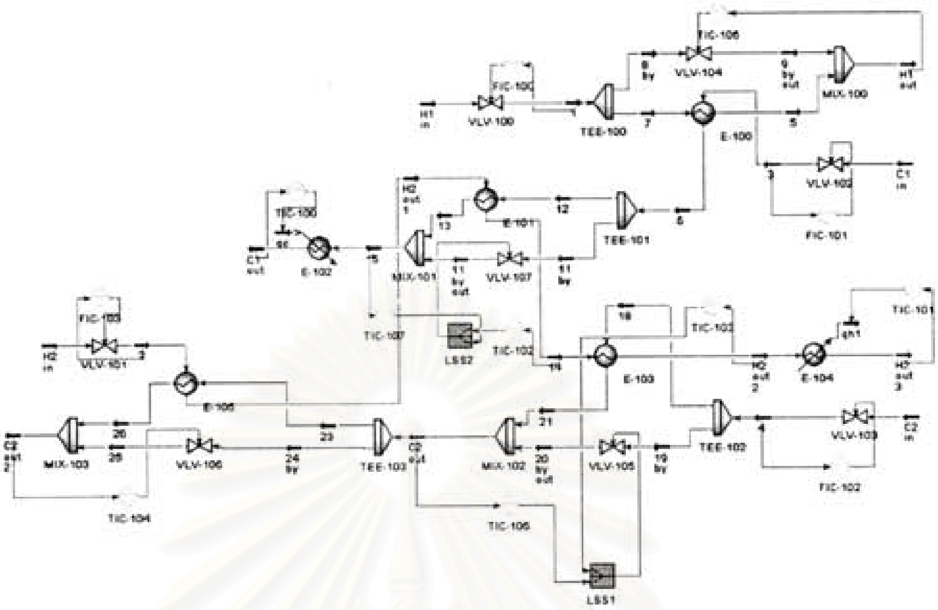


Figure 5.9 Heat exchanger network with LSS of example 1 frcm HYSYS flow sheet

5.2.3 Dynamic Simulation Result for HEN in example 1

In order to evaluate the dynamic behaviors of the HEN in Example 1, several disturbance loads were made, the dynamic responses of the control systems are shown in Figure 5.10-5.18. Left side shows dynamic behavior of system without LSS and the right side presents the dynamic behavior of the new control system using the LSS to select appropriate heat pathway through the network.

Change in Supply Temperature of Hot Stream H1 Temperature for Example 1

Figure 5.10 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of H1. In order to make these disturbances, first the fresh feed H1 temperature decreases from 140°C to 135 °C at time equals 10 minutes and the temperature increases from 135 °C to 145 °C at time equals 150 minutes then its temperature returns to its nominal value of 140 °C at time equals 300 minutes.

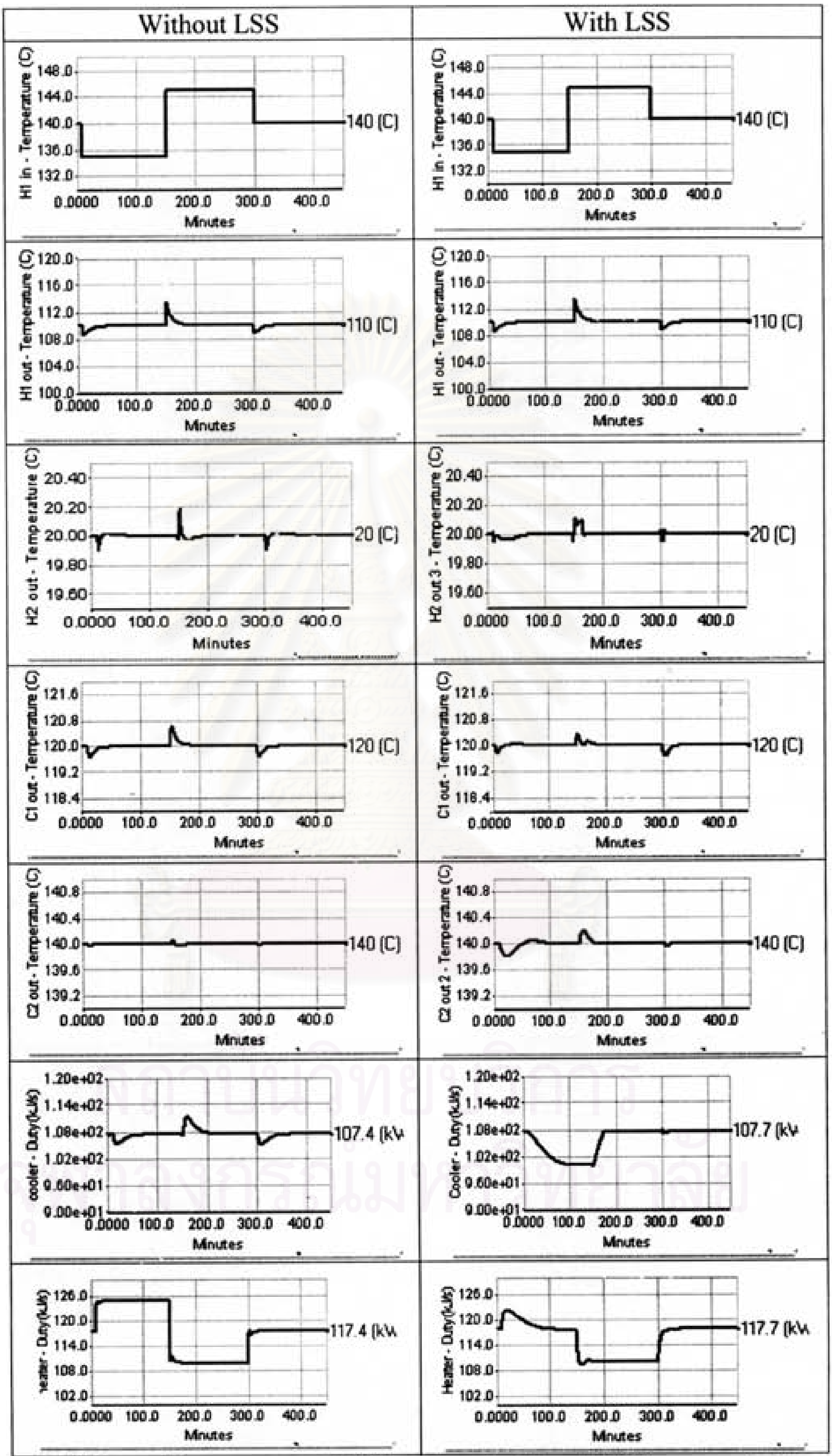


Figure 5.10 Dynamic responses of HEN with and without LSS in example 1 to a change in the supply temperature of H1

As can be seen, first the hot stream inlet temperature (H1) decreases. That is saying negative disturbances, (D-). Heat pathway is shown in Figure 5.7b. As a result, the hot outlet of HE1 temperature decreases below its minimum value, the LSS takes an action to control the cold outlet temperature of HE1 so the cooler duty decreases from 107.7 kW to 99.1 kW. Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of HE1. Consequently, following Figure 5.7a, the heater duty will be decreased from 117.7 kW to 110 kW (Figure 5.10) while the duty of cooler still the same.

Change in Target Temperature of Hot Stream H1 for Example 1

Figure 5.11 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of H1. In order to make these disturbances, first the target temperature of H1 decreases from 110°C to 105 °C at time equals 10 minutes and the temperature increases from 105 °C to 115 °C at time equals 150 minutes then its temperature returns to its nominal value of 110 °C at time equals 300 minutes.

As can be seen, first the hot stream outlet temperature (H1) decreases. That is saying positive disturbances, (D+). As a result, the hot outlet temperature can be reached the desired value. Heat pathway is shown in Figure 5.8a. The LSS takes an action to control the hot outlet temperature of HE2 so the heater duty decreases from 117.7 kW to 110 kW. Then, the negative disturbance load of hot stream is shifted to a cooler utility by controlling the cold outlet temperature of HE2. Consequently, following Figure 5.8b, the cooler duty will be decreased from 107.7 kW to 98 kW (Figure 5.11) while the duty of cooler is going to the nominal value.

Change in Supply Temperature of Hot Stream H2 Temperature for Example 1

Figure 5.12 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of H2. In order to make these disturbances, first the fresh feed H2 temperature decreases from 160°C to 155 °C at time equals 10 minutes and the temperature increases from 155 °C to 165 °C at time equals 150 minutes then its temperature returns to its nominal value of 160 °C at time equals 300 minutes.

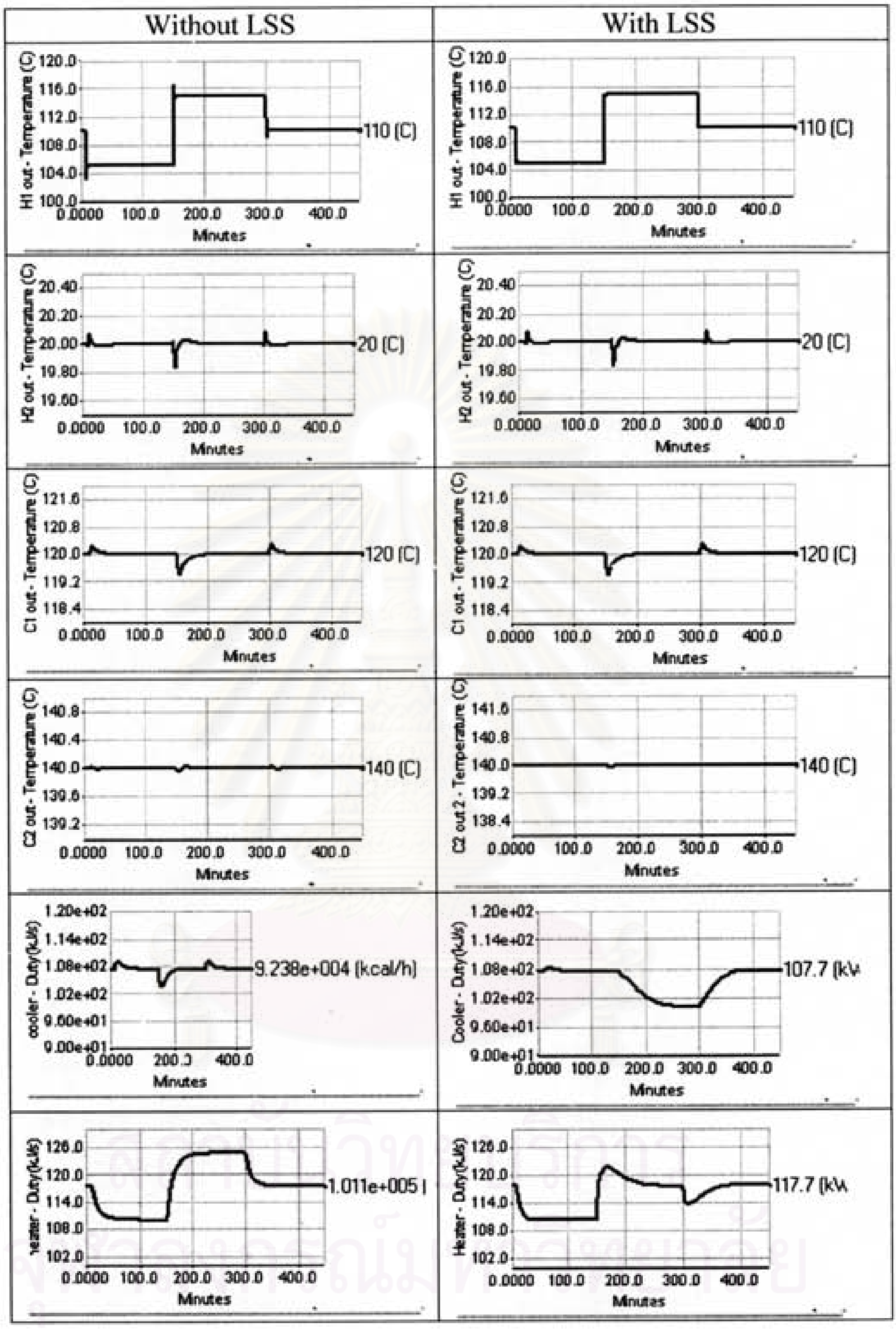


Figure 5.11 Dynamic responses of HEN with and without LSS in example 1 to a change in the target temperature of H1

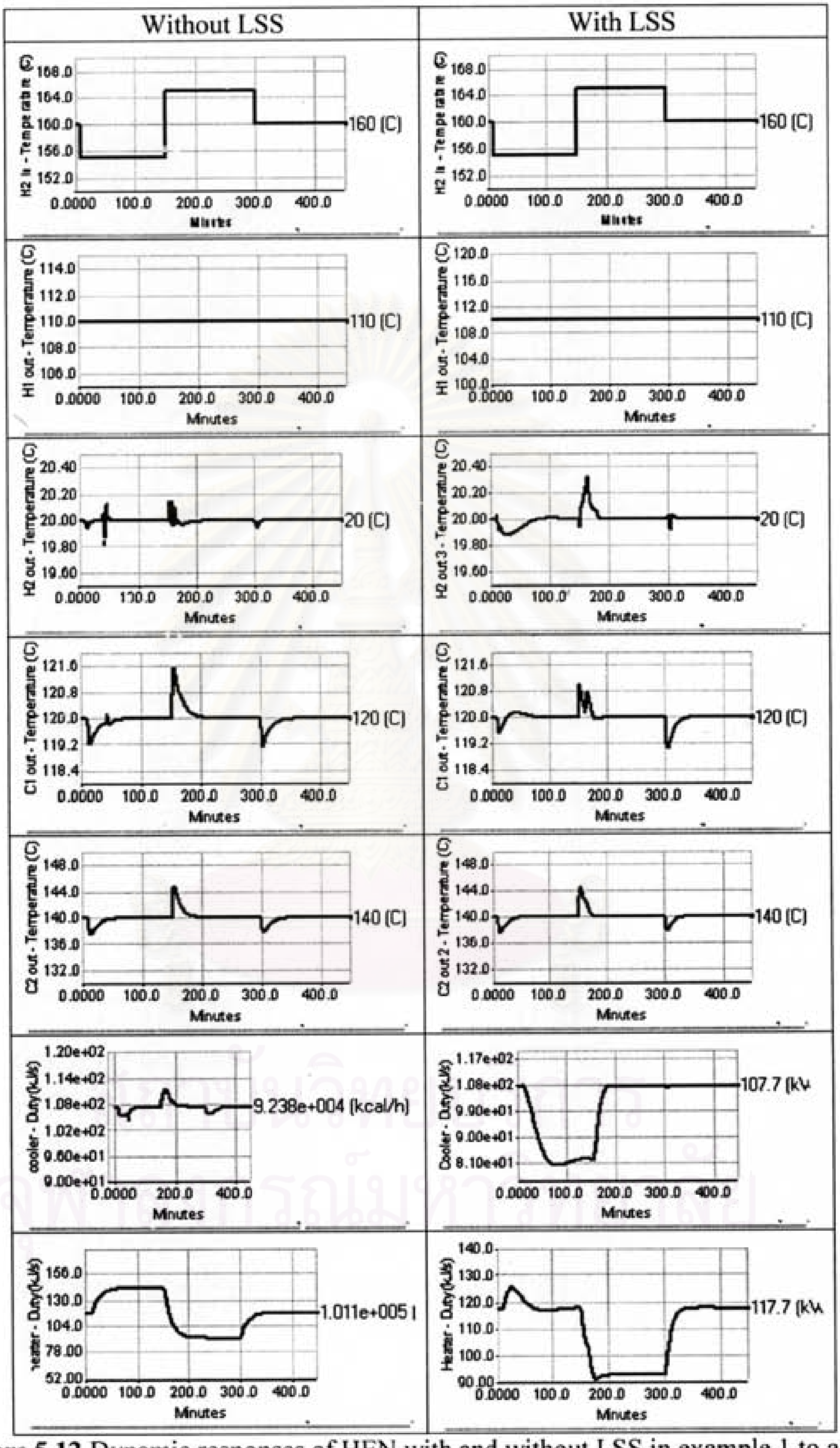


Figure 5.12 Dynamic responses of HEN with and without LSS in example 1 to a change in the supply temperature of H2

As can be seen, first the hot stream inlet temperature (H2) decreases. That is saying negative disturbances, (D-). Heat pathway is shown in Figure 5.7d. As a result, the hot outlet of HE3 temperature decreases below its minimum value. Then it makes the H2 temperature outlet from HE4 decreases. The LSS takes an action to control the cold outlet temperature of HE1 so the cooler duty decreases from 107.7 kW to 81 kW. Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of HE3. Consequently, following Figure 5.7c, the heater duty will be decreased from 117.7 kW to 93.5 kW (Figure 5.12) while the duty of cooler is going to the nominal value.

Change in Target Temperature of Hot Stream H2 for Example 1

Figure 5.13 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of H2. In order to make these disturbances, first the target temperature of H2 decreases from 20°C to 15 °C at time equals 10 minutes and the temperature increases from 15 °C to 25 °C at time equals 150 minutes then its temperature returns to its nominal value of 20 °C at time equals 300 minutes.

As a result, the hot outlet temperature (H2) can be reached the desired value. Figure 5.8c shows the heat pathway that disturbance will go directly to the cooler utility. There is no effect in temperature of other streams.

Change in Target Temperature of Cold Stream C1 for Example 1

Figure 5.14 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of C1. In order to make these disturbances, first the target temperature of C1 decreases from 120°C to 115 °C at time equals 10 minutes and the temperature increases from 115 °C to 125 °C at time equals 150 minutes then its temperature returns to its nominal value of 120 °C at time equals 300 minutes.

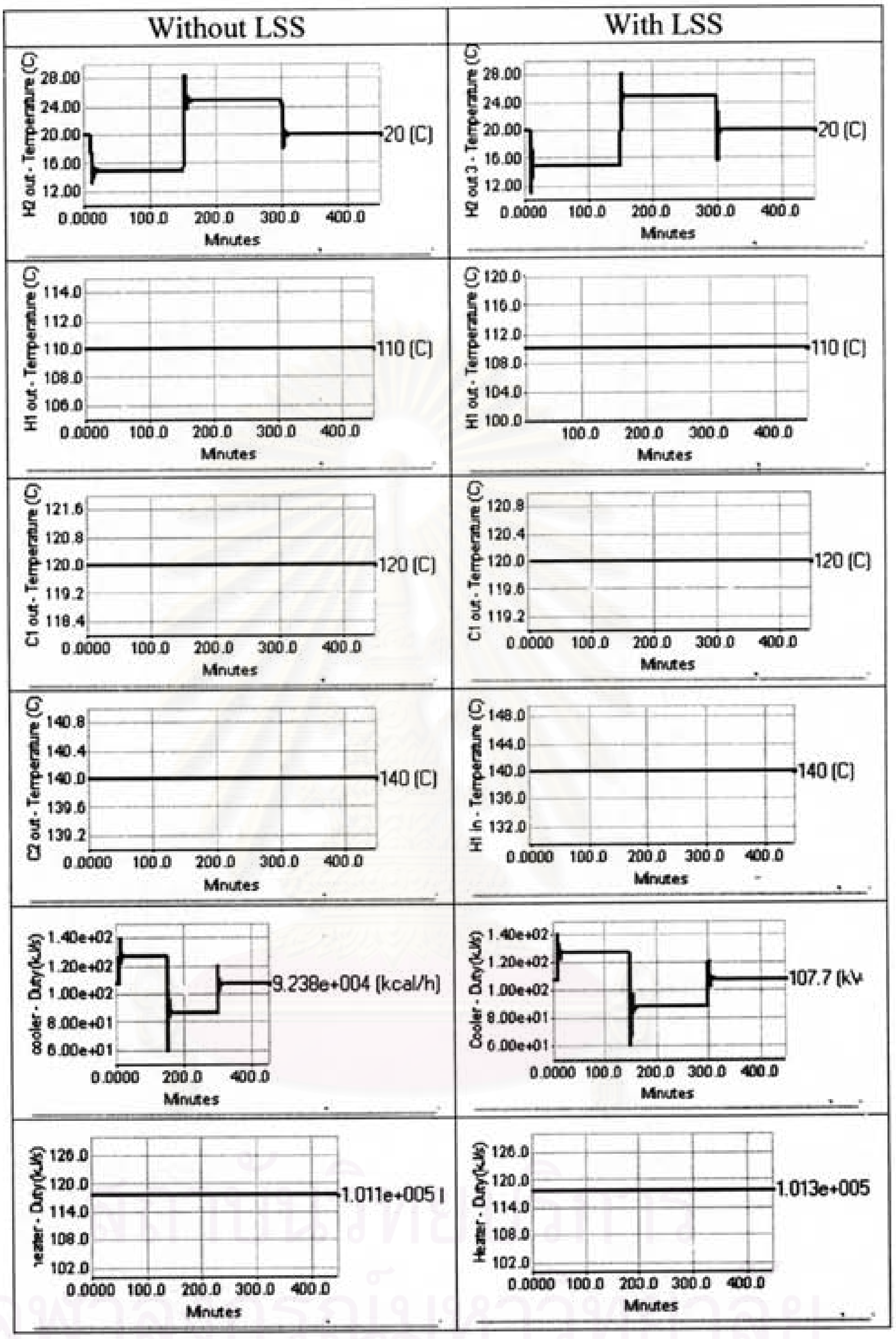


Figure 5.13 Dynamic responses of HEN with and without LSS in example 1 to a change in the target temperature of H2

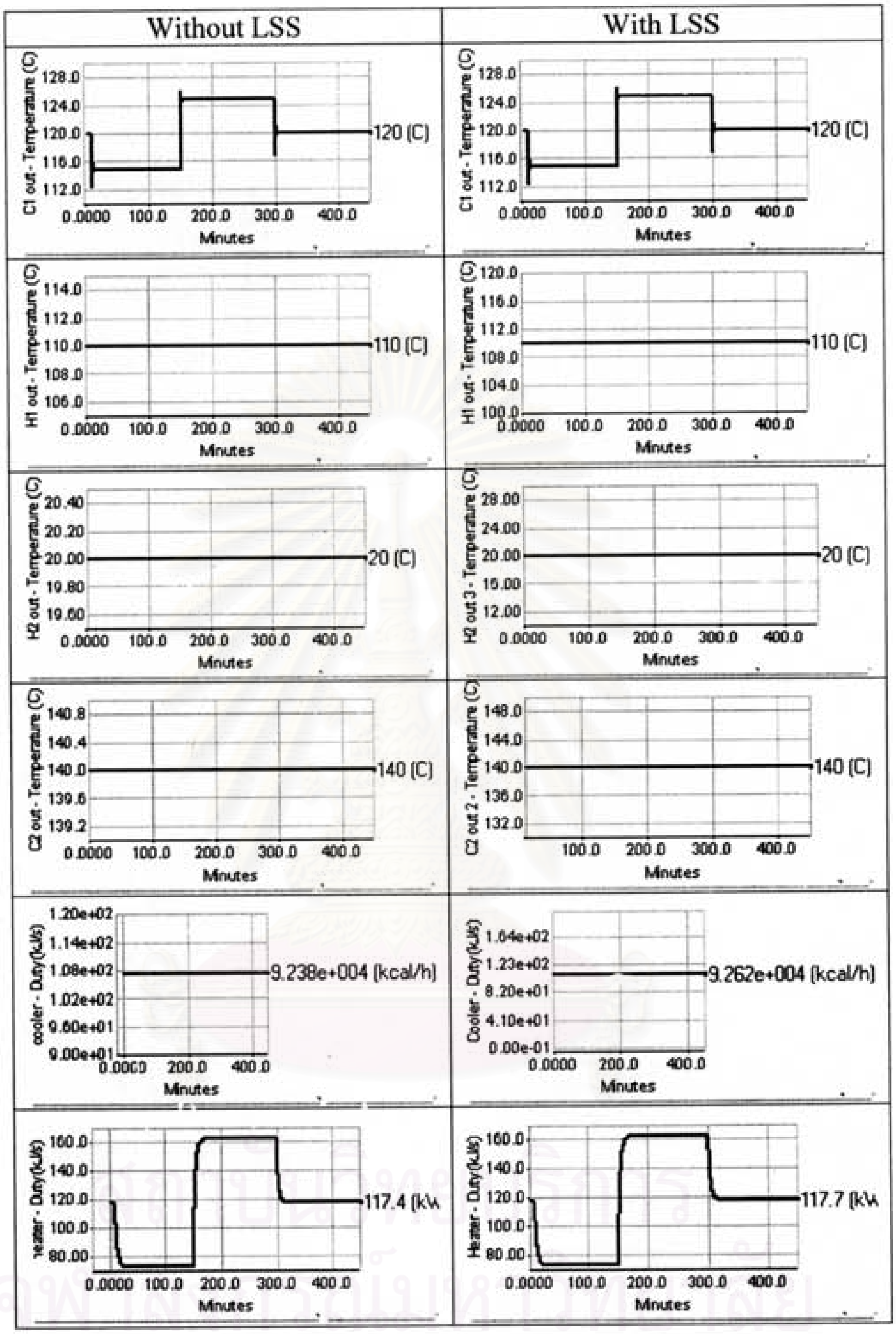


Figure 5.14 Dynamic responses of HEN with and without LSS in example 1 to a change in the target temperature of C1

As a result, the cold outlet temperature (C1) can be reached the desired value. Figure 5.8d shows the heat pathway that disturbance will go directly to the heater utility. There is no effect in temperature of other streams.

Change in Supply Temperature of Cold Stream C2 for Example 1

Figure 5.15 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of C2. In order to make these disturbances, first the target temperature of C2 decreases decreases from 20°C to 15 °C at time equals 10 minutes and the temperature increases from 15 °C to 25 °C at time equals 150 minutes then its temperature returns to its nominal value of 20 °C at time equals 300 minutes.

When C2 temperature decreases, thus it results in decrease of the hot outlet temperature of HE4. The LSS takes an action to control the cold outlet temperature of HE4. Namely, the positive disturbance load of cold stream should be shifted to cooler utility (Figure 5.7g) but without LSS controlled at outlet temperature of C2. The duty of the cooler for without LSS decreases as much as with LSS (Figure 5.7h). Then the negative disturbance load of cold stream is shifted to furnace utility by controlling the hot outlet temperature of HE4. As a result, furnace duty decreases from 117.7 kW to 103 kW (Figure 5.15).

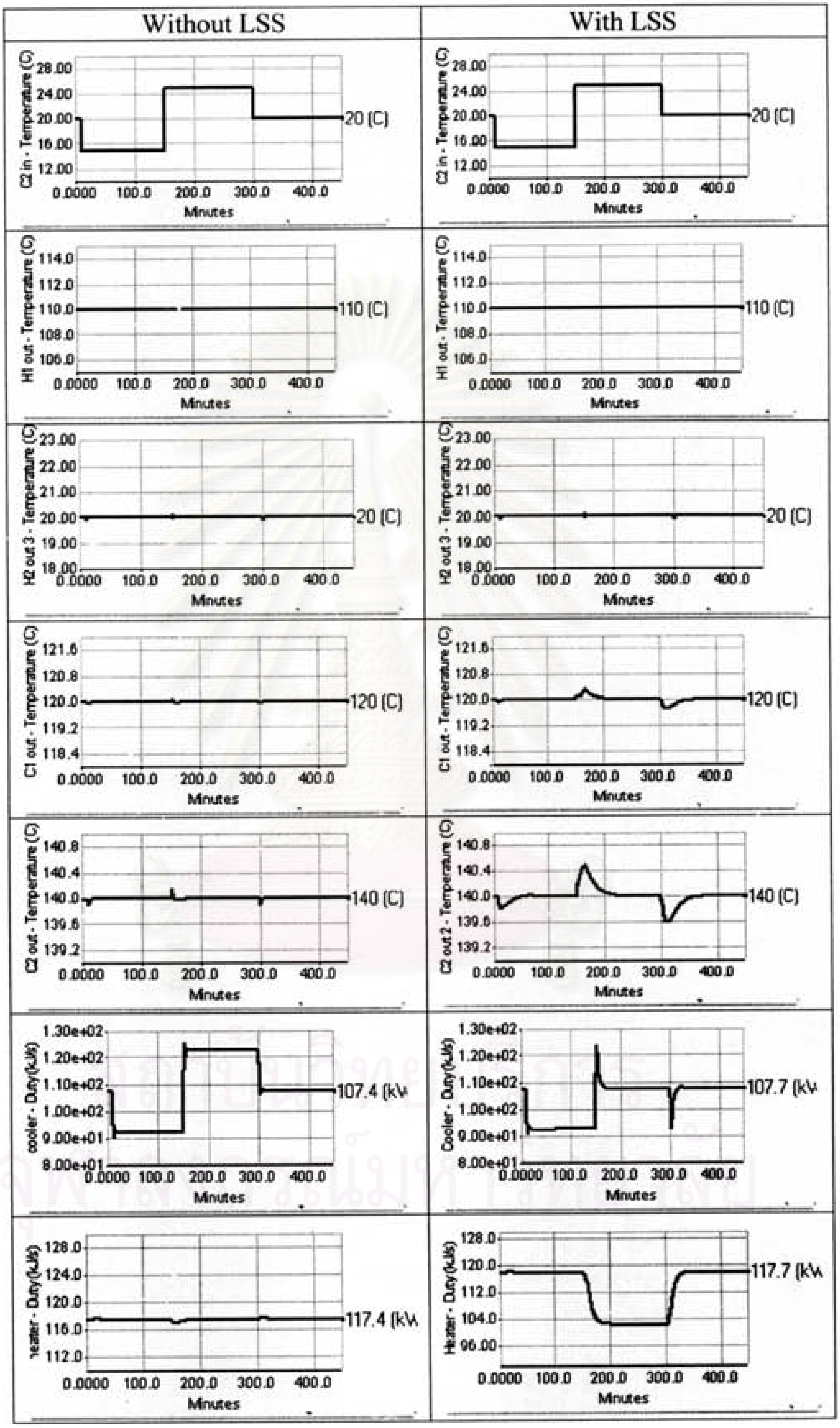


Figure 5.15 Dynamic responses of HEN with and without LSS in example 1 to a change in the supply temperature of C2

Change in Target Temperature of Cold Stream C2 for Example 1

Figure 5.16 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of C2. In order to make these disturbances, first the target temperature of C2 decreases from 140°C to 135 °C at time equals 10 minutes and the temperature increases from 135 °C to 140 °C at time equals 150 minutes then its temperature returns to its nominal value of 140 °C at time equals 300 minutes.

When temperature target of C2 decreases, negative disturbance, thus its load decreases the LSS takes the action to control the cold outlet temperature (Figure 5.8 (e)). The duty of furnace decreases from 117.7 kW to 98 kW while the duty of cooler is going to the nominal value. When temperature target of C2 increase the LSS takes an action to control the cold outlet temperature of HE1 same as negative disturbance. Namely, the positive disturbance load of cold stream should be shifted to cooler utility. The duty of the cooler decreased from 107.7 kW to 89.5 kW.

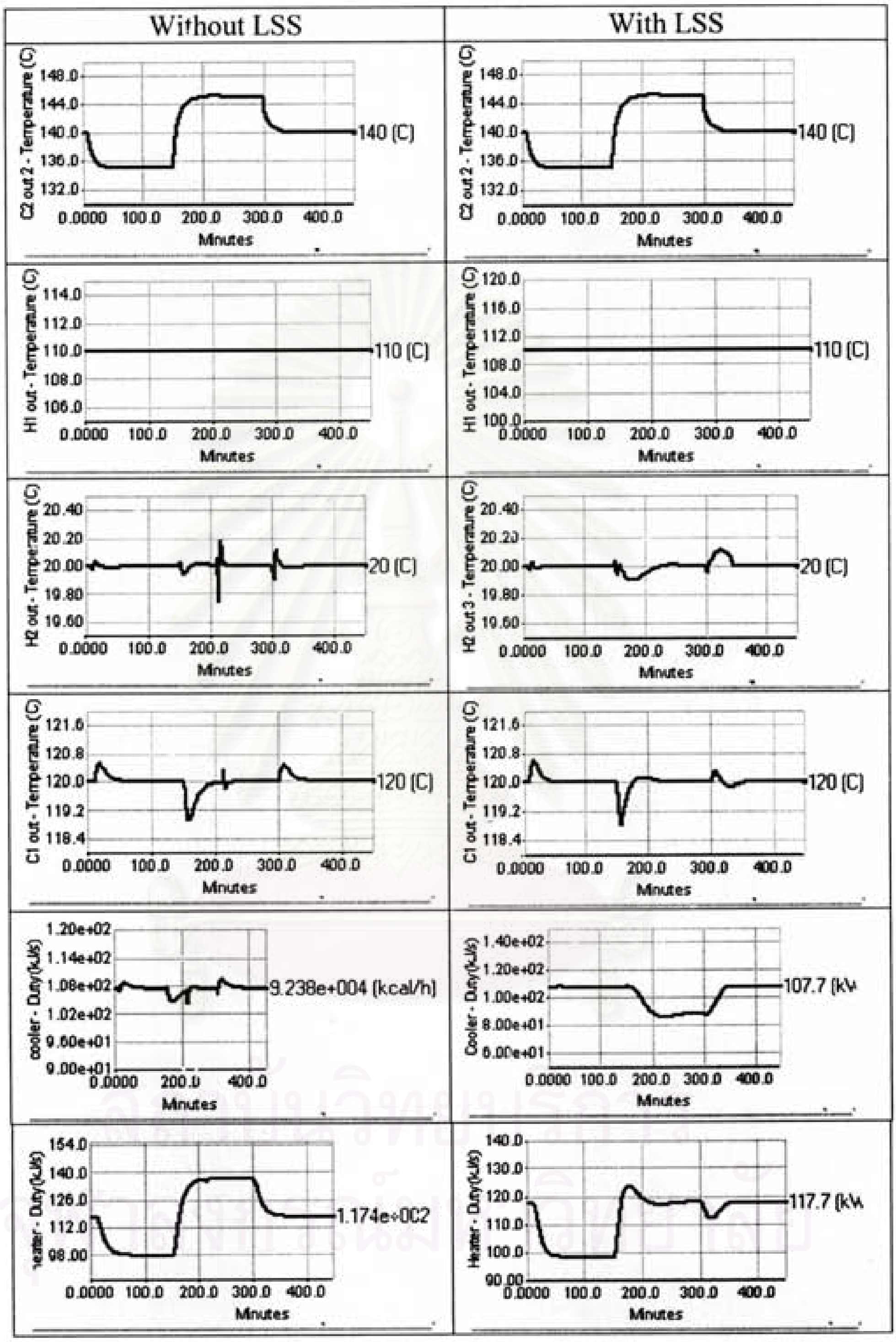


Figure 5.16 Dynamic responses of HEN with and without LSS in example 1 to a change in the target temperature of C2

Change in Flow Rate of Hot Stream H1 for Example 1

Figure 5.17 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of H1. In order to make these disturbances, first the fresh feed flowrate of H1 decreases from 17.76 to 16.57 kgmole/s at time equals 10 minutes and increases from 16.57 to18.94 kgmole/s at time equals 200 minutes then its flowrate returns to its nominal value of 17.76 kgmole/s at time equals 400 minutes.

As can be seen, first the hot stream inlet flow rate (H1) decreases. That is called negative disturbances, (D-). As a result, the LSS1 take an action to control the cold outlet temperature of HE3. Therefore, the cooler duty decreases from 107.7 kW to 104.5 kW. Then, the positive disturbance load (D+) of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of HE2. The Heater duty will be decreased from 117.7 kW to 114.2 kW.

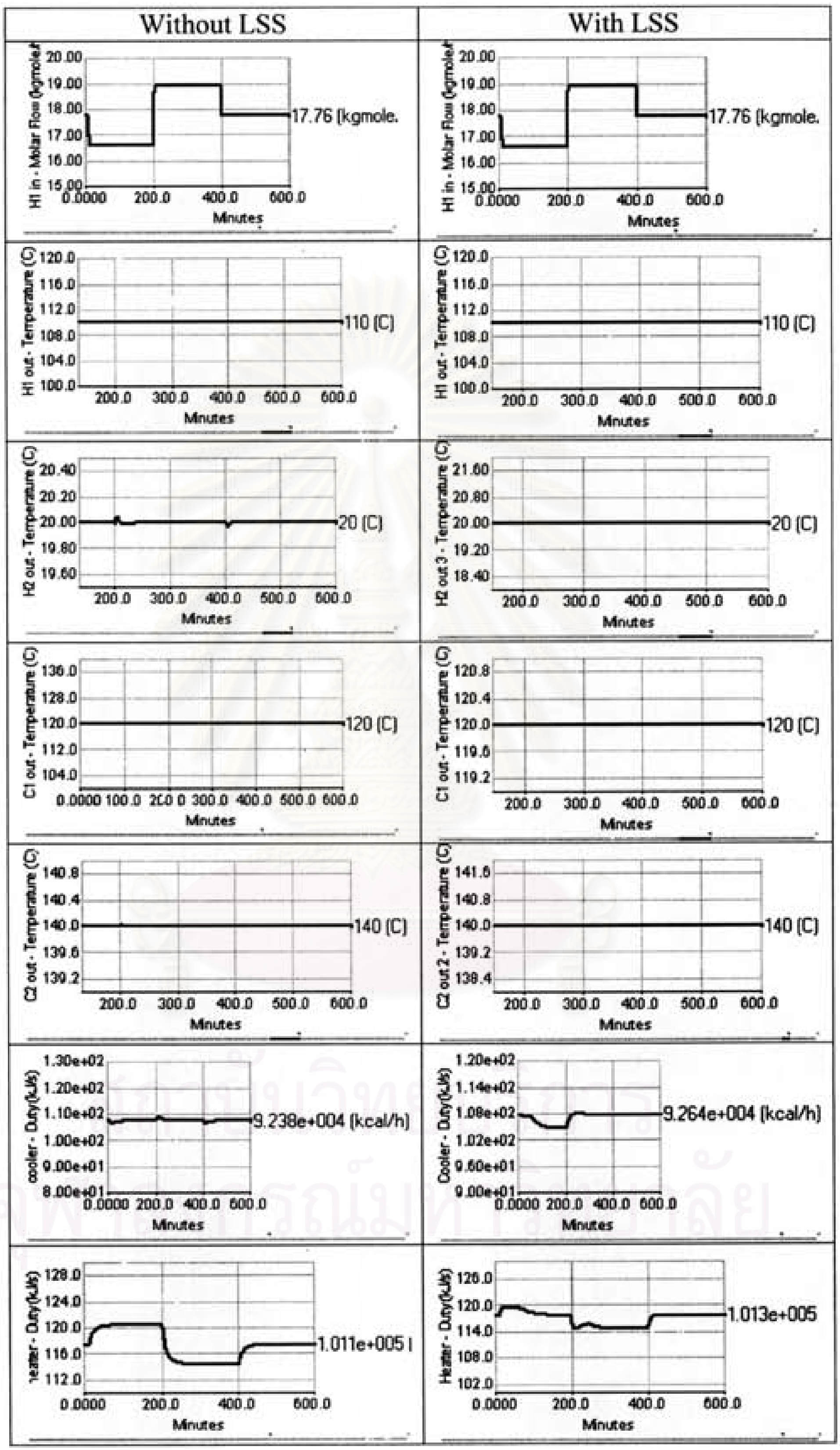


Figure 5.17 Dynamic responses of HEN with and without LSS in example 1 to a change in flowrate of H1

Change in Flow Rate of Cold Stream C1 for Example 1

Figure 5.18 shows the dynamic responses of HEN with and without LSS in example 1 to a change in the disturbance load of H2. In order to make these disturbances, first the fresh feed flowrate of H2 decreases from 74.35 to 73.50 kgmole/s at time equals 10 minutes and increases from 73.50 to 75.19 kgmole/s at time equals 200 minutes then its flowrate returns to its nominal value of 74.35 kgmole/s at time equals 400 minutes.

As can be seen, first the cold stream inlet flow rate (C1) decreases. That is called negative disturbances, (D-). The LSS1 takes an action to control the hot outlet temperature of HE3. Therefore, the Heater duty will be decreased from 117.7 kW to 114.2 kW. Then, the positive disturbance load, (D+) of cold stream is shifted to a cold utility by controlling the cold outlet temperature of HE3. As a result, the cooler duty decreases from 107.7 kW to 104.2 kW.

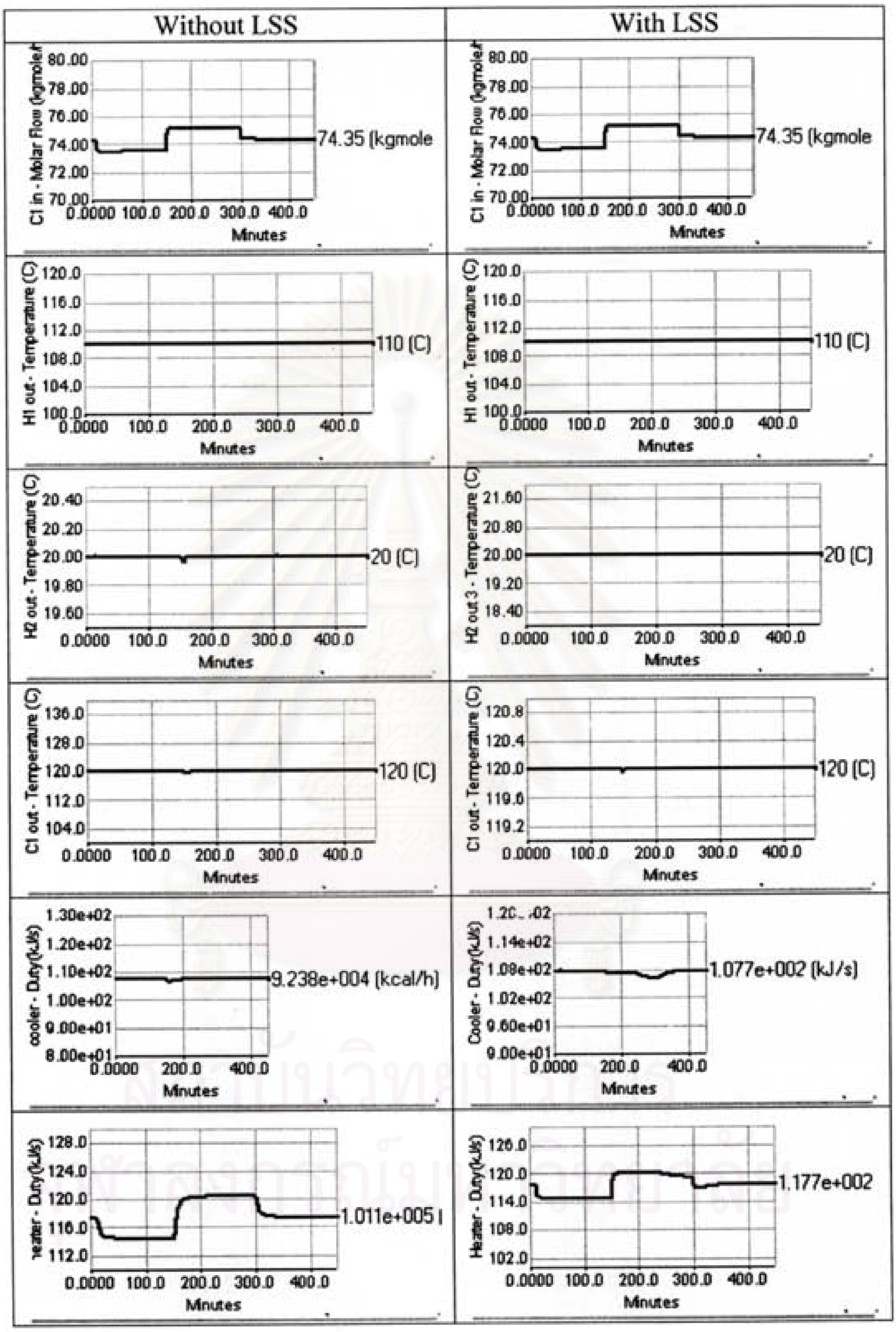


Figure 5.18 Dynamic responses of HEN with and without LSS in example 1 to a change in flowrate of C1

Table 5.5 Comparison of the energy consumption of control structure with and without LSS in the case of Example 1 (temperature changed).

Stream Type	Temperature Variation	Disturbances	Cooler Utility, kW		Heater Utility, kW	
			Without LSS	With LSS	Without LSS	With LSS
H1	Supply Temperature	Negative	107.7	99.1	117.7	110
		Positive	107.4	107.7	110	110
	Target Temperature	Negative	107.7	107.7	125.5	117.7
		Positive	107.7	99.1	110	110
H2	Supply Temperature	Negative	107.7	81	142	117.7
		Positive	107.7	107.7	93.5	93.5
	Target Temperature	Negative	125	125	118	118
		Positive	88	88	118	118
C1	Target Temperature	Negative	107.7	107.7	78	78
		Positive	107.7	107.7	162	162
C2	Supply Temperature	Negative	122	107.7	117.4	103
		Positive	92	92	117.4	117.7
	Target Temperature	Negative	107.7	107.7	98	98
		Positive	107.7	89.5	138	117.7

Table 5.6 Comparison of the energy consumption of control structure with and without LSS in the case of Example 1 (flowrate changed).

Stream Type	Type of Disturbances	Cooler Utility, kW		Heater Utility, kW	
		Without LSS	With LSS	Without LSS	With LSS
H1	Negative	107.7	104.5	121	107.7
	Positive	107.7	107.7	117.7	114.2
C1	Negative	107.7	107.7	117.7	114.2
	Positive	107.7	104.2	121	107.7

From table 5.5 and 5.6 are found that using LSS is likely an effective way to handle with disturbance come along with the variation of temperature that come from supply temperature and target temperature. It brings about control structure of HEN that give dynamic maximum energy recovery.

5.3 Example 2

The HEN synthesis problem is adapted from Cerda et al. (1990) presenting a single pinch jump. The four-stream HEN synthesis problem is shown in Table 5.7.

5.3.1 Design Heat Exchanger network

At the temperature of H1 239 °C, the network is at pinch 229/219 °C (see Table 5.8). When temperature goes up at 249, the new pinch is locate at 239/229 °C. When the inlet temperature of H1 increase from 244 °C, the pinch temperature is the same as minimum heat load as.

Table 5.7 Inlet and outlet condition of network in Example 2

Stream No.	Stream Type	Heat capacity flow rate (kW/°C)	Start Temperature (°C)			Target Temperature (°C)		
			Nominal	Maximum	Minimum	Nominal	Maximum	Minimum
1	Hot	7.032	244	249	239	120	125	115
2	Hot	8.44	239	-	-	148	-	-
1	Cold	6.096	111	116	106	150	155	145
2	Cold	10	131	136	126	250	255	245

Table 5.8 Problem table for Example 2 for minimum heat load

W				T hot (°C)	T cold (°C)	ΣW (kW/C)	ΔT (°C)	Required Heat (kW)	Interval (kW)	Cascade Heat (kW)	Sum Interval (kW)
H1	H2	C1	C2								
0	0	0	0	255	245	0		Qh		-29.68	
0	0	0	10	239	229	-10	16	189.68	-160	160	-160
7.032	0	0	10	229	219	-2.968	10	29.68	-29.68	0	-189.68
7.032	8.44	0	10	150	140	5.472	79	0	432.28	-29.68	242.608
7.032	8.44	6.096	10	148	138	-0.624	2	432.288	-1.248	402.608	241.36
7.032	0	6.096	10	146	136	-9.064	2	431.04	-18.128	401.36	223.232
7.032	0	6.096	0	126	116	0.936	20	412.912	18.72	383.232	241.952
0	0	6.096	0	115	105	-6.096	11	431.632	-67.056	401.952	174.896
										Qc	

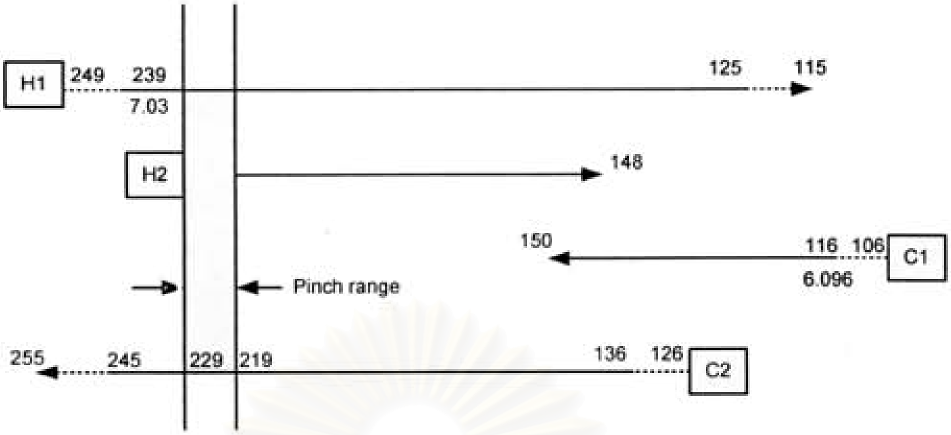


Figure 5.19 Process Streams Partitioning for Example 2

The pinch region is between 239-229 °C on the hot side scale. The stream partitioning procedure:

- H1. The disturbance region of H1 in the hot end appears in the pinch zone (see Figure 1) and also exists outside the pinch zone, so it has not disappeared when the pinch moved up to the highest value. The disturbance in the pinch range diminished to zero only when the pinch is moved up to 239 °C. So H1 exists in both the hot end and cold end. The supply temperature (T1) in the hot end is subjected to a variation in the range of 249-239 °C and the outlet temperature (T2) in the hot end is fixed at 239 °C. The inlet temperature (T1) in the cold end is subjected to variation by the range of the pinch zone.
- H2. The inlet temperature is fixed even its entire part in the hot end is immersed in the pinch zone. Thus there exists a part of H2 in a hot end when the pinch is below its highest point. The inlet temperature of H2 in a hot end is fixed but its outlet temperature is varied according to the pinch temperature.
- C1. C1 is in the cold end.
- C2. C2 is a fixed stream and appear in both hot end and cold. The inlet temperature in the hot end (T2) and the outlet temperature (T1) in the cold end are varied.

The process streams data for the hot end and cold end are shown in Tables 5.9 and 5.10

Table 5.9 Hot End Process Stream Data for Example 2

Stream	W (kW/C)	Supply Temp			Target Temp		
		Nom	Max	Min	Nom	Max	Min
H1	7.032	239	249	239	239	-	-
H2	8.44	239	-	-	-	239	229
C2	10	-	229	219	250	255	245

Table 5.10 Cold End Process Stream Data for Example 2

Stream	W (kW/°C)	Supply Temp (°C)			Target Temp (°C)		
		Nom	Max	Min	Nom	Max	Min
H1	7.032	-	239	229	120	125	115
H2	8.44	-	239	229	148	-	-
C1	6.096	111	116	106	150	155	145
C2	10	131	136	126	-	229	219

The synthesis must follow the procedure for a problem with streams that have variations in both supply and target temperatures. The disturbance loads of the process streams are presented at three points, the supply temperature (D^s), the pinch temperature (D^p) and the target temperature (D^t). The maximum and minimum values of inlet and outlet temperatures of all process streams are needed. The synthesis procedure using the disturbance propagation technique and the match patterns is carried out as following:

1. The starting condition for the hot end is shown in Table 5.11 (a). The first applicable pattern is A[H]. H2 is chosen to match to C2 since it has less heat load.
2. Next match the residual C2 to H1 with the pattern A[H]. The new stream condition is shown in Table 5.12 (b). Finally match C2 to a heating utility stream.

For the cold end synthesis, we see from Figure 5.19 that both H1 and H2 must be matched to C2 first since the target temperature of C2 is higher than of C1 and also the heat flow rate capacity of C2 is greater than both H1 and H2. So, in order to be matched to H1 and H2, C2 must be split.

Table 5.11 Synthesis table for Hot End of Example 2

Stream	Load	W	T1	T2	D^s	D^p	D^t	Action
(a) State 1								
H1	0	7.032	239	239	70.32	0	0	
H2	C	8.44	239	239	0	84.4	0	Selected
C2	160	10	245	229	0	100	100	Selected
(b) State 2								
H2								Matched to C2
H1	0	7.032	239	239	70.32	0	0	Selected
C2	160	10	245	229	0	15.6	100	Selected
(c) State 3								
H2								Matched to C2
H1								Matched to C2
C2	89.68	10	245	236.032	85.92	0	100	To heater

Table 5.12 Synthesis table for Cold End of Example 2

Stream	Load	W	T1	T2	Ds	Dt	Dp	Action
(a) State 1								
H1	731.33	7.032	229	125	0	70.32	70.32	Selected
H2	683.64	8.44	229	148	0	0	84.4	Selected
C1	176.78	6.096	145	116	60.96	60.96	0	
C2	830	10	219	136	100	0	100	Split
C21	219.9	10	219	136	26.5	0	26.5	Selected
C22	610.1	10	219	136	73.5	0	73.5	Selected
(b) State 2								
C21								Matched to H1
C22								Matched to H2
H1	484.93	7.032	173.49	125	26.5	70.32	43.82	Selected
H2	0	8.44	148	148	73.5	0	10.9	
C1	176.78	6.096	145	116	60.96	60.96	0	Selected
(c) State 3								
C21								Matched to H1
C22								Matched to H2
C1								Matched to H1
H1	186.22	7.032	151.48	125	192.24	70.32	0	To cooler
H2	0	8.44	148	148	84.4	0	0	To cooler

The synthesis is carried out stepwise as follows:

1. The starting condition for the cold end is shown in Table 5.12 (a). The first application pattern is B[C]. C2 is split and matched to H1 and H2.

   Calculate the minimum heat capacity flowrate which satisfy the resiliency Requirement for C22 to match to H2:

$$W_{C22} = L_{H2}/(T1_{C2\min} - T2_{C2\min})$$
$$= 683.64/(219 - 126) = 7.35$$

   The split heat capacity flowrate must make a match of H1 and C21 satisfy pattern B[C]:

$$L_{C21} \le L_{H1}$$
$$W_{C21} \le W_{H1}$$

   Also, the resiliency test for a match of H1 and C21:

$$D2_{C21} \le L_{H1} - L_{C21}$$

Example of calculation for the new condition of H1 in State 2.

$$T1^{new}_{H1(\min)} = T1_{H1\min} - \frac{L_{C21} + D2_{C21}}{W_{H1}}$$
$$= 229 - (219.9+26.5)/7.03$$
$$= 193.95$$

2. By satisfying the pattern B[C] and the resiliency, C2 is matched to H1 and H2. The condition of the new state is shown in Table 5.12(b). Since H2 has zero heat load, C1 must be matched to H1 and they satisfy the pattern B[C].
3. The next state shown in Table 5.12(c) has only hot streams left so they are matched to cooling utilities.

It should be noticed that H2, after being matched to C2, has zero heat load at the minimum heat load condition and requires 84.4 kW cooling duty at the maximum heating condition. The cooling duty of 84.4 kW can be supplied by C2. At the minimum heating condition this equivalent to 84.4/(219-136) = 1.01 kWC^{-1}. This amount of heat load can be supplied by C2 by increasing the ratio of C22. The ratio of heat capacity flowrate of C22 can be managed by a conventional controller by monitoring the inlet temperature of C2. Since C2 can supply all the cooling duty to

H2 there is no need to install a cooler for H2. However, the change in flowrate of C2 will introduce a new disturbance in H1. The extra cooling duty (the consequence of increasing flowrate of C21) must be added to the cooler of H1. A resilient network structure solution to the Example 2 problem is show in Figure 5.20. The condition show in the figure is the nominal condition where the network has a pinch temperature at 239 °C on the hot scale. The heating requirement is 210 kW and the cooling requirement is 356.6 kw. The heat exchanger units 1 and 3, 2 and 4 can be merged together and a resilient network structure solution featuring minimum number of units is show in Figure 5.21.

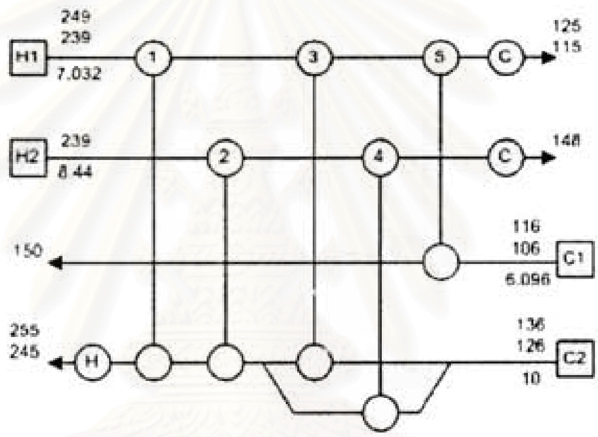


Figure 5.20 Heat Exchanger Network for Example 2

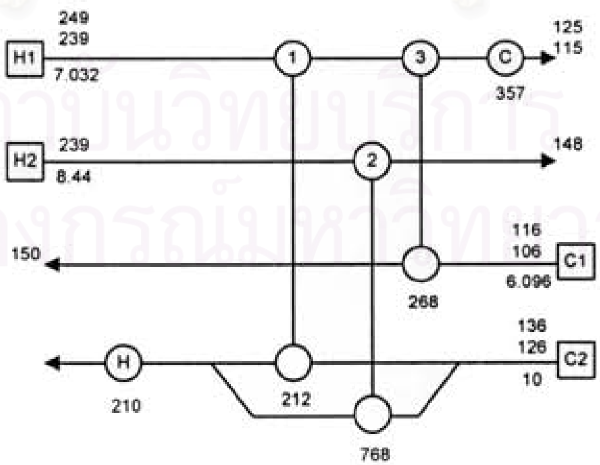


Figure 5.21 Heat Exchanger Network for Example 2 when merged the heat exchanger 1 and 3, 2 and 4

5.3.2 Design Control Structure

From the chapter III, it can be used to design control structure as follows:

Step 1. Design control structure. We consider the maintenance target temperature and heat pathway of disturbance simultaneously.

Beginning with determination of set up control loop at utility of any stream in order to maintain target temperature. Then equip bypass at hot stream of HE 3 HE1 to control C1 outlet temperature. It can adjust the split ratio instead of settling bypass stream to controlling temperature of H2. Hence we have 2 control structures, one the control vale adjusts the flowrate of stream C21 and two the control vale adjusts the flowrate of stream C22.

Step 2. Set up LSS in the network based on the heat path way heuristic approach.

Considering the heat pathway in Figure 5.22, dash lines show the pathway of disturbance, there are 2 ways at HE1. Then, settle up cascade in order to calculate new setpoint temperature of cold stream of HE1 which provides no increase in cooler duty and heater duty. Hence we have 2 control structures in Figure 5.23 and 5.24 to compare the performance.

In Figure 5.25 and 5.26 show the heat pathway of positive and negative disturbance in Example 1 when settled the control structure and LSS. We see that all disturbances will transfer to the utility. In Figure 5.27 shows the simulation in HYSYS flowsheet.

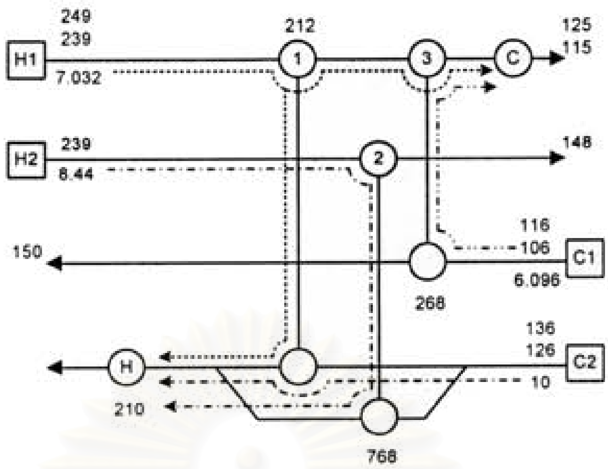


Figure 5.22 Heat pathway of disturbance in Example 2

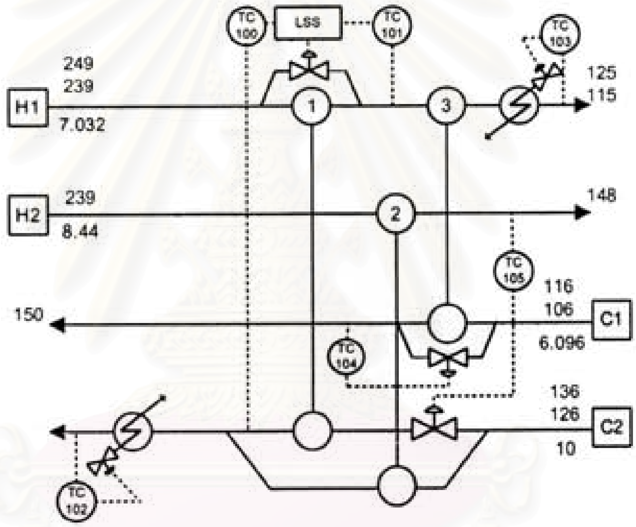


Figure 5.23 Control structure 1 (CS1) for example 2

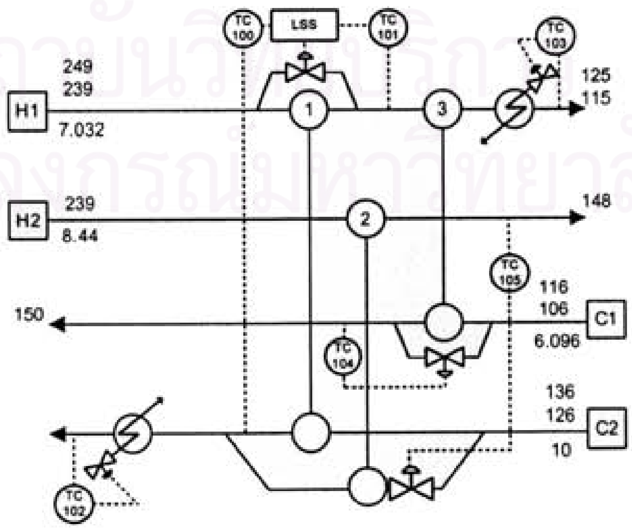


Figure 5.24 Control structure 2 (CS2) for example 2

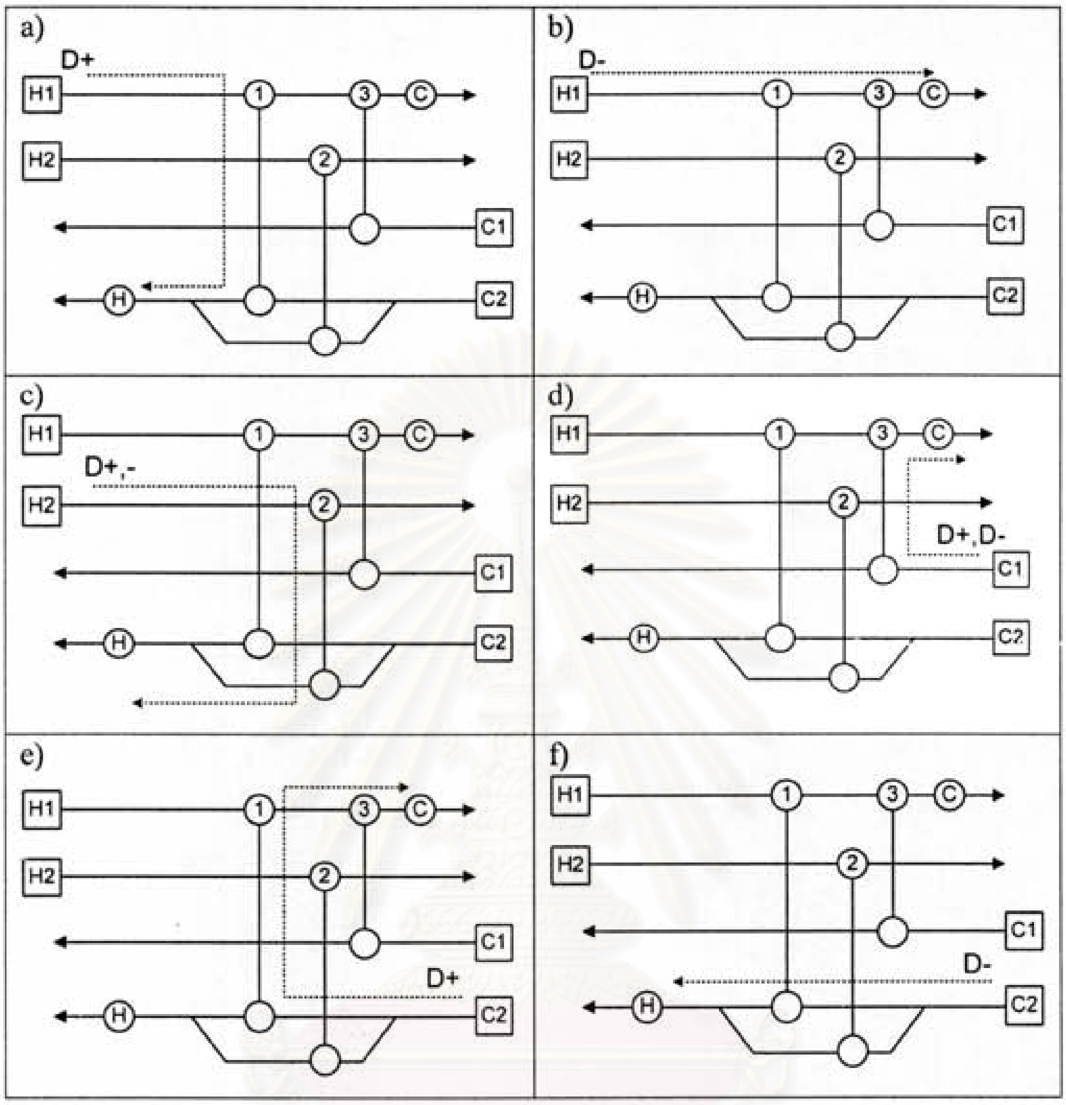


Figure 5.25 Heat pathway of control structure of network equipped with LSS of Example 2 when there is the disturbance at supply temperature a) D+ presented at H1, b) D- presented at H1 c) D+ , D- presented at H2, d) D+ presented at C1 e) D+ presented at C2, f) D- presented at C2.

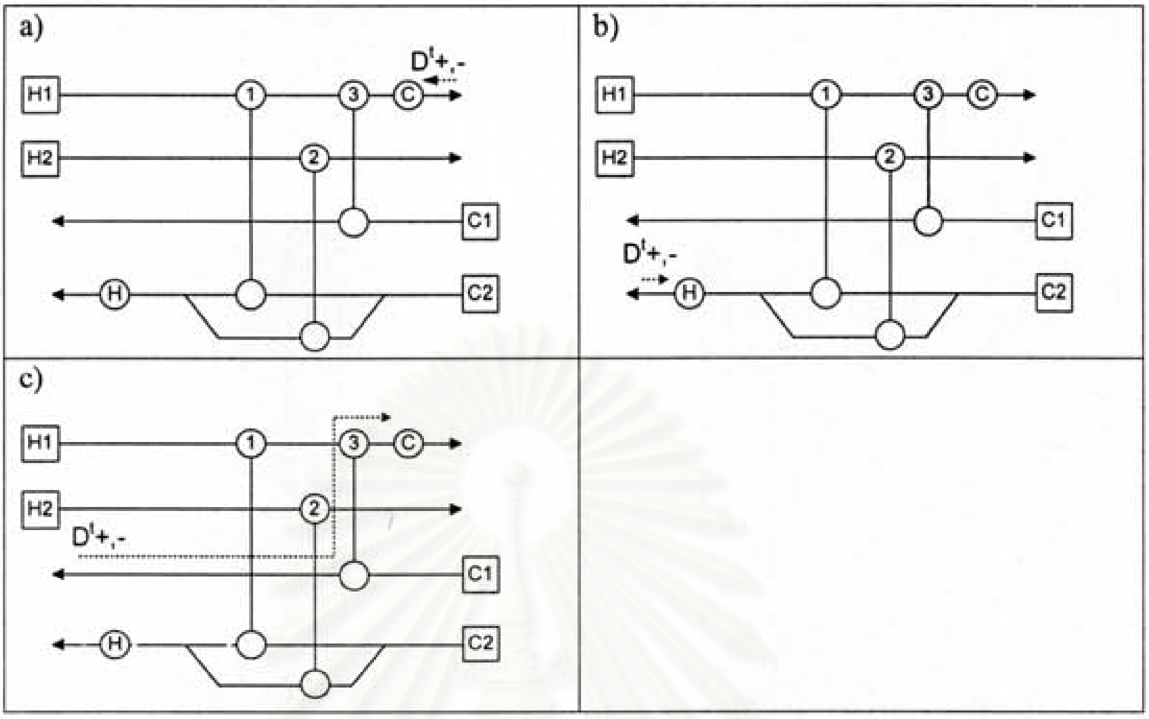


Figure 5.26 Heat pathway of control structure of network equipped with LSS of Example 1 when there is the disturbance at target temperature a) D^t+ and D^t- presented at H1, b) D^t+ and D^t- presented at C2

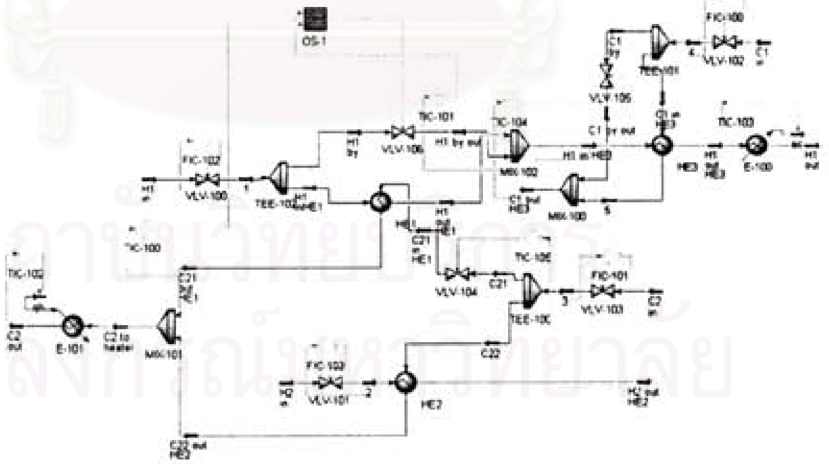


Figure 5.27 Heat exchanger network with LSS of example 2: CS1 from HYSYS flow sheet

In order to show that the HEN in example 2 can achieve the maximum energy recovery and keep their target temperature at their desirable value, several disturbance loads were made.

Change in the Disturbance Load of Hot Stream H1 Temperature for Example 2

Figure 5.28 shows the dynamic responses of HEN between control structure 1 and 2 in example 2 to a change in the disturbance load of H1. In order to make these disturbances, first the fresh feed H1 temperature decreases, first the fresh feed H1 temperature decreases from 244°C to 239 °C at time equals 10 minutes and the temperature increases from 239 °C to 244 °C at time equals 150 minutes then its temperature returns to its nominal value of 244 °C at time equals 300 minutes. The dynamic responses of the control system of CS1 and CS2 are shown in Figures 6.

As can be seen, first the hot stream inlet stream (H1) decreases. That is called negative disturbance, (D-). Heat pathway is shown in Figure 5.25b. As a result, the hot outlet of HE1 temperature decreases below its minimum value, the LSS takes an action to control the cold outlet temperature of HE1 so the cooler duty decreases from 425.7 kW to 391 kW (Figure 5.28q and r). Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of HE1. Consequently, following Figure 5.25a, the heater duty will be decreased from 209 kW to 183 kW (Figure 5.28s and t).

Comparing the dynamic response between CS1 and CS2, control structures CS1 control the process can handle the disturbance as good as CS2. The LSS is likely an effective way to handle disturbance come along with the variation of temperature that come from supply temperature and target temperature.

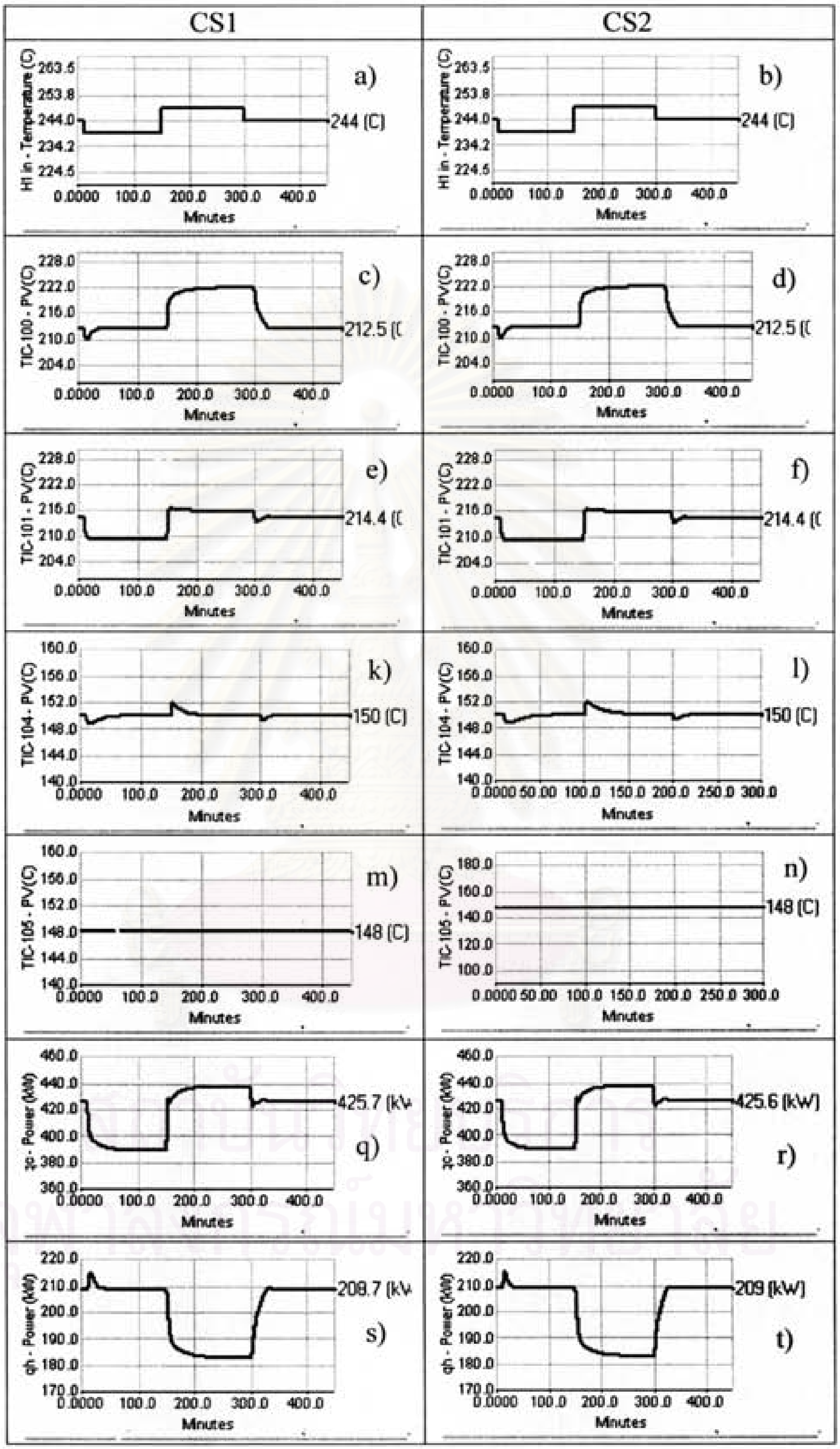


Figure 5.28 Dynamic responses of streams of HEN in Example 2 to a change in the temperature of H1

Change in the Disturbance Load of Cold Stream C1 Temperature for Example 2

Figure 5.29 shows the dynamic responses of HEN between control structure 1 and 2 in example 1 to a change in the disturbance load of C1. In order to make these disturbances, first the fresh feed C1 temperature decreases from 111°C to 106 °C at time equals 10 minutes and the temperature increases from 106 °C to 116 °C at time equals 150 minutes then its temperature returns to its nominal value of 111 °C at time equals 300 minutes.

When C1 temperature decreases, called positive disturbance, thus it results in decrease of the hot outlet temperature of HE3. Heat pathway is shown in Figure 5.25d. The duty of the cooler is decreased from 425.7 kW to 398 kW. Then C1 temperature increases, the negative disturbance, cannot shift to furnace utility so the duty of the cooler is increased to 458.5 kW (Figure 5.29o, p).

Comparing the dynamic response between CS1 and CS2 from Figure 5.29, control structures CS1 can handle the disturbance as good as CS2.

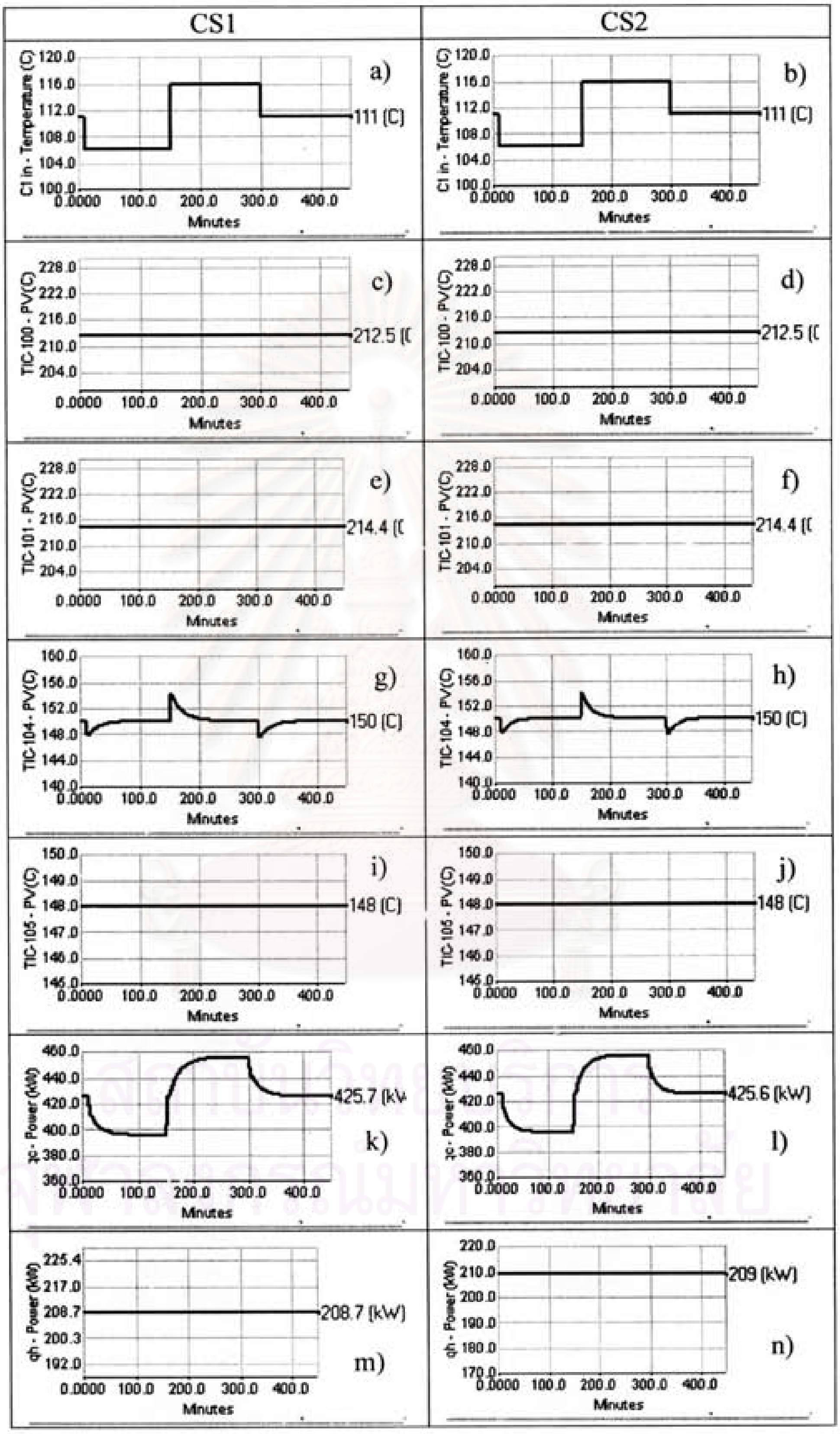


Figure 5.29 Dynamic responses of streams of HEN in Example 2 to a change in the temperature of C1

Change in the Disturbance Load of Cold Stream C2 Temperature for Example 2

Figure 5.30 shows the dynamic responses of HEN between control structure 1 and 2 in example 2 to a change in the disturbance load of C2. In order to make these disturbances, first the fresh feed C2 temperature decreases from 131°C to 126 °C at time equals 10 minutes and the temperature increases from 126 °C to 136 °C at time equals 150 minutes then its temperature returns to its nominal value of 131 °C at time equals 300 minutes.

When C2 temperature decreases, thus it results in decrease of the hot outlet temperature of HE1. The LSS takes an action to control the cold outlet temperature of HE1. Heat pathway is shown in Figure 5.25e. Namely, the positive disturbance load of cold stream should be shifted to cooler utility so the cooler duty decreases from 425.7 kW to 380 kW (Figure 5.30o, p). Then the negative disturbance load of cold stream is shifted to furnace utility by controlling the hot outlet temperature of HE1. Heat pathway is shown in Figure 5.25f. As a result, furnace duty decreases from 208.7 kW to 170 kW (Figure 5.30q, r).

When C2 temperature is changed, Figure 5.30 m, n shows that CS2 provides better control responses than CS1. Because of the position of the valve, the valve in C22 can control the outlet temperature of H2 directly.

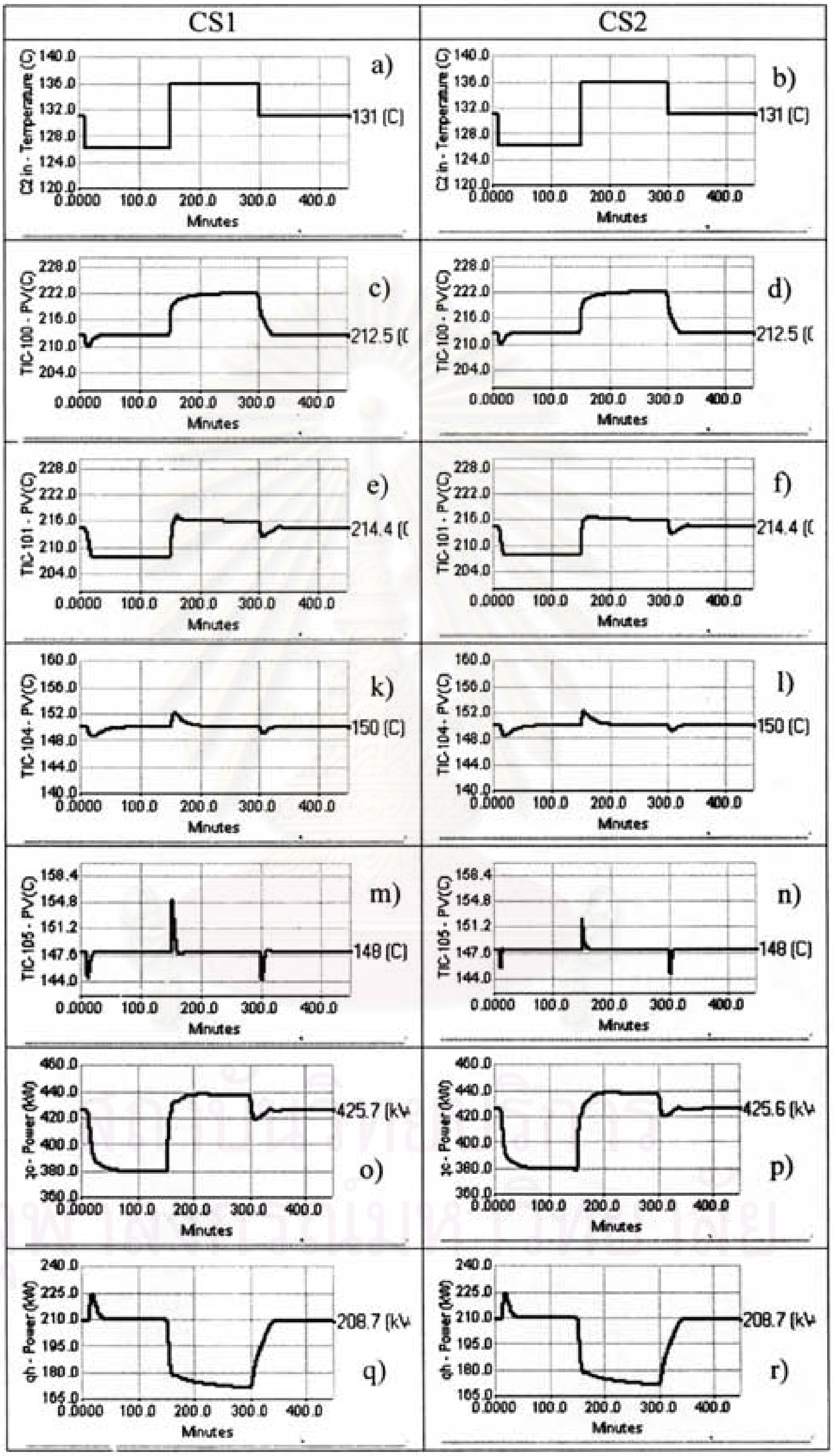


Figure 5.30 Dynamic responses of streams of HEN in Example 2 to a change in the supply temperature of C2

Change in the Target Temperature of Hot Stream H1 and Cold Stream C2 for Example 2

Figure 5.31a-d show the dynamic responses of HEN between control structure 1 and 2 in example 2 to a change in the disturbance load of H1. In order to make these disturbances, first the target temperature of H1 decreases from 120°C to 115 °C at time equals 10 minutes and the temperature increases from 115 °C to 125 °C at time equals 150 minutes then its temperature returns to its nominal value of 120 °C at time equals 300 minutes.

Figure 5.32a-d show the dynamic responses of HEN between control structure 1 and 2 in example 2 to a change in the disturbance load of C2. In order to make these disturbances, first the target temperature of H1 decreases from 250°C to 245 °C at time equals 10 minutes and the temperature increases from 245 °C to 255 °C at time equals 150 minutes then its temperature returns to its nominal value of 250 °C at time equals 300 minutes.

When target temperature of H1 decrease, the duty of cooler change follow the heat pathway in Figure 5.26a. Same as when the target temperature of C2 changes, the duty of heater change follow the heat pathway in Figure 5.26b. There is no effect to the other streams.

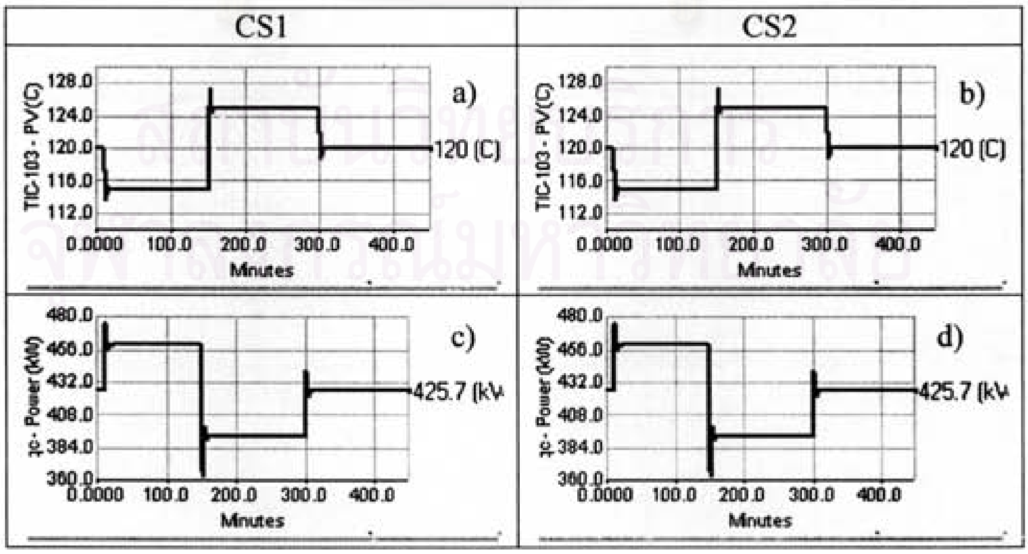


Figure 5.31 Dynamic responses of streams of HEN in Example 2 to a change in the target temperature of H1

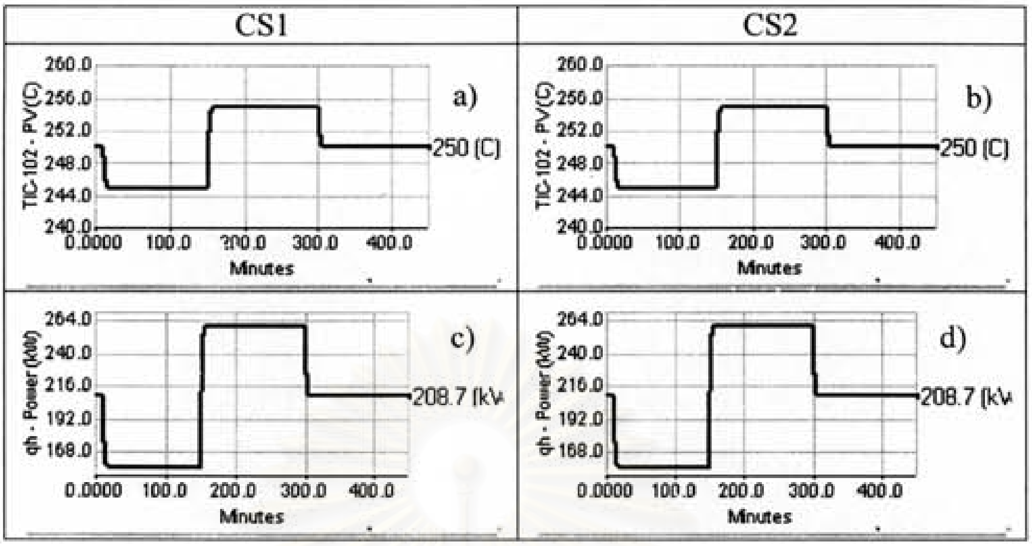


Figure 5.32 Dynamic responses of streams of HEN in Example 2 to a change in the target temperature of C2

Change in the Target Temperature of Cold Stream C2 for Example 2

Figure 5.33 shows the dynamic responses of HEN between control structure 1 and 2 in example 2 to a change in the disturbance load of C1. In order to make these disturbances, first the target temperature of C2 decreases from 150°C to 145 °C at time equals 10 minutes and the temperature increases from 145 °C to 155 °C at time equals 150 minutes then its temperature returns to its nominal value of 150 °C at time equals 300 minutes.

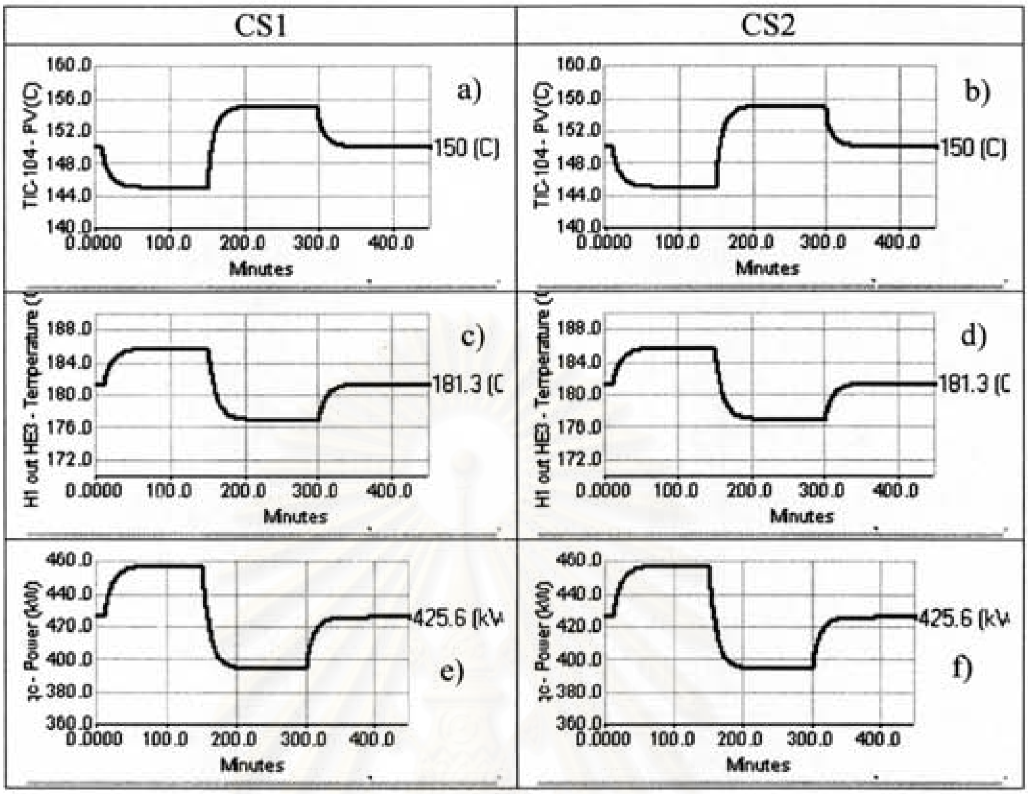


Figure 5.33 Dynamic responses of streams of HEN in Example 2 to a change in the target temperature of C1

As can be seen from Figure 5.32, when target temperature of C1 decrease, the outlet temperature from HE3 of H1 is increased (Figure 5.33c, d). The heat pathway is shown in Figure 5.26c. The negative disturbance of cold stream will result the cooler duty increase (Figure 5.33e, f). When target temperature of C1 increase, the outlet temperature from HE3 of H1 is increased. Again, the positive disturbance of cold stream will result the cooler duty decrease.

Table 5.12(a) Comparison of the IAE of control structure CS1 in the case of Example 2

Disturbance	TC100	TC101	TC102	TC103	TC104	TC105
H1 Supply Tempt	120.48	79.40	1.31	1.10	6.37	0.00
H1 Target Tempt	0.00	0.00	0.00	33.70	0.00	0.00
C1 Supply Tempt	0.00	0.00	0.00	1.18	15.70	0.00
C1 Target Tempt	0.00	0.00	0.00	14.66	178.38	0.00
C2 Supply Tempt	120.48	97.85	2.13	1.30	8.35	6.46
C2 Target Tempt	0.00	0.00	49.27	0.00	0.00	0.00
					Sum	738.12

Table 5.12(b) Comparison of the IAE of control structure CS2 in the case of Example 2

Disturbance	TC100	TC101	TC102	TC103	TC104	TC105
H1 Supply Tempt	119.89	79.36	2.17	1.29	6.37	0.00
H1 Target Tempt	0.00	0.00	0.00	33.37	0.00	0.00
C1 Supply Tempt	0.00	0.00	0.00	1.17	15.70	0.00
C1 Target Tempt	0.00	0.00	0.00	14.58	178.45	0.00
C2 Supply Tempt	120.48	97.63	2.17	1.29	8.14	2.61
C2 Target Tempt	0.00	0.00	49.58	0.00	0.00	0.00
					Sum	734.26

As can be seen the IAEs for CS2 in table 5.12 are less than CS1. When there are disturbance at supply temperature of C2, the position valve at C22 can adjust the outlet temperature of H2 more directly than valve at C21. Other disturbances CS1 can handle the disturbance similar to CS2.

5.4 Example 3 (HDA Process)

5.4.1 Design Heat Exchanger Network

The Problem Table Method is applied to find pinch temperature and reach maximum energy recovery (MER). The information for design is shown in the following Table 5.13(a) and (b).

Table 5.13(a) The information of HDA Process

Stream Name	Tin (°C)	Tout (°C)	W (kW/°C)
H1: Reactor Product Stream (RPS)	621	45	33
H2: Recycle Column Condenser (RCC)	183	181	200
C1: Reactor Feed Stream (RFS)	65	621	32.24
C2: Product Column Rebolier (PCR)	145	193	91
C3: Stabilizer Column Reboiler (SCR)	190	215	59
C4: Recycle Column Reboiler (RCR)	349.5	350.7	456

Table 5.13(b) The information of HDA Process

Stream	W (kW/C)			SUPPLY TEMPS ()			TARGET TEMPS ()		
	Max	Nom	Min	Nom	Max	Min	Nom	Max	Min
H1	-	34	-	621	626	616	45	50	40
H2	-	200	-	183.05	-	-	181	-	-
C1	32.44	32.24	32.04	69.63	75	65	621	-	-
C2	-	91	-	144.38	-	-	193	198	188
C3	-	59	-	189.92	-	-	215	220	210
C4	-	456	-	349.34	-	-	350.7	-	-

We can see that there are six streams in the network so we can find the Pinch temperature by using Problem Table Method as following: See Table 5.14

Table 5.14 Problem table for HDA process 1

W						T hot	T cold	ΣW	ΔT	Required Heat	Interval	Cascade Heat	Sum Interval
H1	H2	C1	C2	C3	C4								
0	0	0	0	0	0	631	621	0		Qh			
0	0	32.2	0	0	0	621	611	-32.24	10	5958.44	-322.40	0.00	-322.40
33	0	32.2	0	0	0	360.7	350.7	0.76	260.3	5640.76	197.83	5838.59	-124.57
33	0	32.2	0	0	456	359.5	349.5	-455.24	1.2	5838.59	-546.29	5292.30	-670.86
33	0	32.2	0	0	0	225	215	0.76	134.5	5292.30	102.22	5394.52	-568.64
33	0	32.2	0	59	0	203	193	-58.24	22	5394.52	-1281.28	4113.24	-1849.92
33	0	32.2	91	59	0	199.92	189.92	-149.24	3.08	4113.24	-459.66	3653.58	-2309.58
33	0	32.2	91	0	0	183	173	-90.24	16.92	3653.58	-1526.86	2126.72	-3836.44
33	200	32.2	91	0	0	181	171	109.76	2	2126.72	219.52	2346.24	-3616.92
33	0	32.2	91	0	0	155	145	-90.24	26	2346.24	-2346.24	0.00	-5958.44
33	0	32.2	0	0	0	69.63	59.63	0.76	85.37	0.00	64.88	64.88	-5898.28
33	0	0	0	0	0	45	35	33	24.63	64.88	812.79	1050.8	-5085.49
												Qc	

By using Synthesis procedure in Chapter III, we can receive 3 resilient networks follow by Table 5.15 -5.18 and Figure5.34-5.36. We have got three control structures in Figure 5.34-5.36. As can be seen we use only one LSS, even there are two heat pathways of disturbance C3. C3 is connected to the distillation column so we have to ensure that it has enough heat loads to the distillation column.

Table 5.15 Synthesis Table for cold end

Synthesis Table for cold end								
Stream	Load	W	T1	T2	Ds	Dw	Dt	Action
a) State1								
H1	3465	33	155	50	0	0	330	Selected B[C]
C1	2242.8	32.04	75	145	0	32	0	Selected
b) State 2								
H1	1190.2	33	86.067	45	32	0	330	To Cooler
C1								Matched to H1

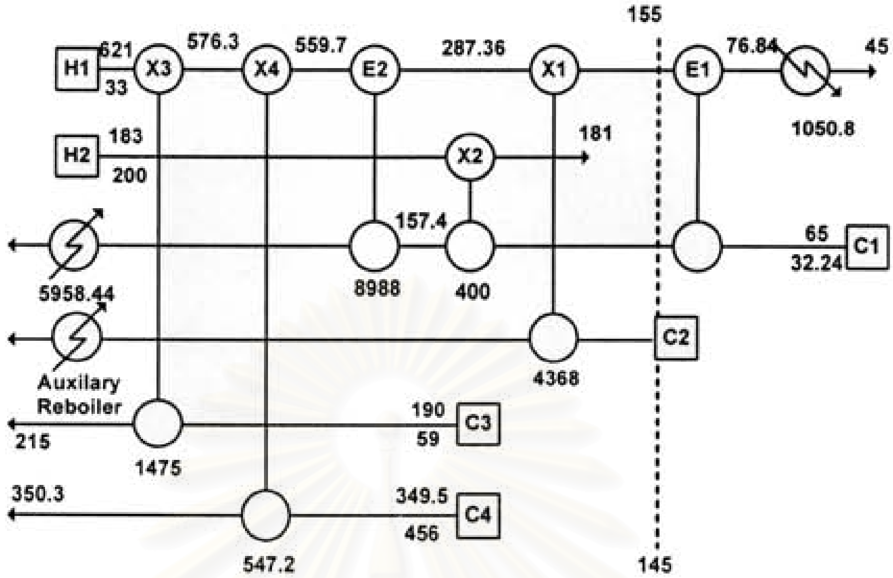


Figure 5.34 Resilient Heat Exchanger Network 1

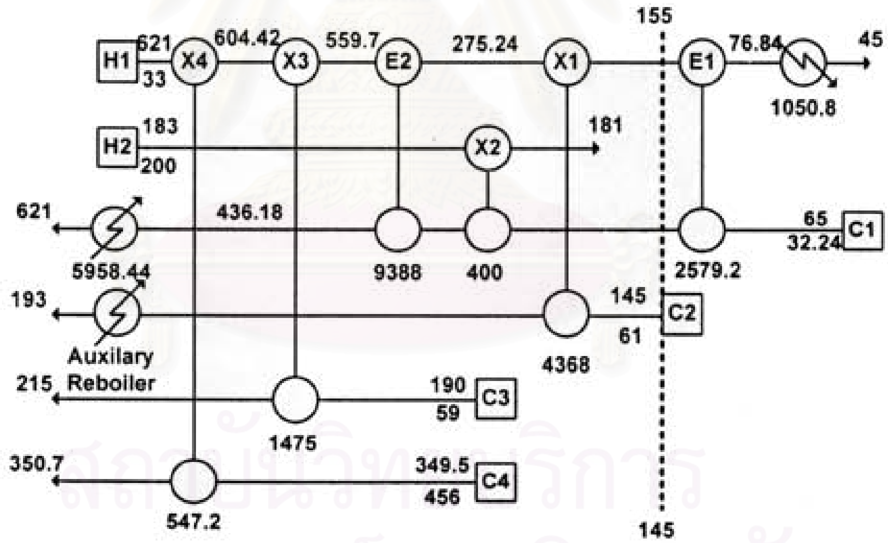


Figure 5.35 Resilient Heat Exchanger Network 2

Table 5.16 Synthesis Table 1 for hot end

Synthesis Table 1 for hot end								
Stream	Load	W	T1	T2	Ds	Dw	Dt	Action
a) State1								
H1	15213	33	616	155	165	0	0	Selected C[H]
H2	410	200	183.05	181	0	0	0	
C1	15251	32.04	621	145	0	285.6	0	
C2	3969.4	91	188	144.38	0	0	910	Selected
C3	1184.7	59	210	189.92	0	0	590	
C4	620.16	456	350.7	349.34	0	0	0	
b) State2								
H1	11244	33	616	275.29	1075	0	0	
H2	410	200	183.05	181	0	0	0	Selected A[H]
C1	15251	32.04	621	145	0	285.6	0	Selected
C2						0		
C3	1184.7	59	210	189.92	0	0	590	
C4	620.16	456	350.7	349.34	0	0	0	
c) State3								
H1	11244	33	616	275.29	1075	0	0	Selected B[C]
H2								Matched to C1
C1	14841	32.04	621	157.8	285.6	0	0	
C3	590	59	200	210	0	0	590	Selected
C4	547.2	456	349.5	350.7	0	0	0	
d) State4								
H1	10064	33	598.12	275.29	1665	0	0	Selected B[C]
C1	14424	32.04	621	157.8	285.6	0	0	
C3								Matched to H1
C4	547.2	456	349.5	350.7	0	0	0	Selected
e) State5								
H1	9516.4	33	581.54	275.29	1665		0	Selected A[H]
C1	14841	32.04	621	157.8	285.6		0	Selected
C4								Match to H1
e) State5								
H1								Matched to C1
C1	3659.7	32.04	621	454.81	1950.6		0	To heater

Table 5.17 Synthesis Table 2 for hot end

Synthesis Table 2 for hot end								
Stream	Load	W	T1	T2	Ds	Dw	Dt	Action
a) State1								
H1	15213	33	616	155	165	0	0	Selected C[H]
H2	410	200	183.05	181	0	0	0	
C1	15251	32.04	621	145	0	285.6	0	
C2	3969.4	91	188	144.38	0	0	910	Selected
C3	1184.7	59	210	189.92	0	0	590	
C4	620.16	456	350.7	349.34	0	0	0	
b) State2								
H1	11244	33	616	275.29	1075	0	0	
H2	410	200	183.05	181	0	0	0	Selected A[H]
C1	15251	32.04	621	145	0	285.6	0	Selected
C2								Matched to C1
C3	1184.7	59	210	189.92	0	0	590	
C4	620.16	456	350.7	349.34	0	0	0	
c) State3								
H1	11244	33	616	275.29	1075	0	0	Selected B[C]
H2								Matched to C1
C1	14841	32.04	621	157.8	0	285.6	0	
C3	594.72	59	200	189.92	0	0	590	
C4	547.2	456	349.5	350.7	0	0	0	Selected
d) State4								
H1	10696	33	599.42	275.29	1075	0	0	Selected B[C]
C1	14841	32.04	621	157.8	0	285.6	0	
C3	594.72	59	200	189.92	0	0	590	Selected
C4								Matched to H1
e) State5								
H1	9511.7	33	581.4	275.29	1665		0	Selected A[H]
C1	14841	32.04	621	157.8	0	285.6	0	Selected
C3								Matched to H1
f) State6								
H1								Matched to C1
C1	3664.4	32.04	621	454.66	1950.6		0	To Heater

Table 5.18 Synthesis Table 3 for hot end

Synthesis Table 3 for hot end								
Stream	Load	W	T1	T2	Ds	Dw	Dt	Action
a) State1								
H1	15213	33	616	155	165	0	0	Selected C[H]
H2	410	200	183.05	181	0	0	0	
C1	15251	32.04	621	145	0	285.6	0	
C2	3969.4	91	188	144.38	0	0	910	Selected
C3	1184.7	59	210	189.92	0	0	590	
C4	620.16	456	350.7	349.34	0	0	0	
b) State2								
H1	11244	33	616	275.29	1075	0	0	
H2	410	200	183.05	181	0	0	0	Selected A[H]
C1	15251	32.04	621	145	0	285.6	0	Selected
C2								Match to H1
C3	1184.7	59	210	189.92	0	0	590	
C4	620.16	456	350.7	349.34	0	0	0	
c) State3								
H1	11244	33	616	275.29	1075	0	0	Selected C[H]
H2								Matched to C1
C1	14841	32.04	621	157.8	0	285.6	0	
C3	590	59	200	210	0	0	590	Selected
C4	547.2	456	349.5	350.7	0	0	0	
d) State4								
H1	10064	33	616	285.29	1665	0	0	Selected B[C]
C1	14936	32.04	621	157.72	0	285.6	0	
C3								Match to H1
C4	547.2	456	349.5	350.7	0	0	0	Selected
e) State5								
H1	9516.4	33	599.42	285.29	1665	0	0	Selected A[H]
C1	14936	32.04	621	157.72	0	285.6	0	Selected
C4								Matched to H1
f) State6								
H1								Matched to C1
C1	3754.9	32.04	621	454.73	1950.6	0	0	To Heater

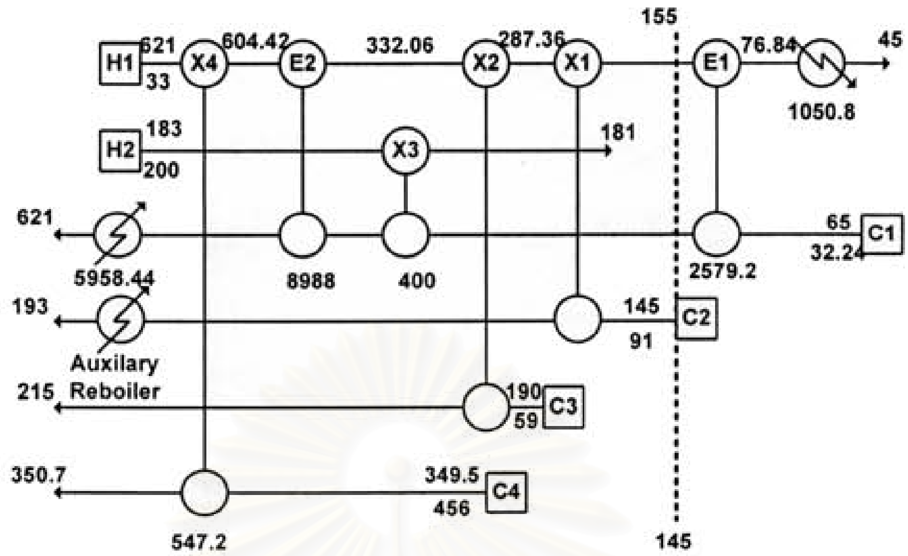


Figure 5.36 Resilient Heat Exchanger Network 3

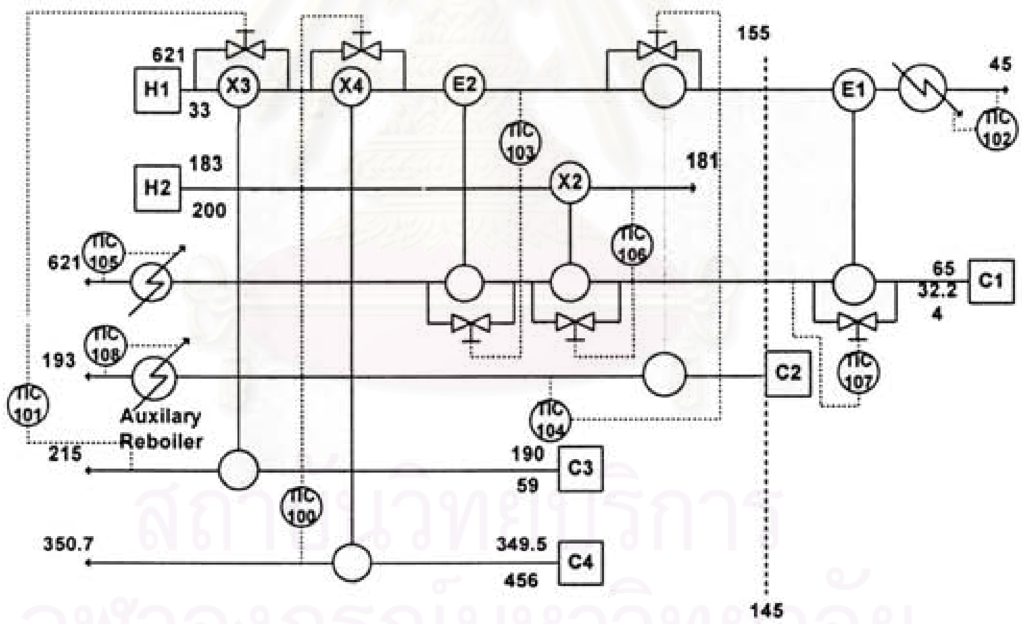


Figure 5.37 Control structure for Resilient Heat Exchanger Network 1

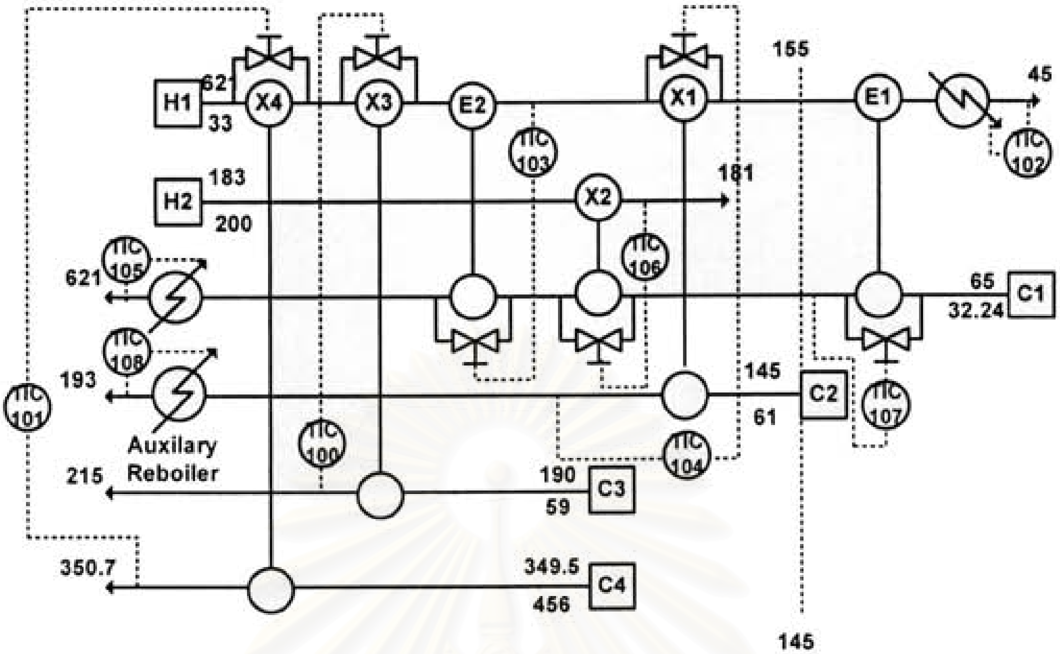


Figure 5.38 Control structure for Resilient Heat Exchanger Network 2

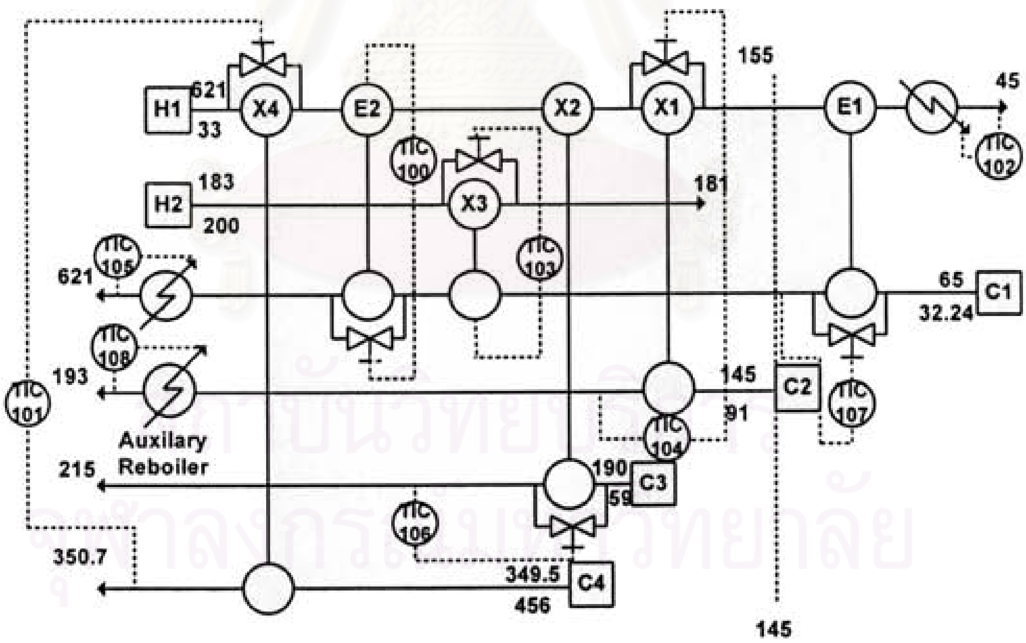


Figure 5.39 Control structure for Resilient Heat Exchanger Network 3

5.4.2 Dynamic Simulation Result for HEN in HDA Process (stream only)

In order to compare three control structures in HDA Process, several disturbance loads were made. After that we calculate the integral absolute error (IAE) for the three control structures and summarized in Table 5.19. The results show that HE3 has minimum IAE. When disturbances present at supply temperature of C3, we see that the heat link which go to the heater in HE3 is shorter than the other. That means it can handle the disturbance faster. So we chose HE3 to simulate in HYSYS to check that it can achieve the maximum energy recovery and keep their target temperature at their desirable value when it is in the real process.

Table 5.19 Comparing the Integral absolute error of three heat exchanger network of HDA Process

HEN	IAE
HEN1	305.27
HEN2	271.90
HEN3	255.72

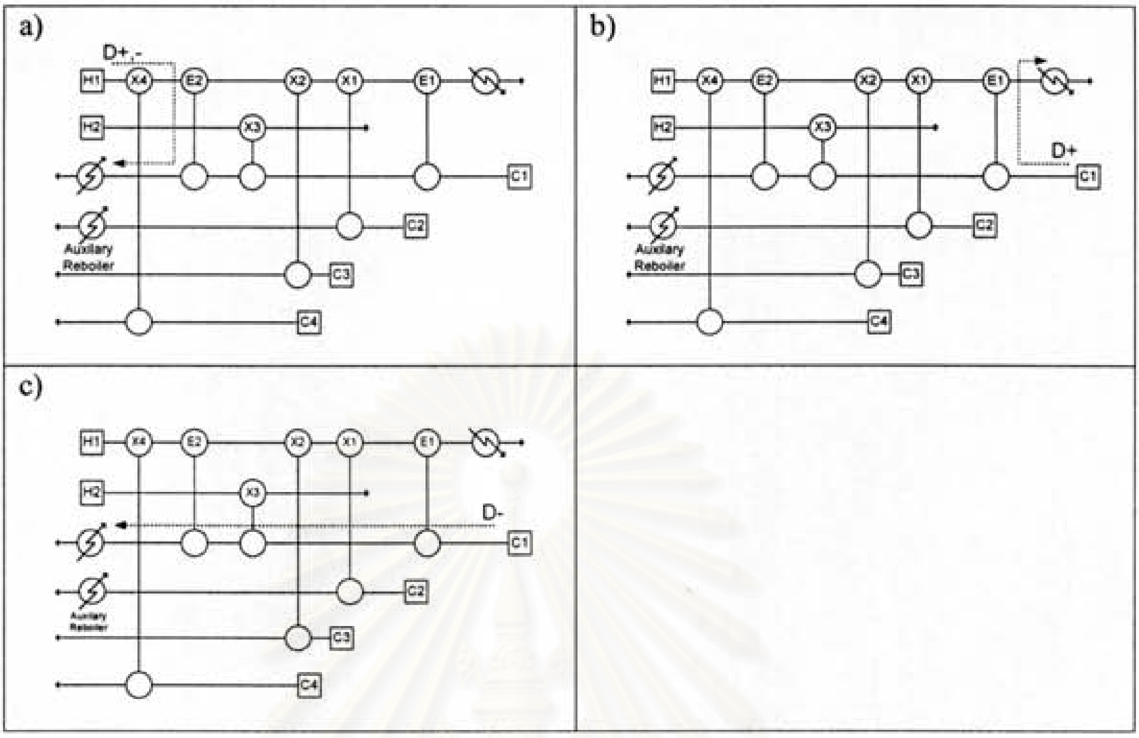


Figure 5.40 Heat pathway of control structure of network equipped with LSS of HDA Process when there is the disturbance at supply temperature a) D+ and D-presented at H1, b) D+ presented at C1, c) D- presented at C1

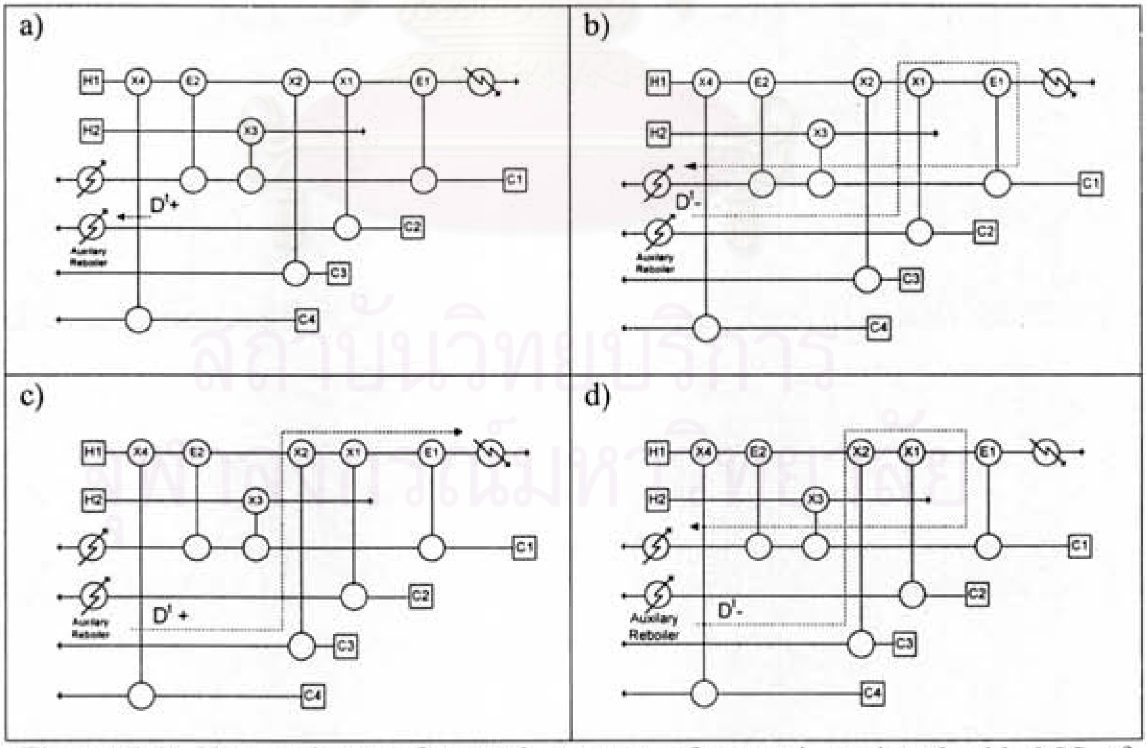


Figure 5.41 Heat pathway of control structure of network equipped with LSS of Example 1 when there is the disturbance at target temperature a) D^t+ presented at C2, b) D^t- presented at C2 c) D^t+ presented at C3 d) D^t- presented at C3

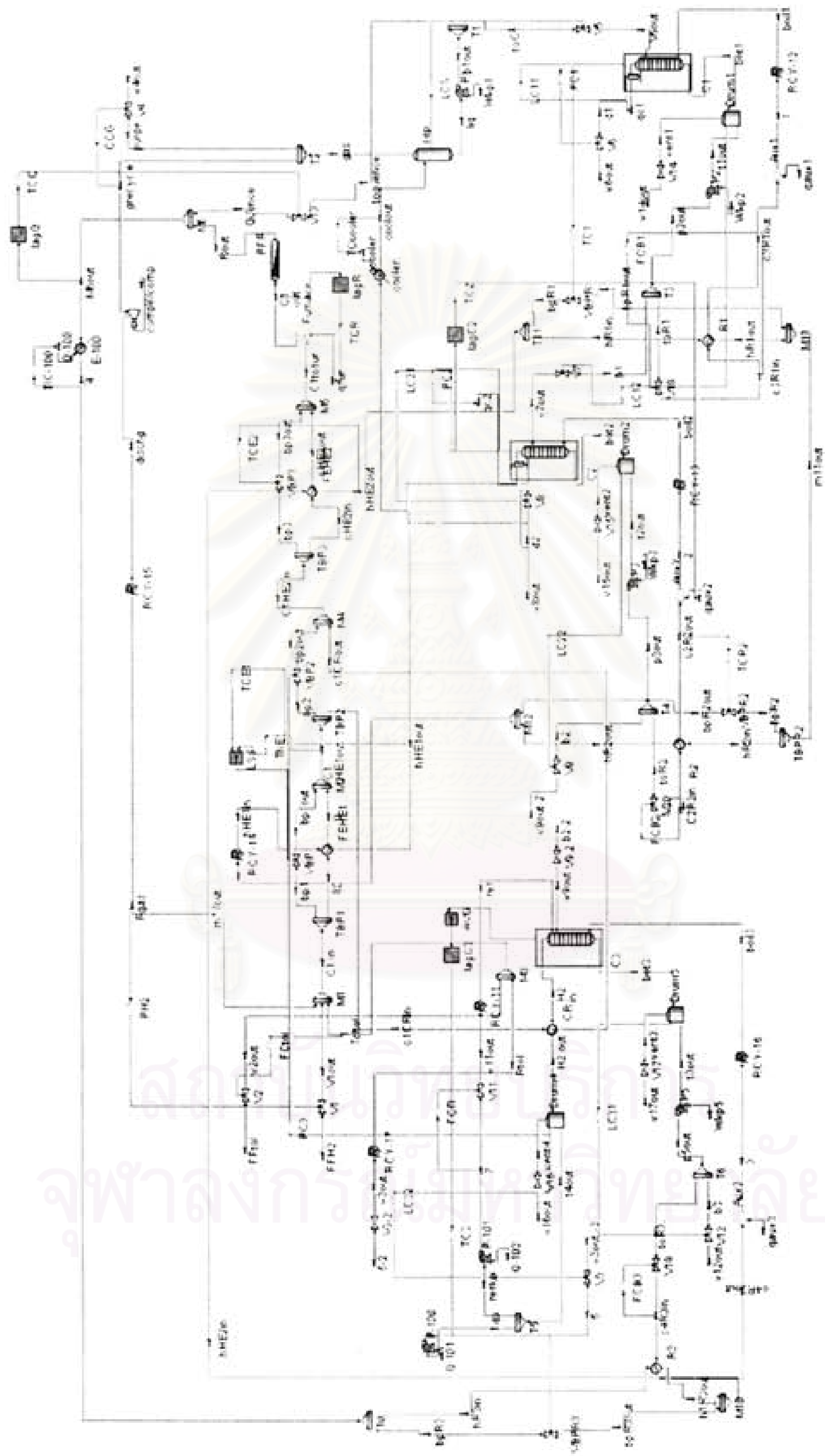


Figure 5.42 Control structure of HDA Process from HYSYS flowsheet

5.4.3 Design of Plantwide Control of HDA Process

The plantwide control systems for the HDA process is developed based on the HPH. However, the designed control systems must achieve certain control objectives within prescribed operational constraints. The control objectives for this process are typical for a chemical processes and listed below:

1. Maintain process variables at desired values
2. Keep process operating conditions within equipment constraints
3. Minimize variability of the product rate and the product quality during disturbances
4. Minimize the disturbance propagation

For the HDA process, several constraints are given by Douglas (1988). These include:

1. The reactor feed ratio of hydrogen to aromatic feed must be greater than 5:1 to prevent coking.
2. The reactor outlet temperature must be less than 704°C to prevent hydro-cracking.
3. The reactor effluent must be quenched to 621°C with liquid from separator to prevent fouling in the process-to-process heat exchanger.
4. The conversion must be less than 0.97 for the product distribution correlation.

Since the hot reactor product is used to drive all reboilers in stabilizer, product and recycle column. In order to obtain a good performance, Luyben et al. (1999) suggested adding an auxiliary reboiler (R2) is needed for to guarantee a workable HDA process. In this control structure, the auxiliary reboiler (R2) duty is manipulated to control the tray temperature in the product column. The hot outlet temperatures of FEHE 2 (the temperature at the entrance of the auxiliary reboilers, R2) are controlled by manipulating bypass valve on the hot stream to prevent the propagation of thermal disturbance to the separation section. In the recycle column, the cold inlet stream of condenser/reboiler (CR) is bypassed and manipulated to control its pressure column. In addition, the averaging tray temperature control in the recycle column is used instead of a single tray temperature control in order to reduce the deviation of temperature response during the disturbance occur. In this work, the type of controller for each control loop is different. P controllers are employed for the level loops, PID controllers are employed for the temperature loops and PI controllers are employed for the remaining loops.

5.4.4 Dynamic Simulation Results for HDA Process

In order to illustrate the dynamic behavior of the control structure in HDA process, several disturbance loads are made. The dynamic responses of the control system are shown in Figures 5.43 to 5.47. Results for individual disturbance load changes are as follows:

5.3.4.1 Change in the supply temperature of Hot Stream H1 (Reactor Product)

Figure 5.43 shows the dynamic responses of HDA process to a change in the disturbance load of hot stream from reactor, by changing its temperature from 620.85°C to 616°C at time equals 10 minutes, and the its temperature is increased from 616°C to 626°C at time equals 200 minutes, then its temperature is returned to its nominal value of 620.85°C at time equals 400 minutes.

The heat load disturbance of the hot stream can be shifted to the cold stream, since the hot outlet temperature of FEHE3 has to be kept constant. Both positive and negative disturbance loads of the hot stream are shifted to a furnace utility (Figure 5.4b). When the hot temperature decreases, it will result in decrease of the furnace inlet temperature (Figure 5.43l). Consequently, the furnace duty increases (Figure 5.43k). On the other hand, when the positive disturbance load is originating from the hot stream (i.e. the hot inlet temperature increases), the furnace duty will be decreased, since the furnace inlet temperature increases. The duty of cooler is quite constant. The recycle column, the separator temperature and the reactor inlet temperature are well controlled (Figure 5.43m, n and o).

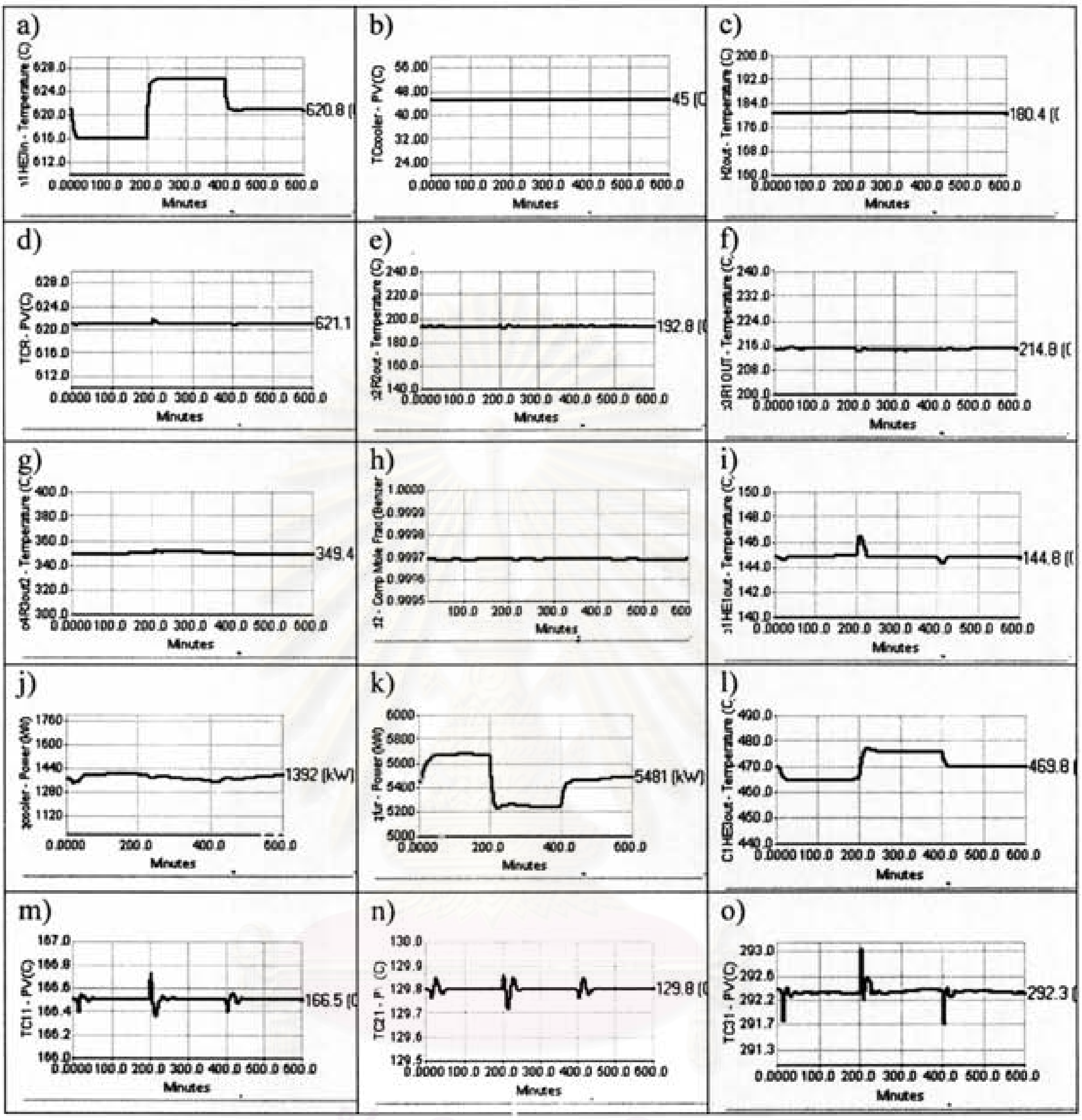


Figure 5.43 Dynamic responses of HDA process to a change in the supply temperature H1 (Reactor Product Stream)

5.3.4.2 Change in the supply temperature of Cold Stream C1 (Reactor Feed Stream)

We cannot change the supply temperature of C1 in the process directly so we have to change the reactor feed stream instead. Figure 6.2 shows the dynamic responses to a change in the disturbance load of cold stream (reactor feed stream). This disturbance is made as follows: first the fresh toluene feed temperature is decreased from 30°C to 20°C at time equals 10 minutes, and the temperature is increased from 20°C to 40°C at time equals 200 minutes, then its temperature is returned to its nominal value of 30°C at time equals 400 minutes.

As can be seen, the supply temperature of C1 decreased from 69.63°C to 65°C at time equals 10 minutes, and the temperature is increased from 65°C to 75°C at time equals 200 minutes, then its temperature is returned to its nominal value of 69.63°C at time equals 400 minutes.

When the cold inlet temperature of HE1 decreases, positive disturbance, the LSS takes the action to control the cold outlet temperature of HE1 (Figure 5.44m). The heat pathway is shown in Figure 5.40 (f). As the result, the hot outlet temperature of HE1 drops to a new steady state value (Figure 5.44l). The cooler duty decreases while the duty of furnace is constant (Figure 5.44 j, k).

When the cold inlet temperature of HE1 increases, negative disturbance the cold outlet temperature of FEHE1 quickly increases to a new steady state value. The LSS takes the action to control the hot outlet temperature of HE1 (Figure 5.44 l). The heat pathway is shown in Figure 5.40g. The negative disturbance load of the cold stream will result in decrease of the furnace duty.

The recycle column, the separator temperature and the reactor inlet temperature are well controlled (Figure 5.43n, o and p).

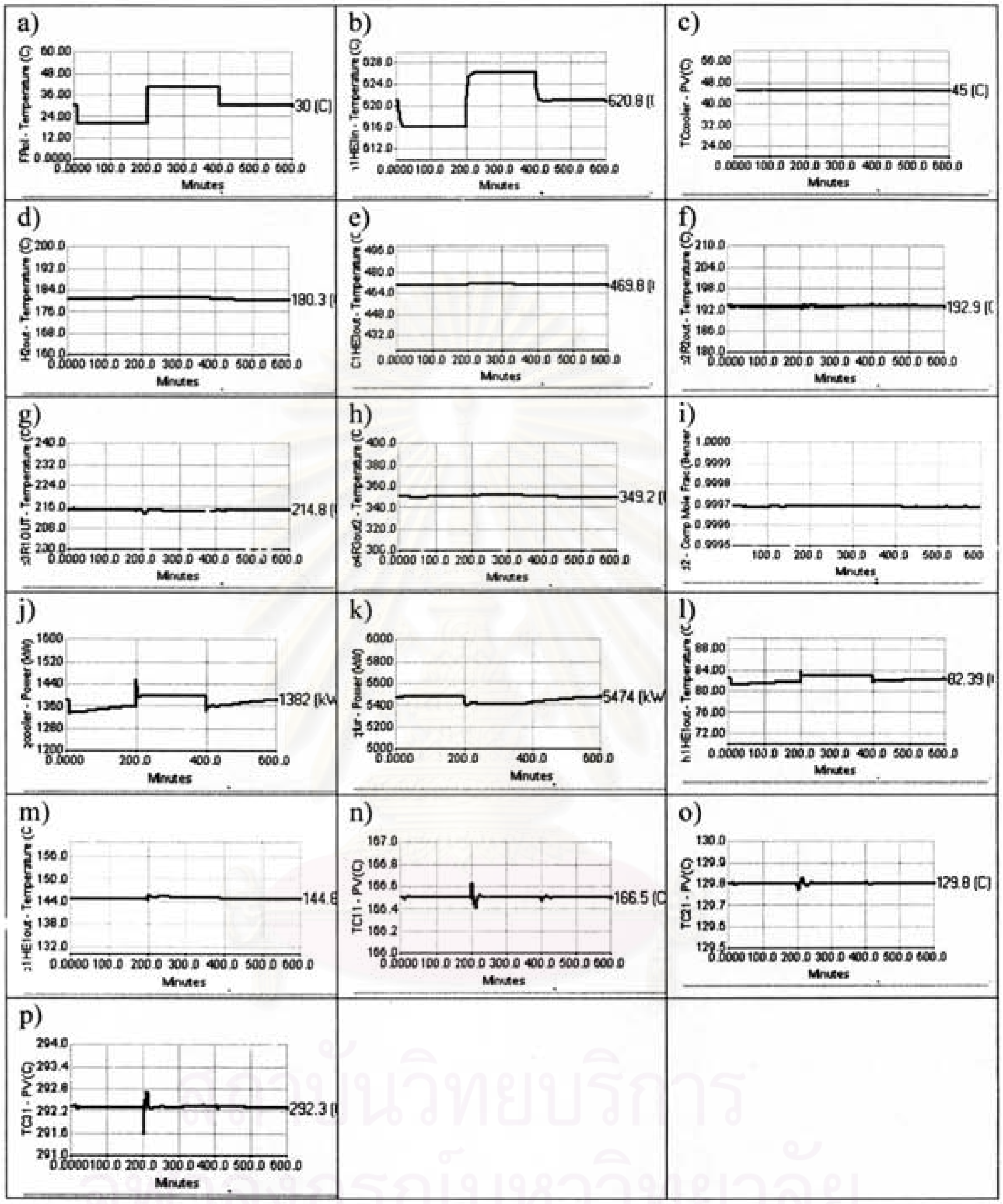


Figure 5.44 Dynamic responses of HDA process to a change in the supply temperature C1 (Reactor Feed Stream)

5.3.4.3 Change in the target temperature of Cold Stream C2 (Product Column Reboiler)

Figure 5.45 shows the dynamic responses to a change in the target temperature of cold stream C2 (Product column reboiler). This disturbance is made as follows: first the target temperature of C2 is decreased from 193°C to 188°C at time equals 10 minutes, and the temperature is increased from 188°C to 198°C at time equals 200 minutes, then its temperature is returned to its nominal value of 193°C at time equals 400 minutes.

When the cold target temperature of C2 decreases, negative disturbance, it makes the hot outlet temperature of R2 increased. The LSS takes the action to control the hot outlet temperature of HE1. The heat pathway is shown in Figure 5.41b). The furnace duty decreases while the duty of cooler is constant (Figure 5.44j and k). The composition of benzene seem to be increased because toluene can vaporize more thand norminal condition.

When the cold target temperature of C2 increases, negative disturbance, it makes the duty of auxiliary increase from 0 kW to 28.6 kW to reach the target temperature. The heat pathway is shown in Figure 5.41c.

The recycle column, the separator temperature and the reactor inlet temperature are well controlled (Figure 5.43l, m and n).

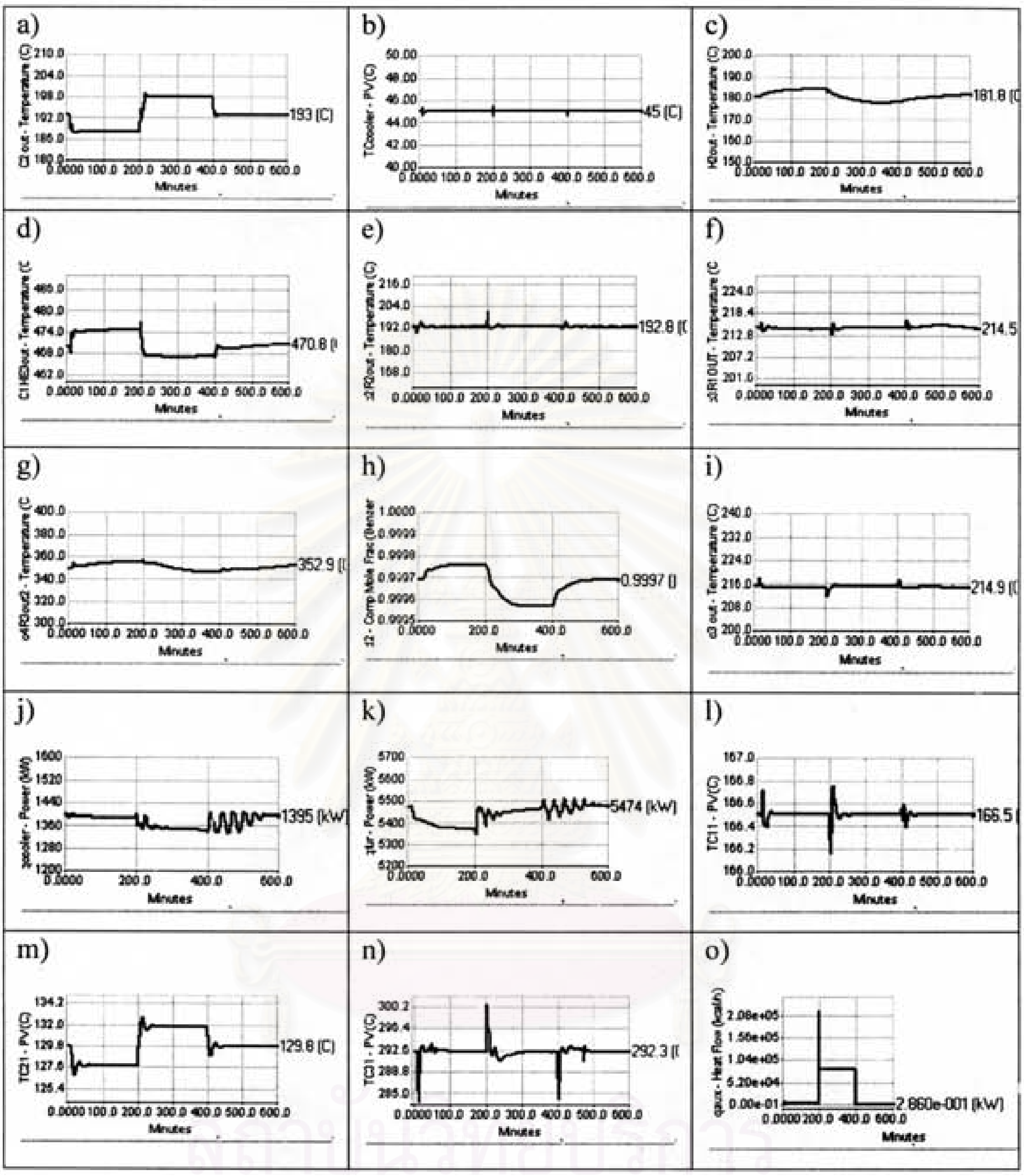


Figure 5.45 Dynamic Responses of HDA process to a change in the target temperature C2 (Product Column Reboiler)

5.3.4.4 Change in the target temperature of Cold Stream C3 (Product Column Reboiler)

We cannot change the target temperature of C3 in the process directly so we have to change the temperature in Stabilizer column instead. Figure 5.46 shows the dynamic responses to a change in the target temperature of Cold Stream C3 (Product Column Reboiler). This disturbance is made as follows: first the stabilizer column reboiler temperature is decreased from 166.5°C to 165.5°C at time equals 10 minutes, and the temperature is increased from 165.5°C to 167.9°C at time equals 200 minutes, then its temperature is returned to its nominal value of 166.5 °C at time equals 400 minutes.

As can be seen, the target temperature of product column reboiler is decreased from 215°C to 210°C at time equals 10 minutes, and the temperature is increased from 210°C to 220°C at time equals 200 minutes, then its temperature is returned to its nominal value of 215 °C at time equals 400 minutes.

When the cold target temperature of C3 decreases, negative disturbance, it makes the hot outlet temperature of R1 increased. The LSS takes the action to control the cold outlet temperature of HE1. The heat pathway is shown in Figure 5.41c. The negativ^ disturbance makes the duty of furnace decreases while the duty of cooler is constant (Figure 5.44i, j).

When the cold target temperature of C3 increases, positive disturbance, it makes the hot outlet temperature of R1 decreased. The LSS takes the action to control the hot outlet temperature of HE1. The heat pathway is shown in Figure 5.41d. The negative disturbance makes the duty of cooler decreases while the duty of furnace is constant. It can be seen that when the target temperature of C3 increase, the temperature in stabilizer column is increased follow the target temperature of C3. It makes the composition of methane at distillate decreased.

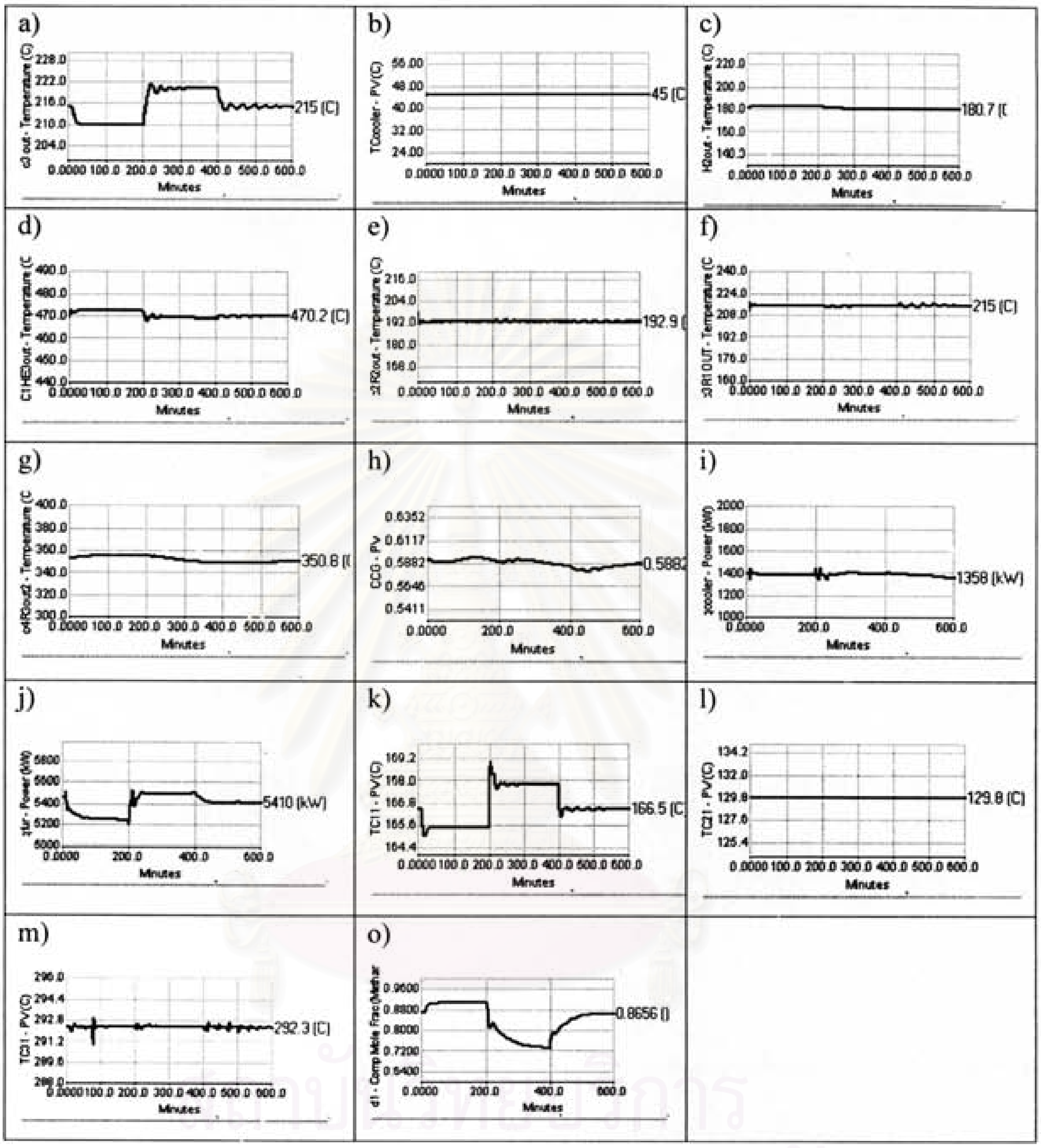


Figure 5.46 Dynamic Responses of HDA process to a change in the target temperature C3 (Stabilizer Column Reboiler)

5.3.4.5 Change in the flowrate of Cold Stream C1 (Total Toluene Feed Flowrate)

Figure 5.47 shows the dynamic responses of HDA process to a change in the total toluene feed flowrates from 169.5 kgmole/hr to 174.5 kgmole/hr at time equals 10 minutes, and the its feed flowrate is decreased from 174.5 kgmole/hr to 164.5 kgmole/hr at time equals 200 minutes, then its flowrates is returned to its nominal value of 169.5 kgmole/hr at time equals 400 minutes.

To increase in total toluene flowrate raises the reaction rate, so the benzene product flowrate increases (Figure 5.47m). On the other hand, the drop in total toluene feed flowrate reduces the reaction rate, so the benzene product flowrates decreases. The oscillations occur in the tray temperature of the recycle column (Figure 5.47l). For the tray temperature of the product column and stabilizer column, they are quite well controlled when this disturbance occurs (Figure 5.47j, k). The duty of furnace and cooler increased when flowrate increase. Because increased flowrate of C1 which called positive disturbance, LSS take the action to control the outlet temperature of C1. But the flowrate of C1 increase, the duty of furnace will increase also. In contrast, the same reason in decrease flowrate.

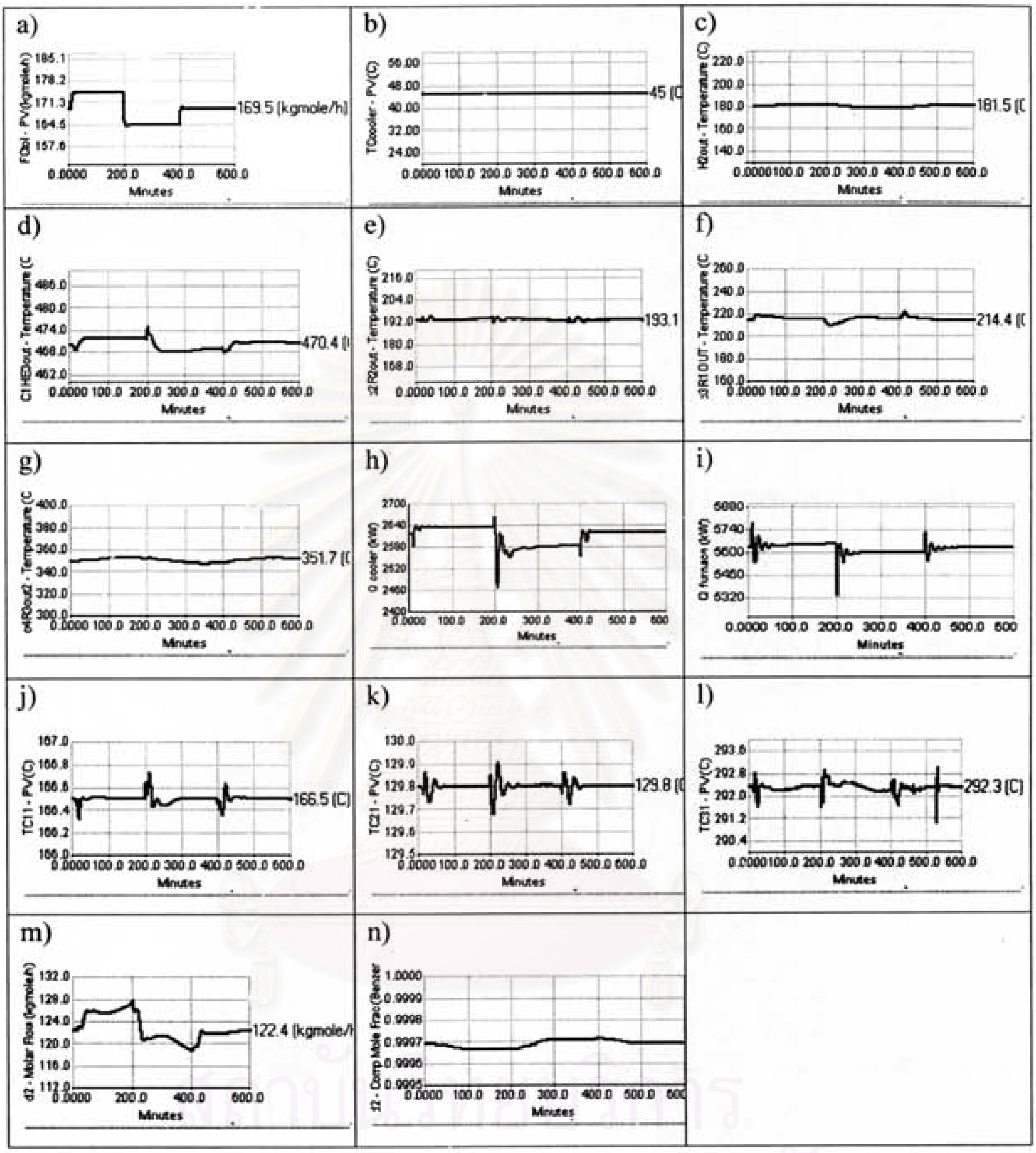


Figure 5.47 Dynamic Responses of HDA process to a change in flowrate of C1 (Reactor Feed Stream)

The results show that the synthesis procedures of design and control resilience heat exchanger network are able to maintain target temperature at specified values. Furthermore, this action should not violate maximum energy recovery.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This research effort is directed toward to develop the procedure for designing control structure of heat exchanger network by considering its network structure combining with heuristic approach which covers General Design, Match Pattern, Loop Control Selection, Bypass Setting, Split Ratio and Selector Switch Setting.

6.1.1 Procedures of Design Heat exchanger network

The synthesis of a resilient heat exchanger network by using (1) match pattern as operators in mapping one design state to the next and (2) heat load propagation technique can be done by the following systematic sequence:

1. Choose the minimum heat load condition in order to make the disturbance positive and guarantee the network.
2. Pop a match pattern operator from the ordered stack of match patterns. If all the patterns are chosen, backtrack to the parent design state and repeat the procedure.
3. Choose a pair of hot and cold streams from the set of unmatched process streams. If all streams have been chosen and none were satisfied, go back to the first step to try a new pattern.
4. Apply the match pattern to the selected pair of streams. If the streams satisfy the pattern test and the resiliency requirement (Table 4.1 and 4.2), go to the next step. Otherwise go back to the previous step to select a new pair of streams.

   Match pattern test: Check whether the heat load, input temperature and heat flow rate capacity satisfy the match pattern description.

   Resiliency test: Check whether the disturbance load of the smaller heat load stream can be shifted to the larger heat load stream.

5. Create a new state to support the new fact. A new state is a descendant of a current one. Change the parameters of the larger heat load stream: the supply or target temperature, the heat load and the disturbance load.
6. For a pinch match of stream i and j for which Wj > Wi and Lj > Li, the disturbance of a residual stream j:

$$D_j = D_i + \left(D_{j,pinch} - D_{i,pinch}\right) \qquad (1)$$

7. If there are unmatched hot and cold streams, go to the second step. Otherwise go to the next step.
8. Match the only hot or cold streams with the utility streams.
9. If there are other unused match patterns go to the first step. This is equivalent to saying that there might be other solutions available, continue.

6.1.2 Procedures of Design Control Structure

1. Use Bypass stream for controlling. The bypass stream should be settled on the cold side because it would be safer to equip measure equipment and control valve on the hot side. On the other hand, it should settle bypass stream on the controlling side regardless whether it is hot or cold stream. However, the selection must bring about the best performance of control system.
2. Control loop must be settled for reducing the disturbance load path. Calandranis and Stephanopoulos (1988) claimed that it should select the disturbance load path related to the least number of heat exchanger namely the shortest path way in order to reduce the effect of disturbance on another part of network.
3. From the economic point of view, we strongly suggest to:
   (3.1) shift D^+ of cold stream or D^- of the hot stream to the cooler utility, thus its duty will be decreased.
   (3.2) shift D^- of cold stream or D^+ of the hot stream to the heater utility, thus its duty will be decreased.
4. A selective controller with low selector switch (LSS) should be employed to select an appropriate heat pathway through the network to carry the associated load to the utility unit.

5. A selective controller with low selector switch (LSS) should be employed to select an appropriate heat pathway through the network to carry the associated load to the utility unit.
6. The number of LSS to be used in a particular case can be determined as follows:
   (6.1) Identify the heat pathway of disturbance
   (6.2) If there is only one heat pathway, it do not need to be set the LSS.
   (6.3) If there are more than one heat pathway, it need to be set the LSS between the outlet temperature of Heat exchanger.

The design procedure of heat exchanger network and control structure earned from this research can be applied to the usual network in the presence of variation from changing in flowrate, inlet temperature and outlet temperature because of this step considering the possible structure of overall network existed. It can, moreover, be used to configure suitable control structure as a convenient and simply tool.

Control structure of heat exchanger network applied from the procedure presented here can be operated with attaining the objective required, i.e., target temperature and dynamic maximum heat recovery with lowest utilities, even in the presence of energy disturbance. Additionally, it is more safety for the industrial purpose because of normally the stream which is used as exchange stream in heat exchanger network is feed stream of reactor or cracking unit. Therefore, to maintain and keep the network temperature at target point by controller is necessary for reduce the effect on another units. It is generally accepted that the appropriate control structure not only leads the response of system to reach the target faster and more efficiently but also lower cost of setting control loop and valve.

6.2 Recommendation

Since the tray temperature control of recycle column in HDA process has oscillations very large when the disturbance from flowrate occured, so we should improve the performance of this loop by understanding and applying control techniques such as feed forward control and cascade control etc.

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APPENDICES

APPENDIX A

TUNING OF CONTROL STRUCTURES

A.1 Tuning Controllers

Notice throughout this work uses several types of controllers such as P, PI, and PID controllers. They depend on the control loop. In theory, control performance can be improved by the use of derivative action but in practice the use of derivative has some significant drawbacks:

1. Three tuning constants must be specified.
2. Signal noise is amplified.
3. Several types of PID control algorithms are used, so important to careful that the right algorithm is used with its matching tuning method.
4. The simulation is an approximation of the real plant. If high performance controllers are required to get good dynamics from the simulation, the real plant may not work well.

A.2 Tuning Flow, Level and Pressure Loops

The dynamics of flow measurement are fast. The time constants for moving control valves are small. Therefore, the controller can be turned with a small integral or reset time constant. A value of τ_I = 0.3 minutes work in most controllers. The value of controller gain should be kept modest because flow measurement signal are sometime noisy due to the turbulent flow through the orifice plate. A value of controller gain of K_c = 0.5 is often used. Derivative action should not be used.

Most level controllers should use proportional-only action with a gain of 1 to 2. This provides the maximum amount of flow smoothing. Proportional control means there will be steady state offset (the level will not be returned to its setpoint value).

However, maintaining a liquid level at a certain value is often not necessary when the liquid capacity is simply being used as surge volume. So the recommended tuning of a level controller is $K_c = 2$. Most pressure controllers can be fairly easily tuned. The process time constant is estimated by dividing the gas volume of the system by the volumetric flowrate of gas flowing through the system. Setting the integral time equal to about 2 to 4 times the process time constant and using a reasonable controller gain usually gives satisfactory pressure control. Typical pressure controller tuning constants for columns and tanks are $K_c = 2$ and $\tau_I = 10$ minutes.

A.3 Relay- Feedback Testing

The relay-feedback test is a tool that serves a quick and simple method for identifying the dynamic parameters that are important for to design a feedback controller. The results of the test are the ultimate gain and the ultimate frequency. This information is usually sufficient to permit us to calculate some reasonable controller tuning constants.

The method consists of merely inserting an on-off relay in the feedback loop. The only parameter that must be specified is the height of the relay, h. This height is typically 5 to 10 percent of the controller output scale. The loop starts to oscillate around the setpoint with the controller output switching every time the process variable (PV) signal crosses the setpoint. Figure B.1 shows the PV and OP signals from a typical relay-feedback test. The maximum amplitude (a) of the PV signal is used to calculate the ultimate gain, K_U from the equation

$$K_U = \frac{4h}{a\pi} \qquad (1)$$

The period of the output PV curve is the ultimate period, P_U from these two parameters controller tuning constants can be calculated for PI and PID controllers, using a variety of tuning methods proposed in the literature that require only the ultimate gain and the ultimate frequency, e.g. Ziegler-Nichols, Tyreus-Luyben.

The test has many positive features that have led to its widespread use in real plants as well in simulation studies:

1. Only one parameter has to be specified (relay height).
2. The time it takes to run the test is short, particularly compared to the extended periods required for methods like PRBS.
3. The test is closedloop, so the process is not driven away from the setpoint.
4. The information obtained is very accurate in the frequency range that is important for the design of a feedback controller.
5. The impact of load changes that occur during the test can be detected by a change to asymmetric pulses in the manipulated variable.

These entire features make relay-feedback testing a useful identification tool. Knowing the ultimate gain, K_U and the ultimate period, P_U permits us to calculate controller settings. There are several methods that require only these two parameters. The Ziegler-Nichols tuning equations for a PI controller are:

$$K_C = K_U / 2.2 \tag{2}$$

$$\tau_I = P_U / 1.2 \tag{3}$$

These tuning constants are frequently too aggressive for many chemical engineering applications. The Tyreus-Luyben tuning method provides more conservative settings with increased robustness. The TL equations for a PI controller are:

$$K_C = K_U / 3.2 \tag{4}$$

$$\tau_I = 2.2 P_U \tag{5}$$

A.4 Inclusion of Lags

Any real physical system has many lags. Measurement and actuator lags always exist. In simulations, however, these lags are not part of the unit models. Much more aggressive tuning is often possible on the simulation than is possible in the real plant. Thus the predictions of dynamic performance can be overly optimistic. This is poor engineering. A conservative design is needed. Realistic dynamic simulations require that we explicitly include lags and/or dead times in all the important loops. Usually this means controllers that affect Product quality or process constraint.

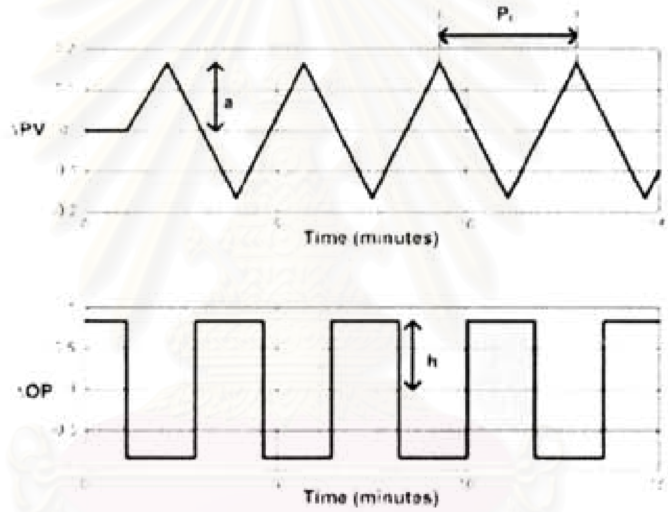

Figure A.1 Input and Output from Relay-Feedback Test

Table A.1 Typical measurement lags

		Number	Time constant (minutes)	Type
Temperature	Liquid	2	0.5	First-order lags
	Gas	3	1	First-order lags
Composition	Chromatograph	1	3 to 10	Deadtime

VITA

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