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DESIGN OF CONTROL STRUCTURE FOR HEAT EXCHANGER NETWORK WITH PINCH MOVE

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ธริศรา ตันกิม : การออกแบบโครงสร้างการควบคุมสำหรับข่ายงานเครื่องแลกเปลี่ยนความร้อนที่พินช์เคลื่อนที่ (DESIGN OF CONTROL STRUCTURE FOR HEAT EXCHANGER NETWORK WITH PINCH MOVE) อ. ที่ปรึกษา: ผศ. ดร. มนตรี วงศ์ศรี, 116 หน้า, ISBN 974-14-2581-3

ข่ายงานเครื่องแลกเปลี่ยนความร้อนเป็นวิธีการหนึ่งในการนำพลังงานความร้อนกลับมาใช้อย่างมีประสิทธิภาพในอุตสาหกรรมกระบวนการการผลิต อย่างไรก็ตามการแลกเปลี่ยนพลังงานภายในกระบวนการจะทำให้เกิดผลกระทบซึ่งกันและกันในกระบวนการและยังอาจทำให้กระบวนการมีความผิดพลาดจนไม่สามารถบรรลุอุณหภูมิเป้าหมายได้ ดังนั้นโครงสร้างการควบคุมของข่ายงานเครื่องแลกเปลี่ยนความร้อนจึงมีความสำคัญอย่างมากต่อการคงอุณหภูมิเป้าหมายและการได้รับการนำกลับคืนพลังงานสูงสุดของข่ายงาน

งานวิจัยนี้จะนำเสนอกฎและวิธีการออกแบบโครงสร้างการควบคุมข่ายงานเครื่องแลกเปลี่ยนความร้อน โดยอาศัยแนวทางฮิวริสติกต่าง ๆ ได้แก่ การออกแบบโครงสร้างการควบคุมกระสวนการจับคู่ การติดตั้งลูพควบคุม การเลือกติดตั้งกระแสบายพาส การใช้สัดส่วนการแยกและการสวิตช์ตำแหน่งที่ควบคุม มาประยุกต์ใช้ในแก้ปัญหาแบบคลาสสอง คือ ตัวแปรรบกวนเข้ามาในระบบมากจนส่งผลให้พินช์เปลี่ยนตำแหน่ง หรือเรียกว่าพินช์กระโดด ซึ่งพบว่าวิธีที่ได้ทำการออกแบบนั้นสามารถที่จะรักษาอุณหภูมิเป้าหมาย และยังสามารถที่จะนำกลับคืนพลังงานสูงสุดอีกด้วย ซึ่งข่ายงานเครื่องแลกเปลี่ยนความร้อนนี้ได้ถูกนำไปจำลองบนโปรแกรมไฮซิส (HYSYS) เพื่อทดสอบสมรรถนะของโครงสร้างการควบคุมด้วย

ภาควิชา.......วิศวกรรมเคมี.......	ลายมือชื่อนิสิต.......ธริศรา ตันกิม.......
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4770579321 : MAJOR CHEMICAL ENGINEERING
KEY WORD: HEAT EXCHANGER NETWORK / LOW SELECTOR SWITCH / MAXIMUM ENERGY RECOVERY / PINCH JUMP

TARISARA TANKIM : DESIGN OF CONTROL STRUCTURE FOR HEAT EXCHANGER NETWORK WITH PINCH MOVE. THESIS ADVISOR: ASST. PROF. MONTREE WONGSRI, D.Sc., 116 pp. ISBN 974-14-2581-3

Heat Exchanger Network (HEN) is an effective method to recover the heat energy used in process plants. However, transference of heat within the enclosure causes the interactions and may cause the process more difficult to maintain the target temperature. This research presents law and procedure for design control structure of heat exchanger network using heuristic approach such as General Design, Match Pattern, Loop Control Selection, Bypass Setting, Split Ratio and Selector Switch Setting, to solve Class II problem which is discontinuity in the pinch zone occurred, the so-called "pinch-jump". It has been shown that our procedure is able to maintain target temperatures at specified values. Furthermore, this action should not violate maximum energy recovery. The heat exchanger network with control structures are programmed using HYSYS for control structure performance tests.

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Finally, I would like to dedicate this dissertation to my family for their edification, support and endless love. Without them, I would not have been the person I am and certainly this work would never have reached completion.

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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.

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. Pinch problems can be divided into two classes according to the location of pinch which is affected by various magnitude of disturbance. Firstly, this is the problem in the presence of only small amount of disturbance which cannot affect to the location of pinch, the so-called class I. Second is called class II problem in which the existence of large amount of disturbance can cause pinch relocation namely pinch jump. The latter problem is generally believed to be more difficult to resolve. Moreover, the energy integration can cause the interactions and lead the process more difficult to maintain the target temperature. Therefore, in order to achieve maximum energy recovery and keep target temperature at their desirable value, the resilient heat exchanger network and control efficiency that can tolerate variations are important and indispensable.

This research is aimed to develop law and procedure for designing the control structure of heat exchanger network in the presence of pinch-jump (Class II problem) by using heuristic approach. Thereafter, the heat exchanger network with control structures designed was modeled using HYSYS PROGRAMMING to test its performance.

1.2 Research Objective

To design control structure of heat exchanger network which is aimed to achieve target temperature and dynamic maximum energy recovery in the occurrence of pinch jump.

1.3 Scope of Research

The target temperatures of streams are not subjected to changes.

1.3.1 No phase changes in all streams.

1.3.2 It is assumed that a utility exchanger can handle all variations of heat load.

1.3.3 Any heat exchanger will have enough heat transfer area to accommodate increases in heat loads of disturbed process streams.

1.3.4 The heat exchanger network with control structures are programmed using HYSYS for control structure performance tests

1.4 Contribution of Research

Procedure and method for designing the suitable control structure of heat exchanger network can be achieved and applied with the process in the presence of disturbance from the variation of inlet temperature. 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 Contents

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 objective of control, selection of manipulated variable and control variable. Design the control structure of heat exchanger network by developing law of control structure design in chapter 3 to the procedure for designing the control structure. This step can be applied with general heat exchanger network in the presence of energy disturbance and Class II problem, i.e., the variation of inlet condition that cause pinch jump 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 REVIEWS

2.1 Introduction

Heat exchanger network (HEN) is widely used for heat recovery purpose in various kinds 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. This chapter presents the literature review related to control and design of heat exchanger network.

2.2 Heat Exchanger Network Design

The objectives of heat exchanger network are to achieve 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 utilized 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 started 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) flow rate 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). Cerda et al. (1990) presented a direct design procedure by using a multioptimization technique to generate a resilience network structure. After that, Ploypaisansang (2003) stated that 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. Six alternatives for the HDA process are redesign to be the resiliency networks for maintaining target temperature and also achieving maximum energy recovery (MER).

2.3 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 also all 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 process 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).

CHAPTER III

THEORIES

3.1 Introduction

It is widely accepted that the design of HEN normally use feed back control. The suitable control structure has a significant effect on control efficiency. Generally, bypass stream is used to control network structure and in some case it is necessary to combine upstream and feed forward control together. Moreover, the appropriate location of bypass setting can lead to better control response or lower split ratio resulting in reducing of investment cost. The heat pathway is also crucial and indispensable factor to control the transfer of energy through the suitable direction in which the network can achieve MER.

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.

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.

3.2.1.1 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), ^{o}C	Target Temperature (Tt), ^{o}C	Heat capacity flow rate (CP), kW/^{o}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**.**

$$\mathbf{CP = Cp \times F}$$

Where CP = heat capacity flow rate (kW/^{o}C)

Cp = specific heat capacity of the stream (kJ/^{o}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 linearized 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, $\Delta T_{min.}$ In the case of ΔT_{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 (Linnhoff and Hindmarsh, 1983).

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

The results of the problem table algorithm can be called “Transshipment heat flow diagram” and diagrammatically represented in Figure 3.1(a) (Linnhoff and Hindmarsh, 1983).

The significance of the pinch is shown in Figure 3.1(b). The pinch separates the problem into two thermodynamic regions, namely, hot end and cold end. The hot end is the region comprising all streams or part of streams 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 streams 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.

As described previously, the hot end requires only hot utility so it acts as a heat sink while the cold end requires merely cold utility so it acts as a heat source. In order to achieve the utility minimum requirement, the design has to follow the pinch principle as listed below.

(1) There must not be heat across the pinch.

(2) There must not be external utility cooling above the pinch.

(3) There must not be external utility heating below the pinch.

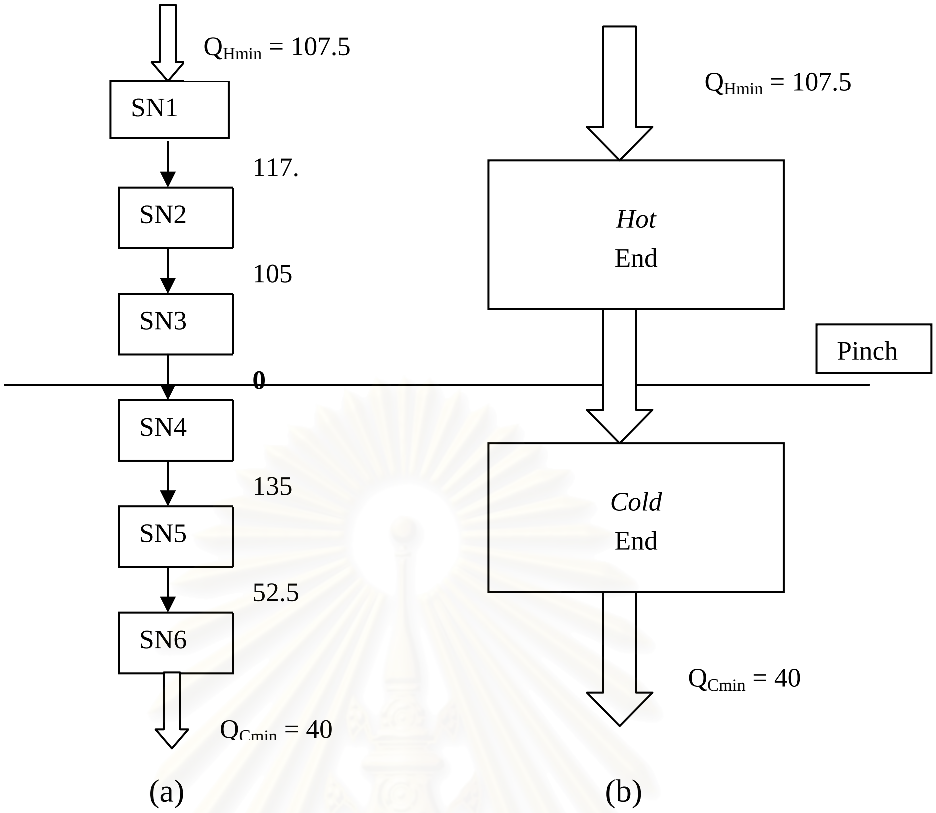


Figure 3.1 (a) Transshipmemt heat flow diagram for data in Table 3.1.
(b) Sub-networks combined into a hot and cold region.

3.2.2 Pinch Problem Classification

Saboo and Morari (1984) classified flexible HENs into two classes according to kind and magnitude of disturbances affected the pinch location. For the temperature variation, they had shown 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 variation in inlet temperature do not affect the pinch temperature location. If explicit function for minimum utility requirement valid over the whole disturbance range dose not exists, the problem is of Class II, at which large change in inlet temperature or flow rate variation cause the discrete change in pinch temperature location.

3.3 Heuristic Approach for Control Structure Design

The design of control structure has been developed for decades from the network structure characteristics combining with disturbance propagation techniques. It also covers the bypass stream selection, the separation ratio adjustment, and the use of upstream heat exchanger and the control of heat exchanger which has outlet temperature as control variable. Furthermore, it can be recently classified as 16 laws in 5 main groups for considering the control structure design as follows:

3.3.1 General Design Laws
3.3.2 Match Pattern Laws
3.3.3 Loop Control Selection Laws
3.3.4 Bypass Sitting Laws
3.3.5 Split Ratio Laws
3.3.6 Selector Switch Setting Laws

3.3.1 General Design Laws

The first law: The stream which comprises of only one heat exchanger is the first priority to consider in process design.

3.3.1.1 Propagated Disturbance

The variation of temperature and flow rate as disturbances must be removed by propagating the disturbance to heat sink as follows:

- Transferring a disturbance to the utility within the subnetwork, hot side or cold side, in order to achieve maximum energy recovery (MER).
- Transferring a disturbance to the utility outside subnetwork. In this case the maximum energy recovery (MER) is not achieved. It should be used when disturbances can not be handled.

3.3.1.2 Disturbance Propagation Method (Wongsri, 1990)

The propagated disturbance of a stream is a disturbance caused by a variation in heat load of ‘up-path’ streams to 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 3.2

In the case of considering the stream which consists of one heat exchanger, it has no remain heat after its transfer with disturbance propagation method of Wongsri (1990). All disturbances must be transferred to an exchanged stream. The only way for disturbance propagation is loop control settled at the heat exchanger. Therefore, it is necessary to consider a stream which consists of one heat exchanger as a first priority.

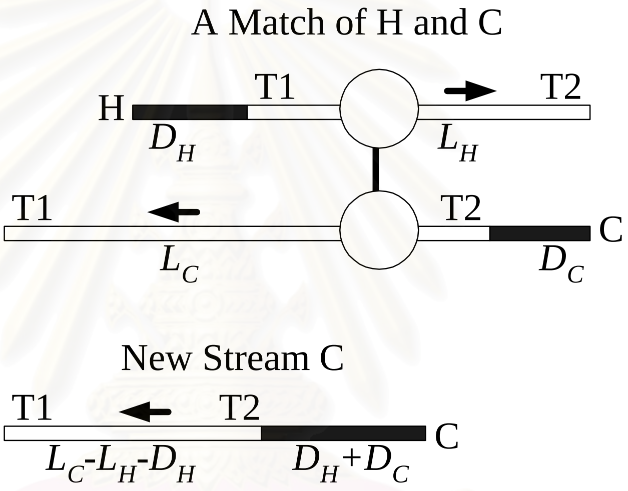


Figure 3.2 A Concept of Propagated Disturbance.

The second law: The heat exchanger used for controlling stream temperature can not be used to control another exchanged stream.

Because the heat exchanger is equipment for transferring energy from one stream to another and it is controlled by adjusting the unit load only (control via bypass adjustment). Thus, there is only one outlet target temperature can be controlled.

The third law: It should always set bypass and control loop at the last unit to maintain target temperature.

The fourth law: The utility flow rate is used to control the stream equipped with utility.

Based on the disturbance propagation method, all disturbances must be transferred to the last utility of stream (The stream temperature must resemble to the target temperature). Hence, the stream equipped with utility is controlled by the utility flow rate. Moreover, in order to ensure that the temperature will reach the target temperature it should always equip bypass and control loop at the last stream.

3.3.2 Match Pattern Laws

The fifth law: Network consisted of class A and B for heat transfer can use only feed back control.

3.3.2.1 Disturbance Load Path

Calandranis and Stephanopolos (1988) contributed that the disturbance will be loaded to network via path. The disturbance load path starts at the point disturbance presented and end at the utility. There are two kinds of disturbance load path as follows:

- **Type 1** In the case of disturbance load path and stream flow direction is parallel, feed back control can be used only.

Example 3.1 From figure 3.3, when inlet temperature of stream H1 changes to 300^{o}C, it causes negative disturbance. So disturbance load path type 1 (P1) will transfer disturbances to the utility by adjusting bypass around E1 and E2 using feed back controller to maintain outlet temperature of hot stream E1 at 292.2^{o}C and E2 at 393.0^{o}C

- **Type 2** If the disturbance load path is transferred in countercurrent flow regard with stream flow direction. Both feed forward and feed back control must be used.

Example 3.2 As illustrated in figure 3.3, when inlet temperature of stream C1 changes to 220^{o}C, it causes negative disturbance and disturbance load path type 1 and 2 (P2) which used to transfer disturbances to the utility. The range of load path type 2 occurs between E2 and E3. Bypass around E3 must be adjusted by feed back controller to maintain outlet temperature of cold stream E3 at 327^{o}C. Moreover, it must use feed forward control to calculate the outlet temperature of hot stream E2 and adjust bypass around E2 with feed back controller to maintain target temperature.

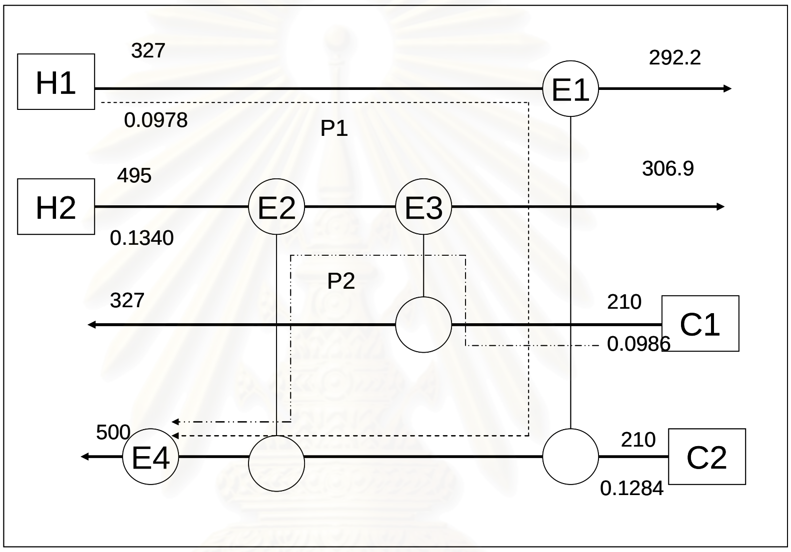


Figure 3.3 Disturbance load path type 1 and 2 (Calandranis and Stephanopoulos 1988).

3.3.2.2 Match Patterns

HEN synthesis is usually considered as a combinatorial matching problem. For a HEN in which a design property is regarded as a network property, or a structural property (e.g. resiliency), It is need to look beyond the match level to a higher level where such a property exists, e.g. to a match structure or match pattern. Match patterns are the descriptions of the match configuration of two, and possibly more, process streams and their properties that are thermally connected with heat exchangers. Not only the match description, e.g. heat duty of an exchanger and inlet and outlet temperatures is required but also the position of a match, e.g. upstream or downstream, the magnitude of the residual heat load and the heat capacity flow rates between a pair of matched streams. So, we regard the resilient HEN synthesis problem as a match pattern combinatorial problem where more high-level design qualities are required.

By using the ‘tick off rule’ there are four match patterns for a pair of hot and cold streams according to the match position and the length (heat load) of streams. The four patterns are considered to the basic match pattern classes. The members of these classes are the patterns where other configurations and properties are specified. The four match pattern classes are simply called A, B, C and D and are shown in Figure 3.4, 3.5, 3.6 and 3.7, respectively. 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 that 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. For a heating subproblem, a Class A match is favored because residual heat load is on the hot portion of the cold stream can be used to make heater. (Figure 3.4)
- **Class B Match Pattern**: The heat load of a hot stream is greater than that 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. For a cooling subproblem, a Class B match is favored because residual heat load is on the cold portion of the hot stream can be used to make cooler. (Figure 3.5)
- **Class C Match Pattern**: The heat load of a hot stream is greater than that 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 3.6)
- **Class D Match Pattern**: The heat load of a cold stream is greater than that 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 3.7)

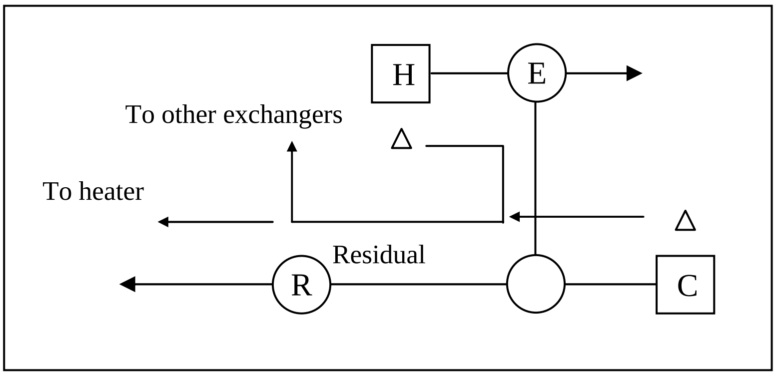


Figure 3.4 Class A Match Pattern.

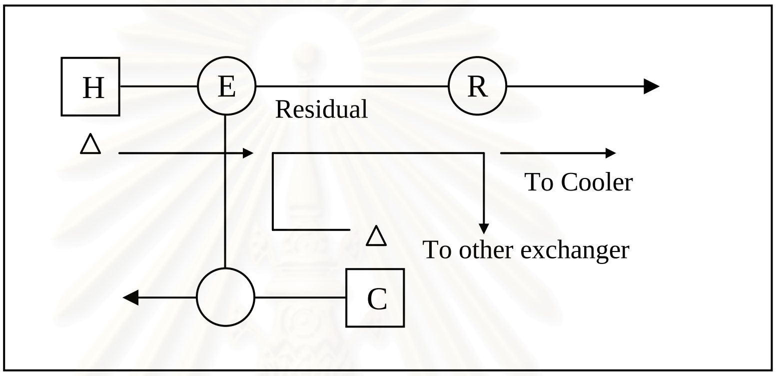


Figure 3.5 Class B Match Pattern.

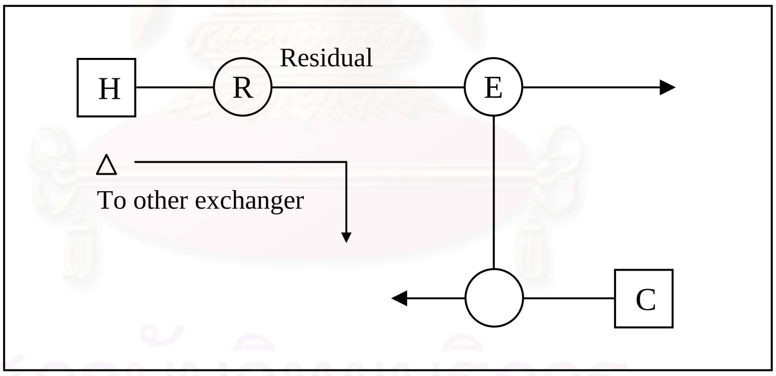


Figure 3.6 Class C Match Pattern.

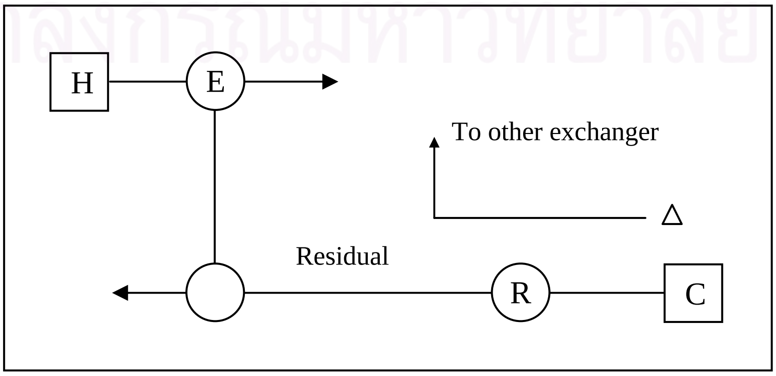


Figure 3.7 Class D Match Pattern.

Match Structure. The four basic match patterns are classified according to match positions and the ‘tick-off’ heuristics. Two of them namely, Class A and Class B, are the potential resilient match structures. For Class C and Class D match patterns where streams are matched at downstream positions can reject disturbance on one stream hence these are regarded as no resilience match. Class C and Class D match are less preferable than Class A Class B matches since they require by-pass lines and control equipment which may not be required with Class A or Class B patterns.

When consider the disturbance propagation, it is apparent that the disturbance which propagates from one stream to another depends on the class and load of process stream. Class A transfers disturbances to cold stream and class B transfers disturbances to hot stream. It is observed that disturbance propagation of both class A and B are type 1 load path which can be used only feed back control.

The sixth law: Network comprised of class C and D must use up stream unit for controlling purpose.

The seventh law: The up stream used must transfer the disturbance to the utility.

Class C and D is a class that outlet temperature is target temperature (it means that no heat for transferring as well). From the second law, the heat exchanger used to control stream temperature can not be used to control the exchanged stream. Consequently, for network comprised of class C and D must use up stream unit for controlling. However, the disturbance must be transferred to the utility and the up stream used must transfer the disturbance to the utility also.

The eighth law: Network comprised of class C and D containing type 1 and 2 must use both feed back control and feed forward control for controlling purpose.

In the presence of disturbance load path type 2, the network temperature changes in the following correlation.

$T_s = T_s^0 \pm \frac{D^+}{W_s}$ Positive when D^+ obtained at cold stream

Negative when D^+ obtained at hot stream

$T_s = T_s^0 \pm \frac{D^-}{W_s}$ Positive when D^- obtained at hot stream

Negative when D^- obtained at cold stream

3.3.3 Loop Control Selection Laws

The ninth law: In the case of overload disturbance, It must be transfer to another utility in network which further equipped with control loop and bypass stream for improving disturbance propagation.

The tenth law: The great heat transfer exchanger unit must be selected for settling bypass and control loop.

For example, when comparing two heat exchangers differing in heat load such as 30 kW of unit 1 and 600 kW of unit 2. In the presence of disturbance around 10 kW, load of unit 1 and 2 will be changed to 40 kW and 610 kW, respectively. It can be seen that the disturbance affects more significant to the outlet temperature of unit 1 than unit 2.

The eleventh law: 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.

3.3.4 Bypass Setting Laws

3.3.4.1 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)

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

3.3.4.2 The Number of Bypass Stream in Network

From the investment viewpoint, it is unnecessary to equip bypass for controlling utility load. For instance, in case of reducing heater and cooler load, bypass can cause the constant utility in contrast to the flow rate adjustment which can lower the number of utility.

Calandranis and Stephanopoulus (1988) said that in the case of network without pinch point (subnetwork at heat side or cold side), the least number of manipulated variable must be equal to the number of stream expected for temperature control target. For this reason, if the network considered is subnetwork including hot side and cold side and if all the utility flow rate in network can be adjusted for controlling purpose, the least number of bypass required must be $N_y - N_{UX}$ to control the target temperature. So, the number of bypass must be in this range.

$$N_y - N_{UX} \leq N_{byp} \leq N_{HX}$$

N_{UX} is the number of utilities

N_{byp} is the number of bypass stream

N_{HX} is the number of heat exchanger in network

Moreover they stated that in the presence of pinch point (subnetwork at heat side or cold side) the temperature different in network must be controlled to the lowest value (ΔT_{min}) for achieving the highest heat recovery. So it must have more manipulated variable than process without pinch point. The further addition variable must be equal to the number of stream crossed the pinch point and the number of bypass stream are shown as follows:

$$N_y - N_{UX} + N_p \leq N_{byp} \leq N_{HX}$$

N_p is the number of stream across pinch point

The twelfth law: Bypass stream should be settled in the lower flow rate side, Aruilera and Marchetti (1998)

The thirteenth law: If two streams are equal in flow rate, bypass stream should be settled on the temperature controlling side.

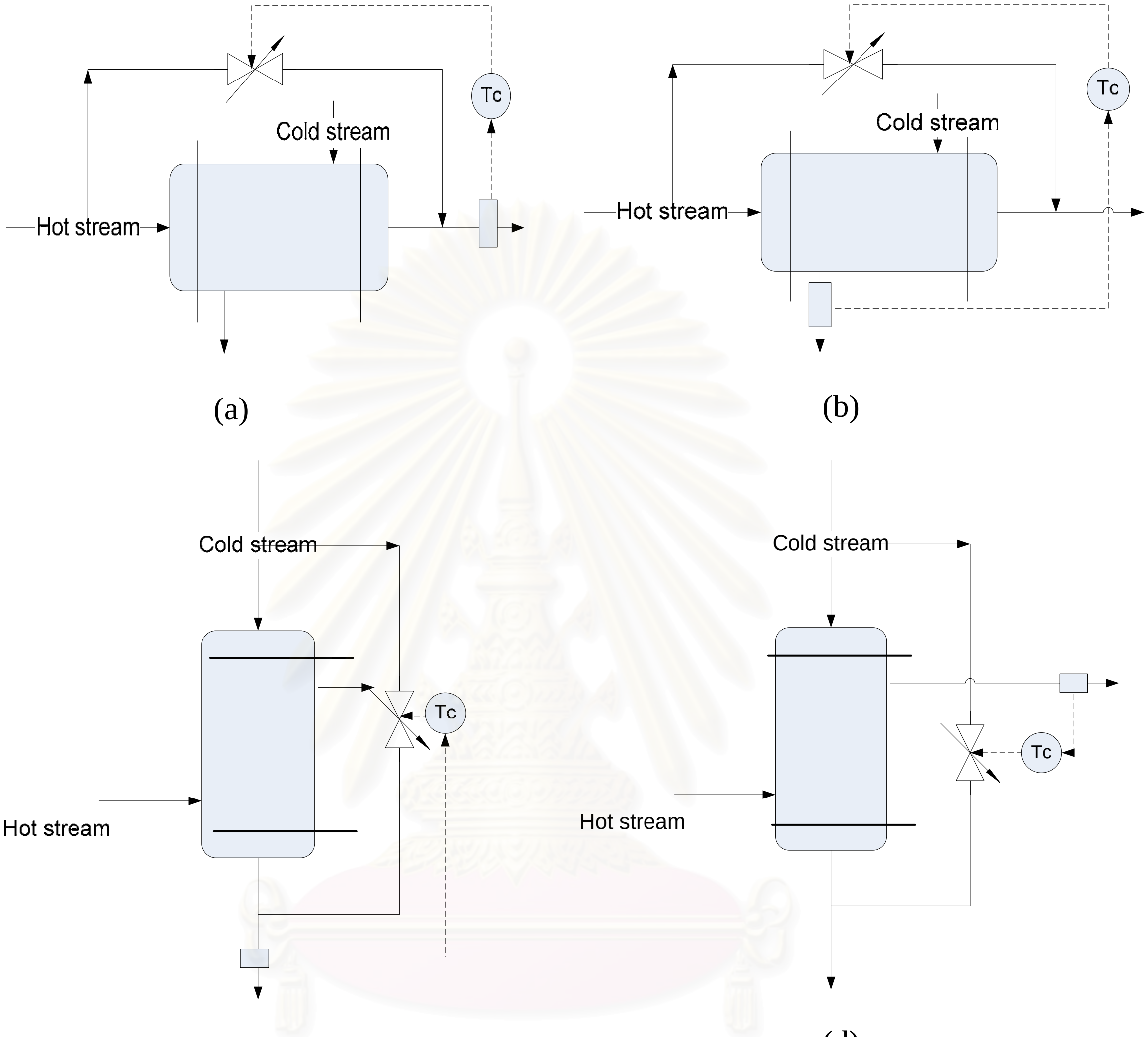
3.3.4.3 Setting of Bypass Stream for Controlling

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 3.8. 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 3.8a and 3.8c. 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. Actually, the flow rate plays an important role for considering the setting of bypass.Kulaniteewat (2001) demonstrated that the settle of by pass stream at the lower flow rate side have faster response than the higher flow rate side.

Figure 3.9 shows the controlling outlet temperature of hot stream when outlet temperature of cold stream increases 5°C and when that of hot stream decreases 5°C.

It is found that IAET of bypass settled on hot side = 53.187×10^4 and that on cold side = 4.6467×10^4. Hence bypass should be settled on cold side which is lower flow rate side. (Kulaniteewat, 2001)



(a) (b)

(c) (d)

Figure 3.8 The alternation of choosing bypass for controlling heat exchanger.

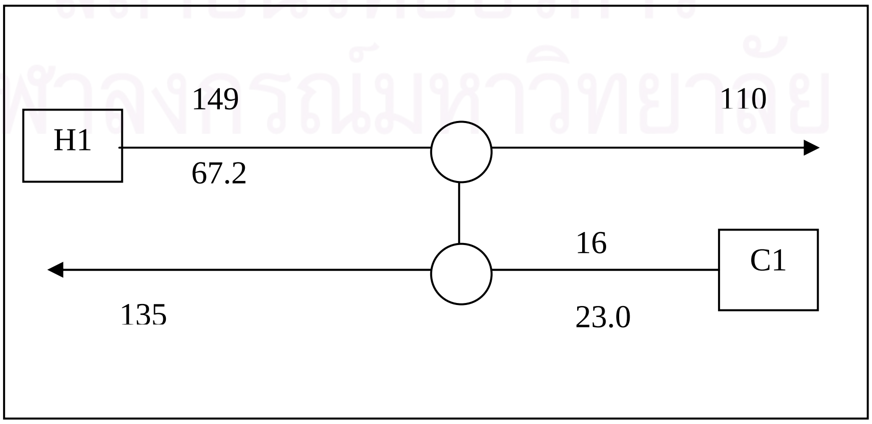


Figure 3.9 Heat exchanger network 1 (Kulaniteewat, 2001).

Figure 3.10 shows the controlling outlet temperature of cold stream when outlet temperature of cold stream increases 5°C and when that of hot stream decreases 5°C. It is found that IAET of bypass settled on hot side $=1.6878\times10^5$ and that on cold side $=10.6827\times10^5$. Hence it should set bypass on hot side which is lower flow rate side (Kulaniteewat, 2001).

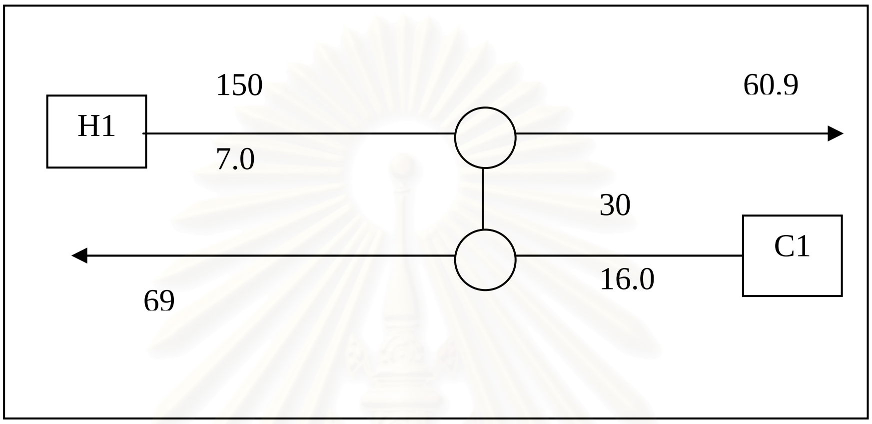


Figure 3.10 Heat exchanger network 2 (Kulaniteewat 2001).

Figure 3.11 shows the controlling outlet temperature of hot stream when outlet temperature of cold stream increases 5°C and when that of hot stream decreases 5°C. It is found that IAET of bypass settled on hot side $=9.9925\times10^3$ and that on cold side $=11.3338\times10^3$. Hence it should set bypass on hot side which is controlling side of outlet temperature (Kulaniteewat, 2001).

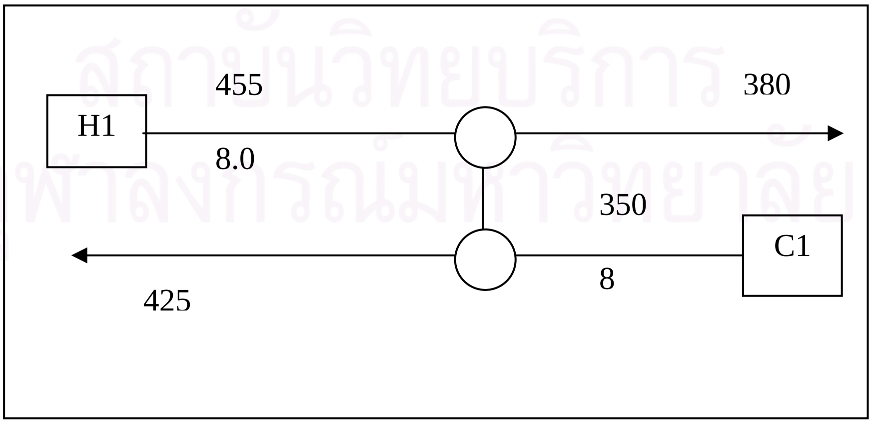


Figure 3.11 Heat exchanger network 3 (Kulaniteewat, 2001).

If two streams are equal, the principle mentioned above can be used for controlling purpose (Marselle et al., 1982; Calandranis and Stephanopoulos, 1988; Mathisen et al., 1992; Aguiler and Marchetti, 1998). That is to say it should settle the bypass stream on the controlling side in order to directly affect on the controlling factor.

3.3.5 Split Ratio Laws

The fourteenth laws: 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.

The fifteenth law: If the controlling temperature is the temperature of aggregated stream, bypass should be settled on heat exchanger at split stream to control that temperature.

3.3.5.1 Network Comprises of Split Stream

From figure 3.12, 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 from figure 3.12. The temperature control of C2 can be performed in 3 ways: 1. bypass on E1, 2. bypass on E2 and E3 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.

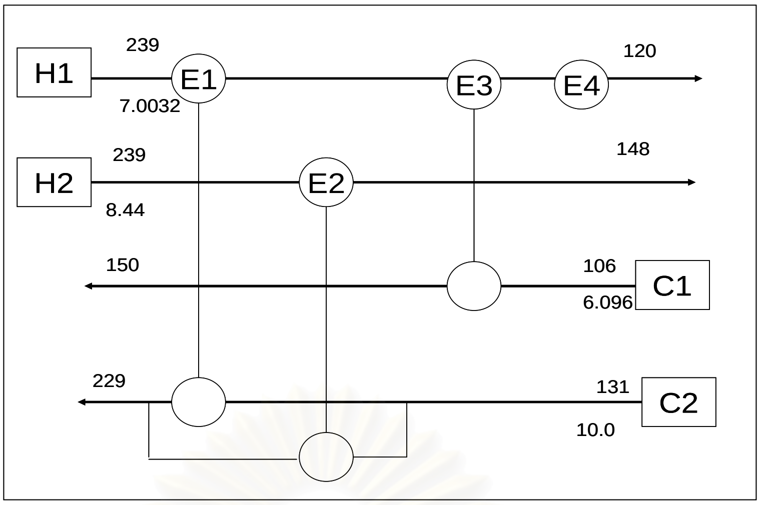


Figure 3.12 Heat exchanger network consist spilt stream.

3.3.6 Selector Switch Setting Laws

The sixteenth laws: Set up low selector switch in network in order to support the operation of heat pathway management to achieve the requirement of dynamic maximum energy recovery.

3.3.6.1 Heat Pathways Management

In this work, the heuristics of selection and manipulation of heat pathways for heat exchanger networks control are proposed. It is expected that the disturbance load through the network vary significantly, so does the dynamic maximum energy recovery (DMER). Therefore, the control strategies are necessary to direct the disturbance loads where should they go, i.e. go to the hot stream linked with cooler utility or to the cold stream linked with heater utility. As a first step, kinds of the disturbance loads and heat pathways through the network are identified, then strategy for HEN control to achieve MER are considered.

3.3.6.1.1 Influence of Disturbance Loads on the Utility Requirements

In process heat integration, there are two kinds of disturbance loads (Wongsri, 1990). The first disturbance load is *Positive disturbance load* D^+ i.e. a disturbance that will increase the heat load of stream. For example, when the inlet temperature of a disturbed hot stream increases or when the inlet temperature of a disturbed cold stream decreases. The disturbance heat load must be dissipated as much as possible by transferring or shifting it to the streams that are serviced by utility exchangers. The positive disturbance load of a hot stream will increase heat duties of coolers and decrease heat duties of heaters and vice versa for the cold stream.

The second disturbance load is *Negative disturbance load* D^- i.e. a disturbance that will decrease the heat load of stream. For example, when the inlet temperature of a disturbed hot stream decreases or when the inlet temperature of a disturbed cold stream increases. The negative disturbance load of a hot stream will increase heat duties of heaters and decrease heat duties of coolers and vice versa for the cold stream.

Table 3.3 Influence of disturbance loads on the utility requirements

disturbance load	source	effects on the utility requirements
positive disturbance load *(D+)* of cold *stream*	the inlet temperature of cold *stream decreases*	decreases heat duty of cooler or *increases heat duty of heater*
positive disturbance load *(D+)* of hot stream	the inlet temperature of hot stream increases	decreases heat duty of heater or increases heat duty of cooler
negative disturbance load (D-) of cold stream	the inlet temperature of cold stream increases	decreases heat duty of heater or increases heat duty of cooler
negative disturbance load (D-) of hot stream	the inlet temperature of hot stream decreases	decreases heat duty of cooler or increases heat duty of heater

3.3.6.2 Design of Heat Pathways for Dynamic MER

As we mentioned that actually MER is not constant, its value varies according to the operating conditions, e.g. the input heat load disturbances. Furthermore, 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.

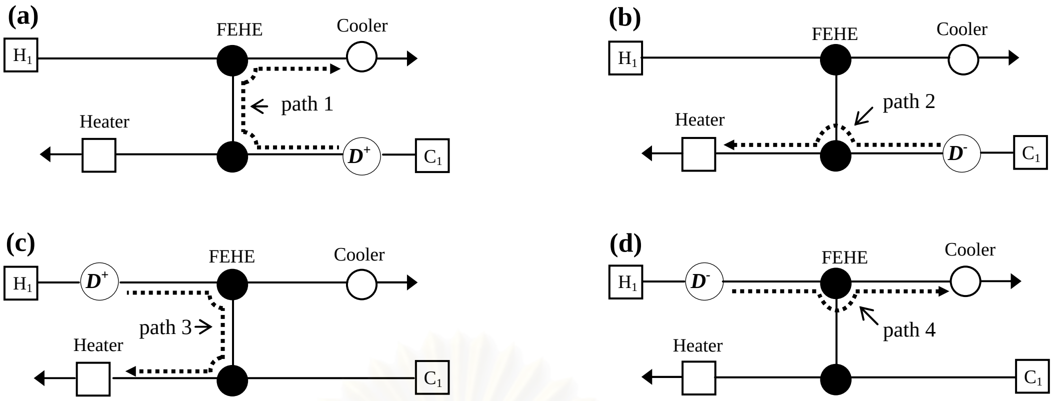


Figure 3.13 Heat pathways in the simplified HEN to achieve the highest possible dynamic MER, where: (a) path 1 is used to shift the positive disturbance load of the cold stream C_1 to the cooler, (b) path 2 is used to shift the negative disturbance load of the cold stream C_1 to the heater, (c) path 3 is used to shift the positive disturbance load of the hot stream H_1 to the heater, and (d) path 4 is used to shift the negative disturbance load of the hot stream H_1 to the cooler.

3.3.6.3 Design of the Heat Pathways in the Simplified HEN

A simplified HEN as shown in Figure 3.13 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 3.13a) 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. Consider the case when the inlet temperature of a disturbed cold stream increases, path 2 (Figure 3.13b) 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 3.13c) 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 3.13d) 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.

3.3.6.4 Control Strategy for Dynamic MER

In this work, to obtain the dynamic MER, the disturbance loads are eventually shifted to either cooler or furnace utility according to the heat pathway heuristics (HPH), so its utilities duties will be decreased based upon the input heat load disturbance. A control strategy for the heat exchanger is needed such as an appropriate designed pathway will be selected at any given time so that the dynamic MER will be obtained.

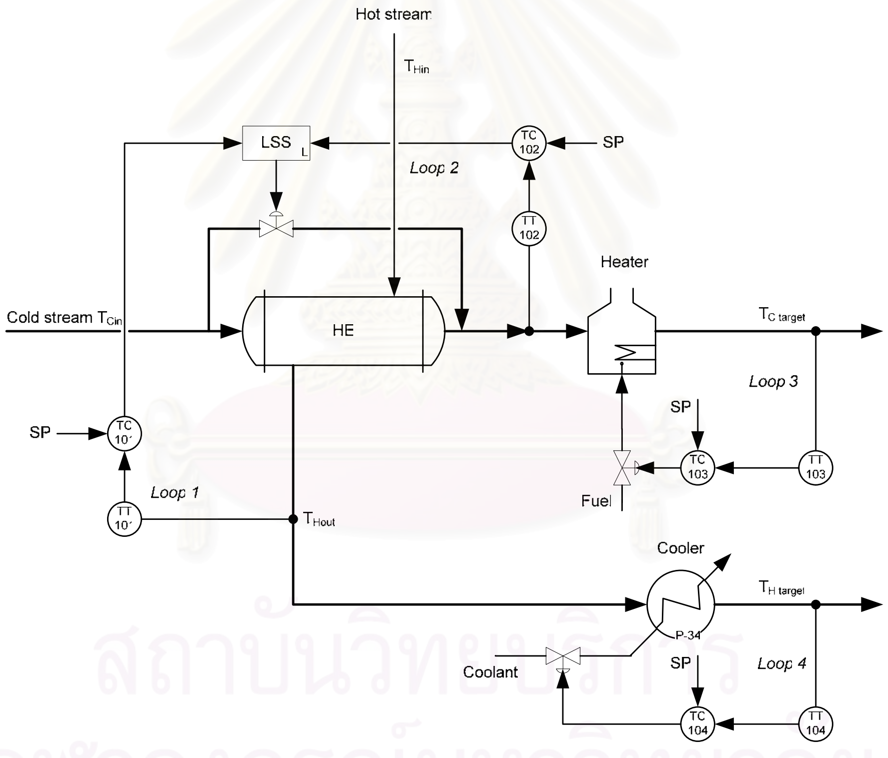


Figure 3.14 A selective controller for HEN to achieve DMER.

Figure 3.14 shows the control strategy for HEN to obtain the dynamic MER. During the normal operation of the heat exchanger (HE) unit in a plant, it is possible that unwanted-conditions may arise which may lead to move the heat load to other utility units. For examples, when the cold outlet temperature (T_{Cout}) of HE decreases to values smaller than its nominal temperature the heater utility duty will increase. Alternatively, when the hot outlet temperature (T_{Hout}) of HE increases to values larger than its nominal temperature the cooler duty will consequently increase. In such cases it is necessary to switch from the normal control strategy and attempt to prevent a process variable from exceeding an allowable upper or lower limit. This can be achieved through the use of special types of switches. The high switch (HS) is used whenever a variable should not exceed an upper limit and the low switch (LS) is employed to prevent a process variable from exceeding a lower limit. This is known as an override control.

Thus, a selective controller i.e. a low selector switches (LSS) for HE is employed as shown in Figure 3.14. This is a control system that involves one manipulated variable and two controlled variables. This control system works as follows: The hot outlet temperature (T_{Hout}) of HE is controlled at its normal set point by manipulating the valve on the bypass line i.e. loop 1 in Figure 3.14. At the same time, the cold outlet temperature (T_{Cout}) of HE should not be allowed to drop below a lower limit value, which is necessary to keep the heater utility duty at a good level. Whenever the temperature T_{Cout} drops below the allowable limit due to, for example, a disturbance load entering the process, the LSS switches the control action from the hot temperature control (TC101) to the cold temperature control (TC102), i.e. switches the control action from loop 1 to loop 2, and closes the valve on the bypass line. As a result, $\mathrm{TC}_{\mathrm{O}}\mathrm{M}$ will rise to its normal temperature and T_{Cout} will be further decreased, so the cooler duty will also be decreased.

Whenever the temperature T_{Cout} increases above a lower limit, a desired-condition during operation, due to the disturbance load entering the process, the LSS switches the control action from loop 2 to loop 1, and closes the valve on the bypass line. Consequently, THOUI will drop to its normal temperature and T_{Cou}t will be further increased, so the furnace duty will also be decreased. The use of heat pathway manipulator (i.e. LSS) to achieve dynamic MER has been presented in Chapter 4 for HEN based on rigorous dynamic simulation using the commercial software HYSYS.

3.3.6.5 Design and Control of Heat Pathways for Heat Exchanger Networks

A selective controller, i.e. a low selector switch (LSS) can be used to select an appropriate heat pathway to carry associated load to a utility unit. In this chapter, we figure out the heuristics of selection and manipulation of heat pathways for some typical HEN examples that widely used in the petroleum and chemical industries (e.g. HEN alternatives of HDA plant given by Terril and Douglas, 1987). We also show where the LSS should be placed on a heat exchanger unit so that it can be used to direct the disturbance load to a specified utility unit.

For all of the examples of HENs, we assume that:

- The utility exchangers can handle all variations of heat load.
- The target temperatures are not subject to changes. Only the variation in input
- Any heat exchanger will have enough heat transfer area to accommodate increases in heat loads of disturbed process stream.
- Bypass lines are provided to all heat exchangers as a standard feature to adjust heat load.

3.3.6.6 Implementation of Heat Pathway Manipulator

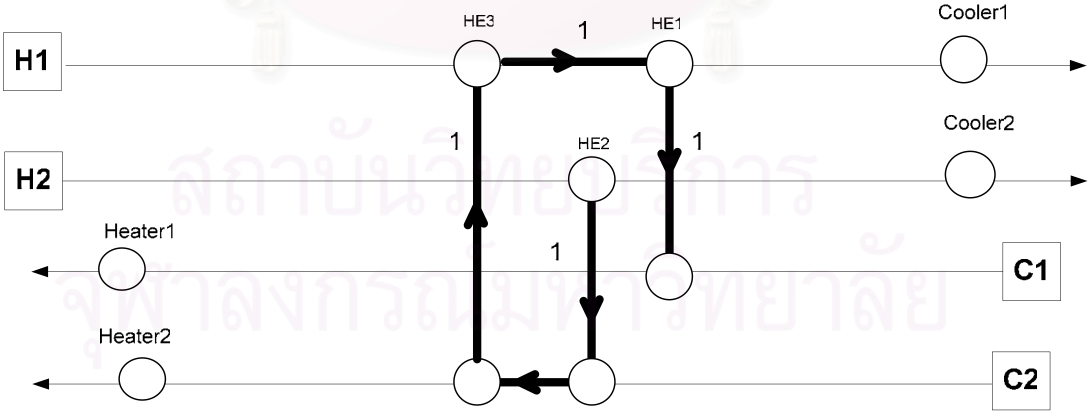
For a complex HEN, which contains more than one heat exchanger, some questions may arise such as, where the LSS should be placed and how many LSS are needed to direct the disturbance load to a utility unit. This section discusses the implementation of heat pathway manipulator for some typical HEN examples.
In order to know how many LSS should be employed and where they should be placed, first we must identify the heat link in HEN, since it can be used for the propagation of the disturbance load. Then, we must find the last heat exchanger of the identified heat link. The LSS should be placed on the last heat exchanger. In the case that the end of heat link is not supported by utility and that temperature is a target temperature, it should consider to set up with the former unit. The solid lines in Figure 3.15 show the heat link for the propagation of the disturbance load in some typical HENs. Note that the propagation of the disturbance load is co-current with all of the process streams. The implementation of heat pathway manipulator for several typical HEN examples is as follows:

- HEN Model 1

HEN Model 1 is defined as the HEN contains two cold streams and two hot streams, three HE units, as shown in Figure 3.15.a. As can be seen that, this HEN has only one heat link, started from HE2, continued to HE3, and finally to the last exchanger HEl (see solid line in Figure 3.15.a). Since HEN Model 1 has only one heat link that ends up at the last exchanger HEl, only one LSS is employed and placed on HEl.The cold outlet temperature of HE3 is controlled by manipulating the valve on the cold bypass line, whereas the hot outlet temperature of HE2 is controlled by manipulating the valve on the hot bypass line. The Cooler 1 and Heater 1 utilities are used as heat load absorbers. The control system of HEN Model 1 to achieve DMER is given in Figure 3.16.a.

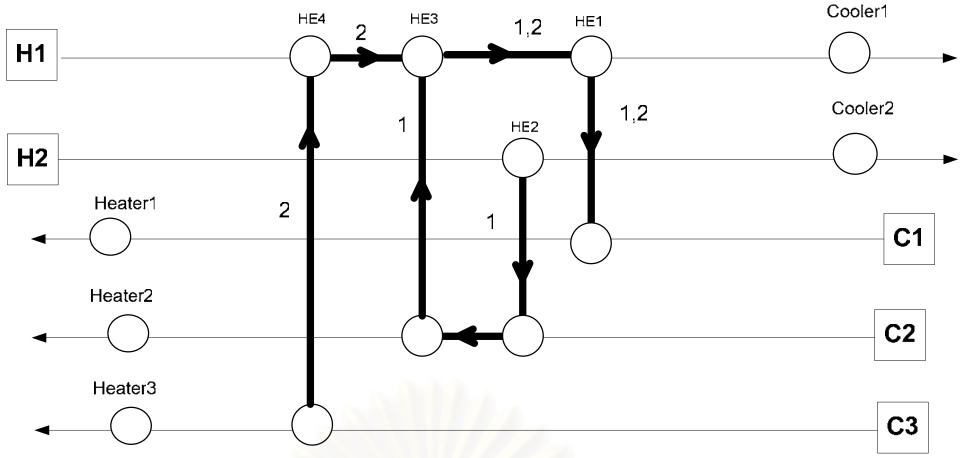
- HEN Model 2

As can be seen that, there are two heat links in this HEN. In this particular case, i.e. HEN contains more than one heat link, in order to reduce the number of LOS, design all heat links so that they will end up at the same heat exchanger. In HEN model 2, it is possible to design the third heat link so that it will end up at exchanger HE1 (see Figure 3.15.b). Consequently, we need only one LSS for both heat link 1 and 2. It employed and placed on HE1. The other control loops in HEN Model 2 are the same as those in HEN Model 1, except the cold outlet temperature of HE4 is controlled by manipulating the valve on the cold bypass line, as shown in Figure 3.16.b.



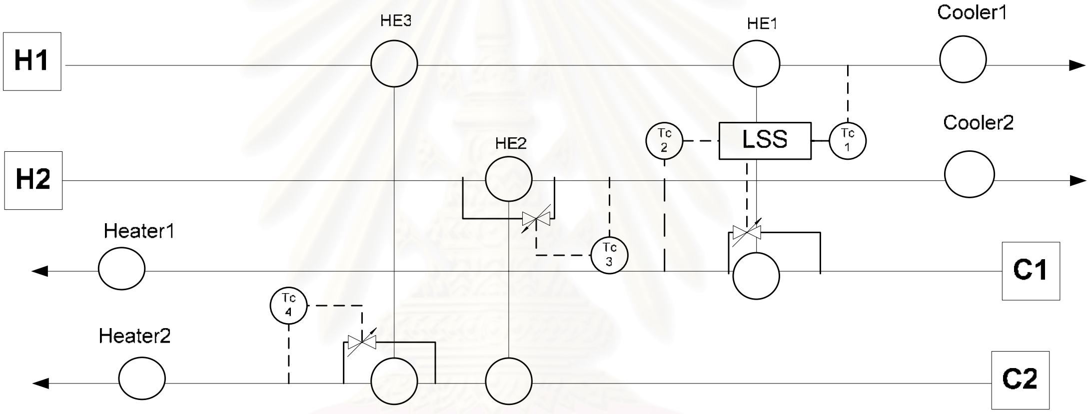
(a) Model 1

Figure 3.15 Several typical HEN examples with its specified heat links

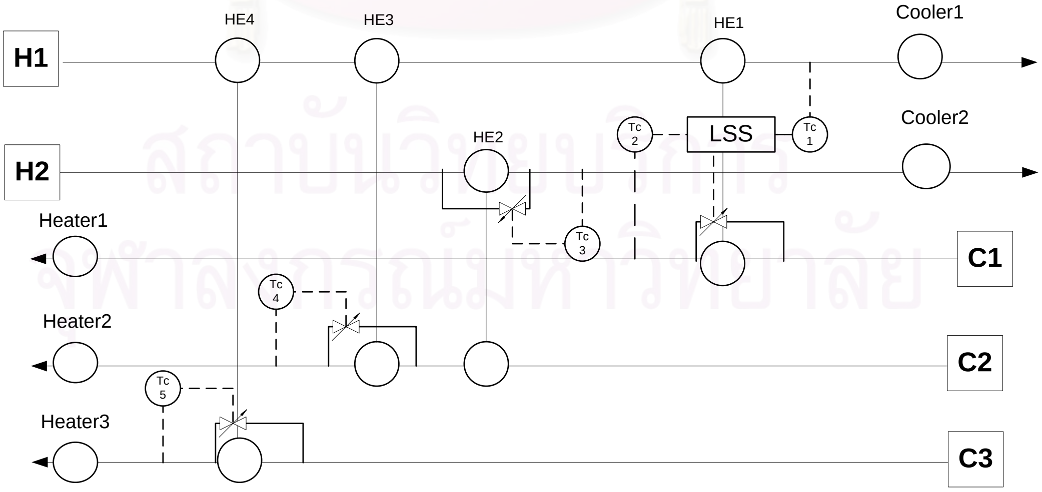


(b) Model 2

Figure 3.15 Several typical HEN examples with its specified heat links (continue)



(a) Model 1



(b) Model 2

Figure 3.16 Control configurations for the typical HEN examples to achieve DMER

3.4 The number of LSS to be used in particular case can be determined as follows:

3.4.1 Identify the heat like in HEN that can be used for the propagation of disturbance load, note that the propagation is co-curerent with the process stream

3.4.2 If there is only one heat link the only one LSS is employed and placed on the last heat exchanger unit used in the heat link.

3.4.3 If there are more than one heat link

3.4.3.1 Design the heat links so that all of them will end up at same heat exchanger unit in order to reduce the number of LSS.

3.4.3.2 If all heat links end up at the different heat exchanger units, so the number of LSS is equal to the number of heat link.

3.4.3.3 If there are some heat links, which end up at the same heat exchanger unit , the number of LSS can be determined following the equation below:

$$N_{LSS} = \text{Number of LSS} = N_H - N_s + 1$$

where N_H is defined as the total number of heat links and N_S is defined as the number of heat links, which end up at the same heat exchanger unit.

3.4.4 In the case that the end of heat link is not supported by utility and that temperature is a target temperature, it should consider to set up with the former unit.

By following these steps, a workable HEN control configuration for dynamic maximum energy recovery (DMER) can be obtained.

3.5 Heuristic Approach for Control Structure Design

In the present Chapter, the resulting data was able to summarize into laws of control structure design, consisting of 16 laws. It was developed from the characteristic of network structure together with disturbance propagation technique. Moreover, it covered all critical parameters including the selection of bypass stream, the use of splitting ratio and upstream for the controlling purpose and the important factor, which help the network use less energy from outside network that is to say the network can reach the dynamic maximum energy recovery, is heat pathway management.

Law of control structure design is respectively listed as follows:

The first law: The stream which comprises of only one heat exchanger is the first priority to consider in process design.

The second law: The heat exchanger used for controlling stream temperature can not be used to control another exchanged stream.

The third law: It should always set bypass and control loop at the last unit to maintain target temperature.

The fourth law: The utility flow rate is used to control the stream equipped with utility.

The fifth law: Network consisted of class A and B for heat transfer can use only feed back control.

The sixth law: Network comprised of class C and D must use up stream unit for controlling purpose.

The seventh law: The up stream used must transfer the disturbance to the utility.

The eighth law: Network comprised of class C and D containing type I and II must use both feed back control and feed forward control for controlling purpose.

The ninth law: In the case of overload disturbance, It must be transfer to another utility in network which further equipped with control loop and bypass stream for improving disturbance propagation.

The tenth law: The great heat transfer exchanger unit must be selected for settling bypass and control loop.

The eleventh law: Control loop must be settled for reducing the disturbance load path.

The twelfth law: Bypass stream should be settled in the lower flow rate side

The thirteenth law: If two streams are equal in flow rate, bypass stream should be settled on the temperature controlling side.

The fourteenth laws: 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.

The fifteenth law: If the controlling temperature is the temperature of aggregated stream, bypass should be settled on heat exchanger at split stream to control that temperature.

The sixteenth laws: Set up selector switch in network in order to support the operation of heat pathway management to achieve the requirement of dynamic maximum energy recovery.

CHAPTER IV

CONTROL STRUCTURE DESIGN

The suitable control structure has pronounced effects on the control efficiency. This chapter is being aimed at considering the design of control structure of heat exchanger network covering the objective of control and also the selection of manipulate variables and control variables. In addition to configure the control structure, it was determined with rules of control design as described previously in chapter 4. These rules have already summarized to the sequent step for designing control structure in which the design procedure can be applied with the usual heat exchanger network in the presence of energy disturbance and Class I problem (Saboo and Morari, 1984). It can, moreover, operate with maintaining the objective required, i.e., target temperature and maximum heat recovery with lowest utilities.

4.1 Introduction

It is now widely recognized that the plantwide control structure was started and developed since 1980 by many researchers (Morari et al., 1980; Govind et al., 1982; Luyben et al., 1998). However, up to now less attention has been paid to the control structure design using that principle used in plantwide. The process for energy recovery in heat exchanger network is crucial and indispensable for the process in chemical industries due to their large amount of energy consumption and production. The suitable control structure of heat exchanger network can keep the process more safety and bring about lowering in energy consumption and setting cost.

Marselle et al. (1982), Calandranis and Stephanopoulus (1988), Aguiler and Marchetti (1998) proposed the control structure design of heat exchanger network in which all heat exchanger equipped with bypass stream and control that stream with the last heat exchanger settled in that stream. From this aspect, it may be useful to look more closely at 1) selection of bypass placement, 2) split fraction choose, 3) in the case of the outlet temperature of heat exchanger is both control variable and (Match pattern Class C and D as described in Chapter IV), 4) the control of upstream heat exchanger instead of controlling downstream heat exchanger.

This chapter is focused on the consideration of control structure design of heat exchanger network including the selection of control objective, manipulated variable, control variable and control structure design by using rules of control design as described previously in chapter III and finally summarized in procedure for determining design and selection of control structure containing all topic previously ascribed. For testing the design control, heat exchanger network was modeled in computer using HYSYS program and the model selected was lump model as proposed in chapter III.

4.2 Problem in Control Structure Design

The procedure for control structure design comprises of consideration steps as follows (Marselle et al., 1982):

4.2.1 Selection of control objectives
4.2.2 Selection of controlled outputs
4.2.3 Selection of measurements
4.2.4 Selection of manipulated variables
4.2.5 Selection of control structure

4.2.1 Selection of Control Objectives

The objectives in heat exchanger network control perspective are divided into 2 groups.

- Main objective: control outlet temperature of network to keep target objective.
- Secondary objective: highest heat recovery with least utility.

From the industrial viewpoint safety, environmental effect and most of the operating cost depend on reactor section and separating system. These units will be safely and efficiently operated, if the feed temperature is maintained at target. Feed stream has been widely employed passing through heat exchanger for the heat remove or heat introduction purpose. Therefore, it is important to control outlet temperature of network to attain the target temperature and in order to safe the energy consumption, the (secondary objective) should be considered to reach the highest heat recovery purpose.

4.2.2 Selection of Control Variable

Most of the control variable in heat exchanger network is the outlet temperature of network stream. Nevertheless, in order to transfer disturbance to the utilities (heater or cooler) it is necessary to control temperature at some point inside network. Furthermore, in the case of network which comprises of sub-network both hot side and cold side it is important to control temperature inside network to reach the minimum temperature different (ΔT_{min}). The target of control variable is as follows:

- Keep constant at one value
- Keep in the desired range
- Keep not lower or over the setting value

4.2.3 Selection of Measure Variable

Temperature is generally used as measure variable in heat exchanger network because of it is more convenient and simply to measure.

4.2.4 Manipulated Variable

Manipulated variable used in heat exchanger network is in the following lists:

- Utility flow rate
- Bypass fraction
- Split fraction
- Process stream flow
- Exchanger area

The current study is focused on the effect of 1, 2 and 3. It is difficult and dangerous to adjust stream flow as a consequence of the variation in exchange stream flows have a significant influence on upstream unit.

4.2.5 Control Structure Design

The problem of design the control structure is where the control loop should be settled. Aguilera and Marchitti (1998) considered the control structure design using mathematic tools (linear equation and non-linear equation) to select the position for settled control loop but this method is quite difficult and complex to find the value and result. Calandranis and Stephanopoulos (1988) purposed the guidance for considering the control structure design from network structure existed. This way is a useful and simply tool which is giving the good control result.

This research work used the consideration of network structure existed in combination with disturbance transfer technique of Wongsri (1990). The preceding consideration can bring about rules of control as described in chapter 3 according to this rule it can be used to propose the procedure to design the suitable control structure as described in 3.3.

4.3 Control Structure Design

This topic purposes the procedure of control structure design using rules of control as described in chapter 3 on the assumption that.

- Take variation in an inlet condition of network into account without considering the change in target value.
- Give enough utility for disturbance remained.
- Control any stream temperature in network to attain the target value.

4.4 Control Structure Design for Pinch Jump Case

Pinch relocation is an attempt by the network to reestablish a balance between heat surplus and deficiency of the new process conditions to achieve a new MER. It is caused by the changes of one or a combination of inlet temperatures, heat capacity flow rates. 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. Such structure changes arise from the fact that the change in direction of a part of net energy transfer from heaters to coolers or vice versa. In fact, the researches about design control structure for HEN in Class II problem are very few. Therefore, this research develops strategic for design control structure for this case.

The design of HEN control start with find the least number of bypass stream required. And then divided partitioned into three subnetworks namely, strictly heating subnetwork, middle subnetwork and strictly cooling subnetwork. The middle subnetwork has two representations: as a heating and as a cooling problem. There are four subnetworks to be designed and designed them with heuristic approach which review in this chapter and used this approach to another path. After that, combine them together. Then apply LSS into problem for Maximum Energy Recovery (MER)

4.5 Control Structure Design Procedure

Step 1. Identify heat link in order to find the minimum number of LSS.

Step 2. Set up LSS in the network based on the sixteenth law in order to maintain DMER.

Step 3. Design control structure with regard to the law of control structure design no. 1-15 as aforementioned in Chapter III. It is not necessary to consider the factor in consequence so the order can be changed to the appropriate condition.

This research will address the resilient HEN design problem where the input temperatures and flow rates of process streams are fluctuating. Two types of HEN problems (Saboo and Morari, 1984) are considered:

(a) Class I problem. The problem comprises small temperature and flow rate variation. There is only a continuous pinch change.

(b) Class II problem. The problem comprises large temperature variations or flow rate variations. The pinch relocation includes discrete changes or ‘pinch jump’.

This research is being aimed at proposing a new systematic design method wherein the HEN control structure can be directly incorporated at the HEN structure generation level. The network will provide maximum energy recovery together with achieving target temperature

4.6 Example 4.1: Class I problem

With considering the problem from Table 4.1, it could generate problem table as shown in Table 4.2.

Table 4.1 Inlet and outlet condition of network in Example 4.1.

Stream No.	Stream type	Start Temperature (Ts), ^{o}C	Target Temperature (Tt), ^{o}C	Heat capacity flow rate (CP), kW/^{o}C
1	Hot	140	110	1.4
2	Hot	160	20	4.5
3	Cold	90	125	8.7
4	Cold	20	150	3.5

Table 4.2 Problem table for Example 4.1.

W				T hot	T cold	ΣW	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	(°C)	(°C)	(kW/ °C)	(°C)	(kW)	(kW)	(kW)
0	4.5	0	-3.5	160	150					202.5
1.4	4.5	0	-3.5	140	130	1	20	20	20	222.5
1.4	4.5	-8.7	-3.5	135	125	2.4	5	12	32	234.5
1.4	4.5	-8.7	-3.5	130	120	-6.3	5	-31.5	0.5	203
0	4.5	-8.7	-3.5	110	100	-6.3	20	-126	-125.5	77
0	4.5	0	-3.5	100	90	-7.7	10	-77	-202.5	0
0	4.5	0	-3.5	90	80	1	10	10	-192.5	10
0	4.5	0	-3.5	70	60	1	20	20	-172.5	30
0	4.5	0	0	30	20	1	40	40	-132.5	70
0	0	0	0	20	10	4.5	10	45	-87.5	115

From the resulting data, it can drawn the heat exchanger network as illustrated in Figure 4.1

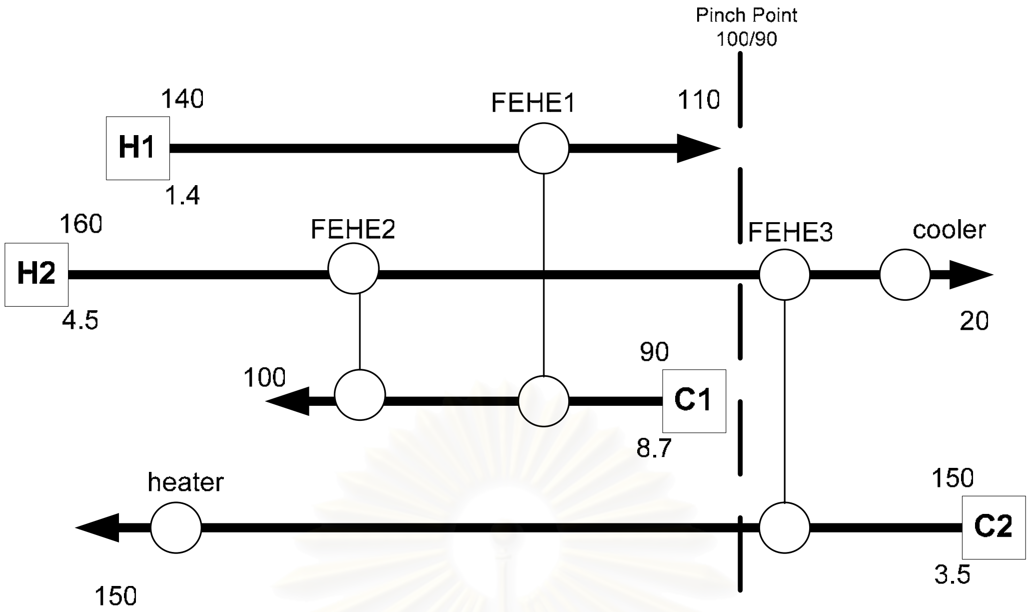


Figure 4.1 Heat exchanger network of Example 4.1.

From the procedure in 4.5, it can be used to design control structure as follows:

Step 1. Identify heat link to find the minimum number of LSS

Heat link in this example are given in Figure 4.2. It is obvious that the network comprises 1 heat link and FEHE3, which is the last heat exchanger of heat link, It is able to transfer heat through the utility therefore setting one LSS is adequate in this case.

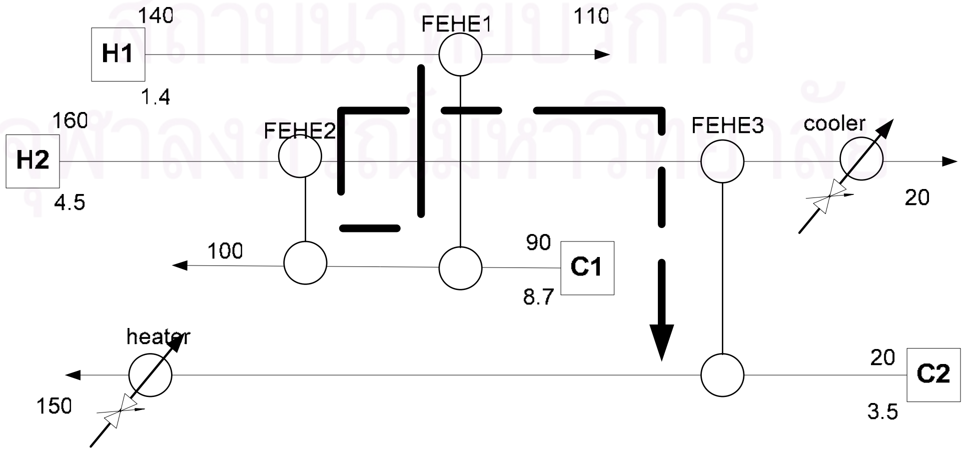


Figure 4.2 heat link of example 4.1

Step 2. Set up LSS in the network based on the heat path way heuristic approach. The setting is upon to fifteen laws as previously mentioned. In typical, considering to the twelfth law bypass should be settled at C2 stream due to its less FCP and LSS should be settled at the same position to control outlet temperature of both hot and cold stream as displayed in Figure 4.3

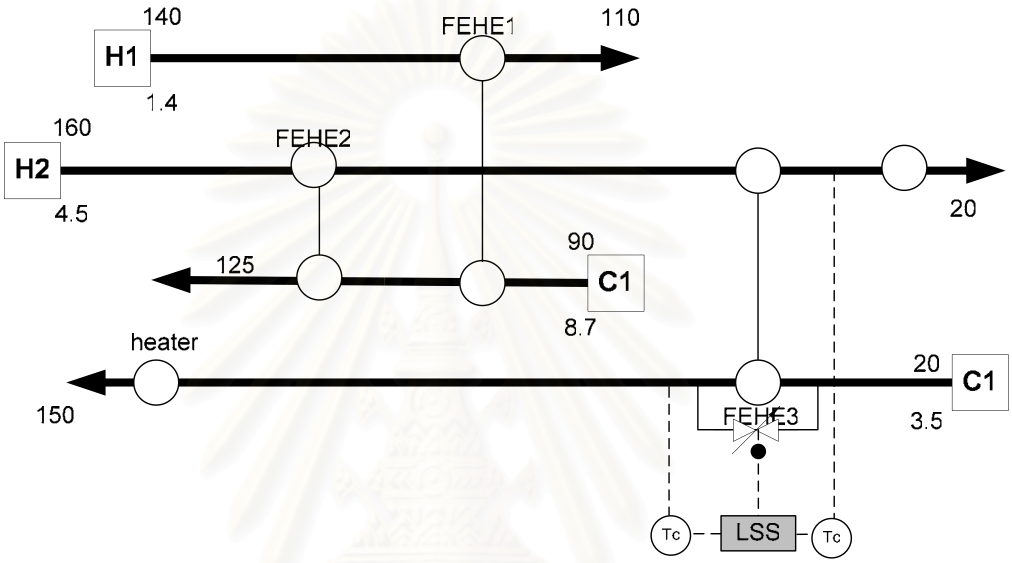


Figure 4.3 Set up LSS for Example 4.1

Step 3. Design control structure with regard to the law of control structure design no. 1-15 as aforementioned in Chapter III. It is not necessary to consider the factor in consequence so the order can be changed to the appropriate condition.

To begin 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 FEHE 1 to control H1 outlet temperature. In the case of FEHE 2 it is class C problem (Wongsri, 1990), as aforementioned it should use heat exchanger at upstream unit to control and transfer disturbance to the utility via heat link. Control structure and heat path way of Example 4.1 are given in Figure 4.4 and Figure 4.6, respectively.

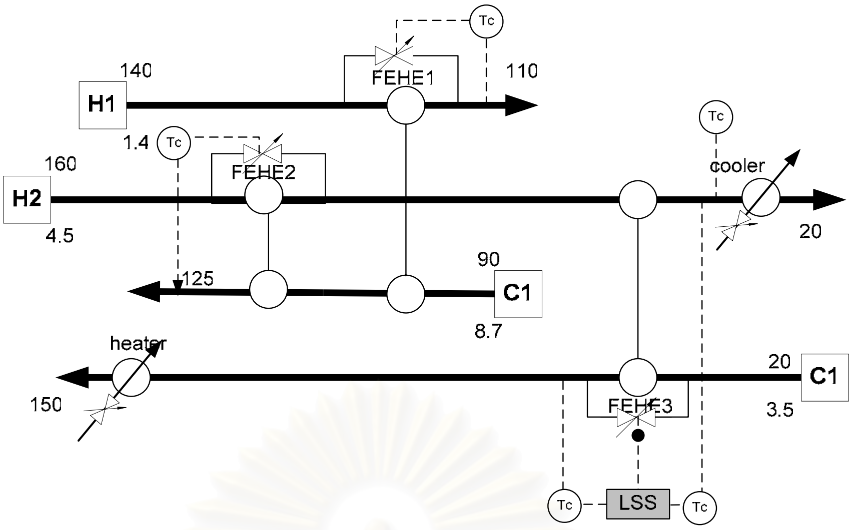


Figure 4.4 Control structure of network equipped with LSS of example 4.1

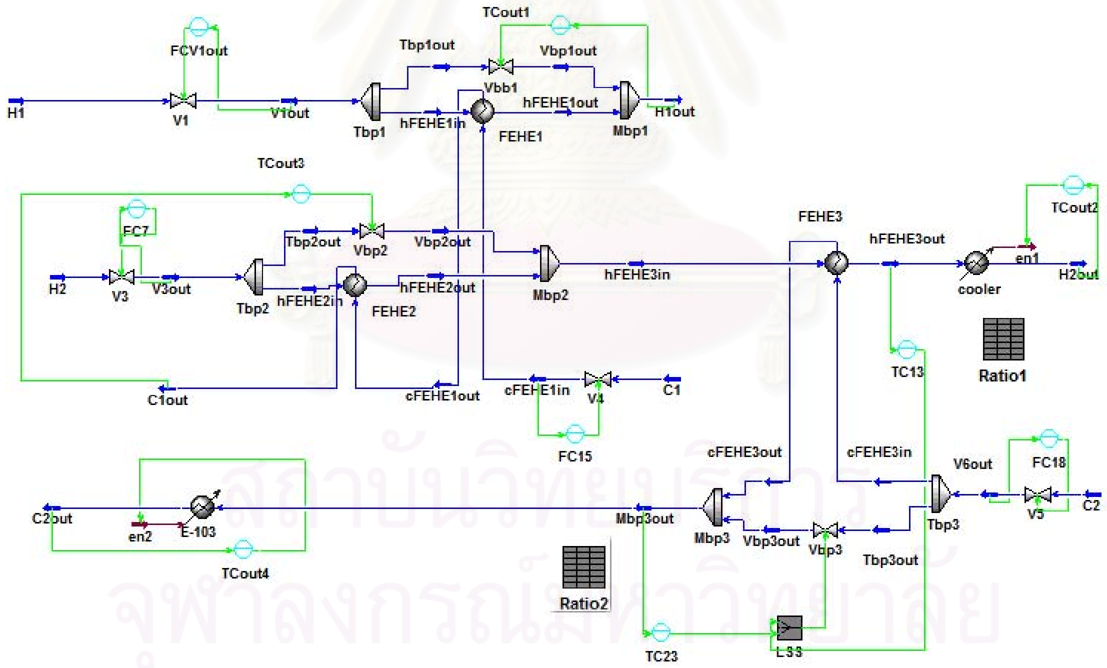


Figure 4.5 HEN from HYSYS flow sheet of example 4.1 HEN from HYSYS

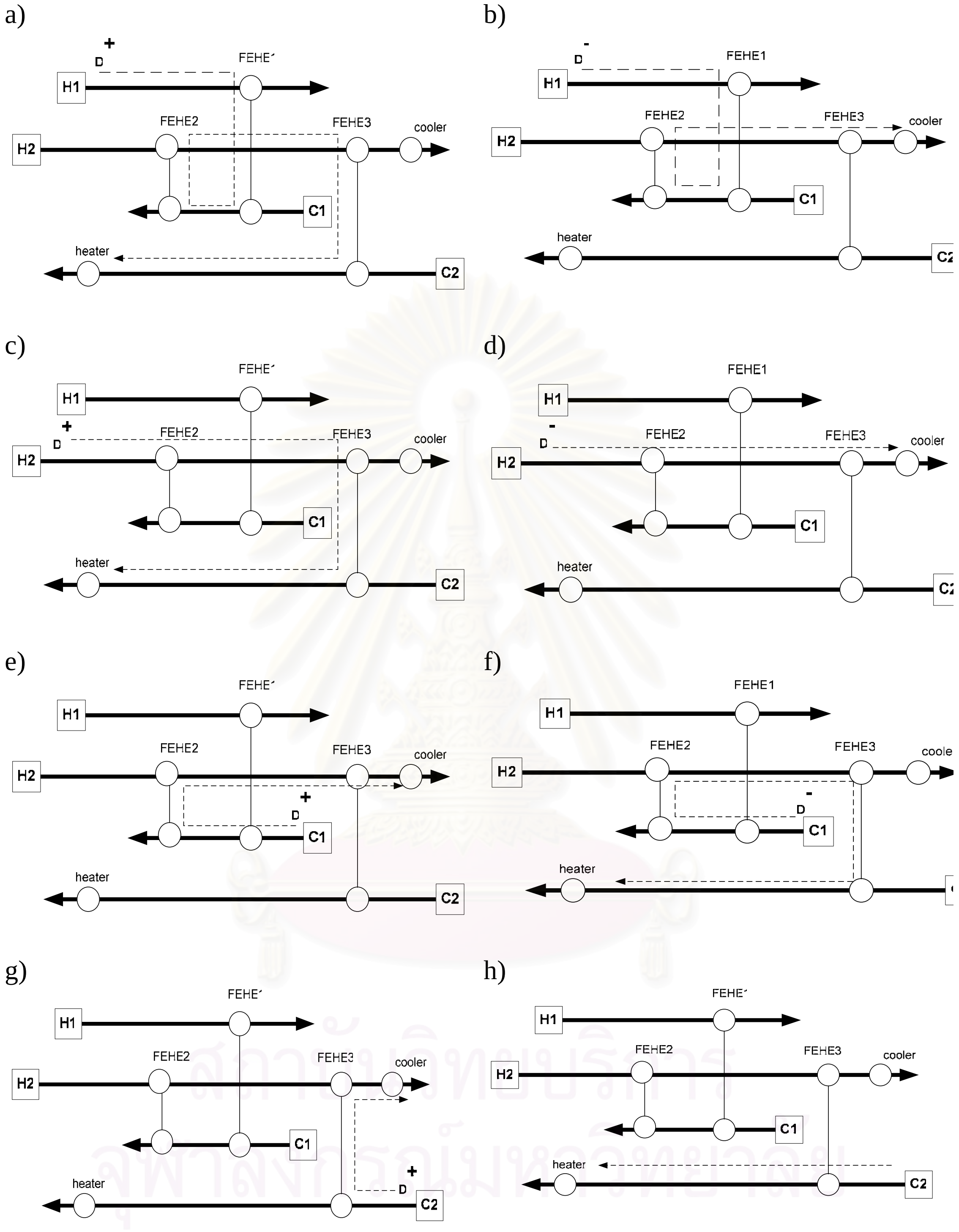
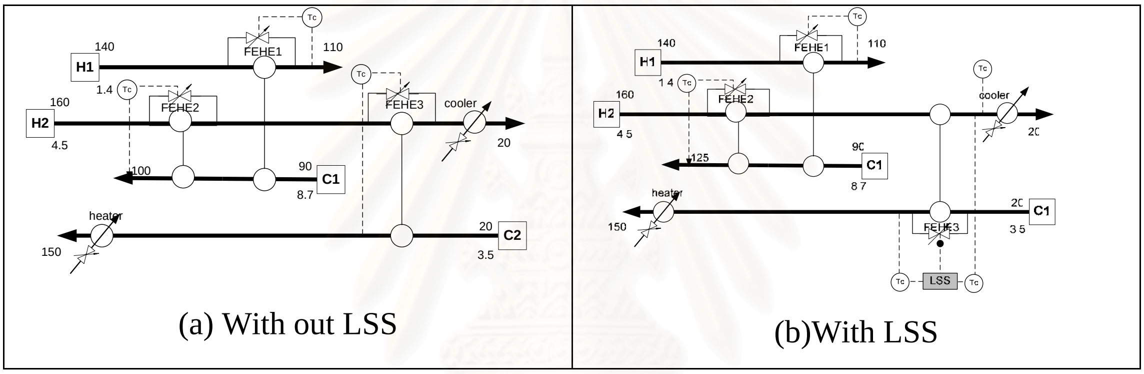


Figure 4.6 Heat pathway of control structure of network equipped with LSS of example 4.1. a) D^+ presented at H1, b) D^- presented at H1, c) D^+ presented at H2, d) D^- presented at H2, e) D^+ presented at C1 , f) D^- presented at C2, g) D^+ presented at H1, h) D^- presented at C2.

4.6.1 Dynamic Simulation Results for HEN in Example 4.1

In order to evaluate the dynamic behaviors of HEN in Example 4.1 and the control performance of LSS, the comparison between control structure with and without LSS (Figure 4.7a and b) is addressed. Then several disturbance loads is made (ie H1, H2, C1, C2), the dynamic responses of the control systems are shown in Figures 4.8 to 4.15. Left side shows dynamic behavior of system without LLS. On the other hand, right side presents the dynamic behavior of the new control system using the LSS to select appropriate heat pathway through the network.



(a) With out LSS

(b)With LSS

Figure 4.7 Control structure of network equipped; (a) With out LSS, (b)With LSS

4.6.1.1 Change in the Disturbance Load of Hot Stream H1 Temperature for Example 4.1

Figure 4.8 and 4.9 show the dynamic responses of HEN with and without LSS in example 4.1 to a change in the disturbance load of H1. In order to make these disturbances, first the fresh feed (i.e. H1 in Figure 4.6(a)) temperature decreases from 140 ^{o}C to 130^{o}C at time equal to 50 minutes, and the temperature increases from 130^{o}C to 150^{o}C at time around 200 minutes, then its temperature returns to its nominal value of 140°C at time equal to 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figures 4.8and 4.9.

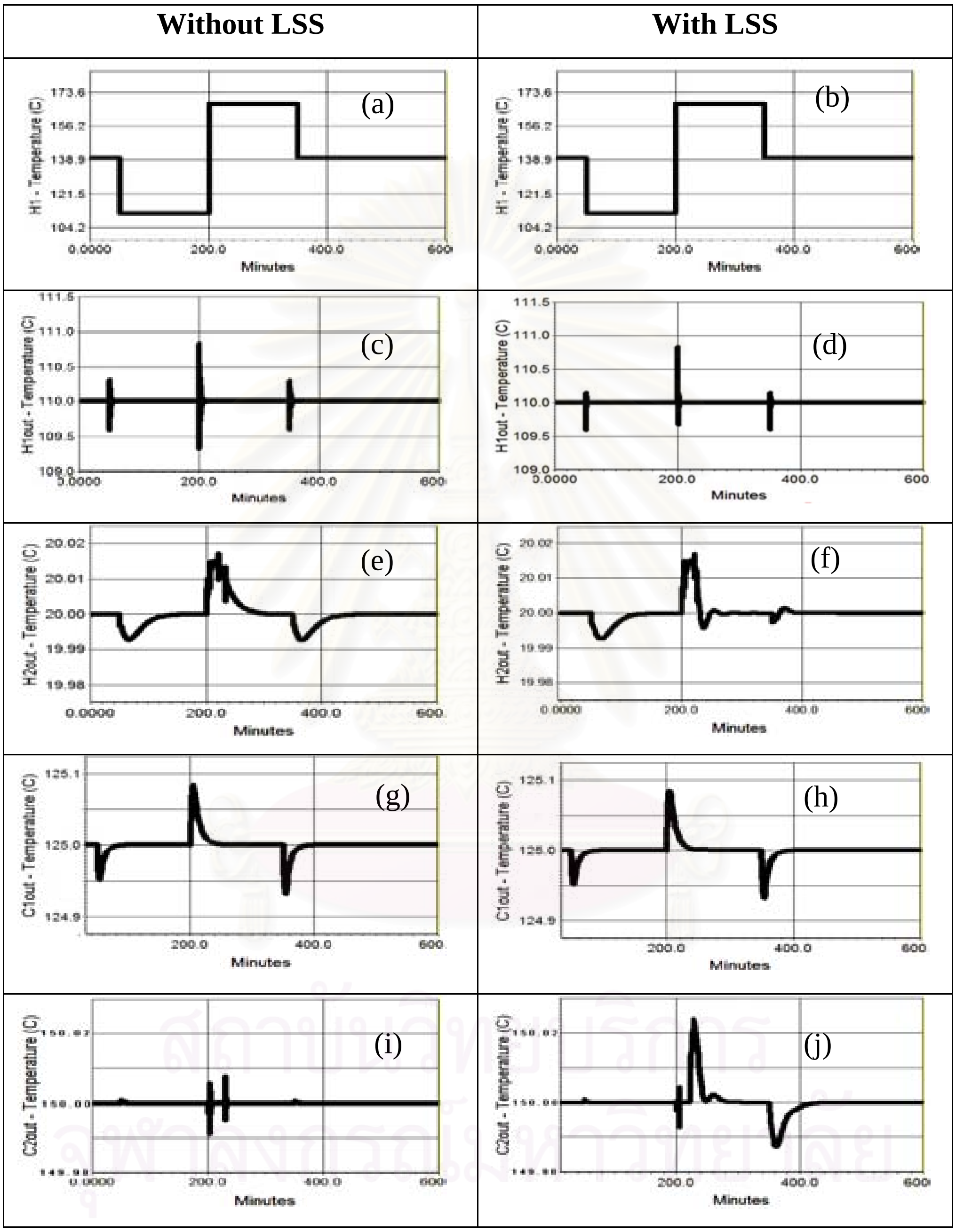


Figure 4.8 Dynamic responses of streams of HEN in Example 4.1 to a change in the disturbance load of H1.

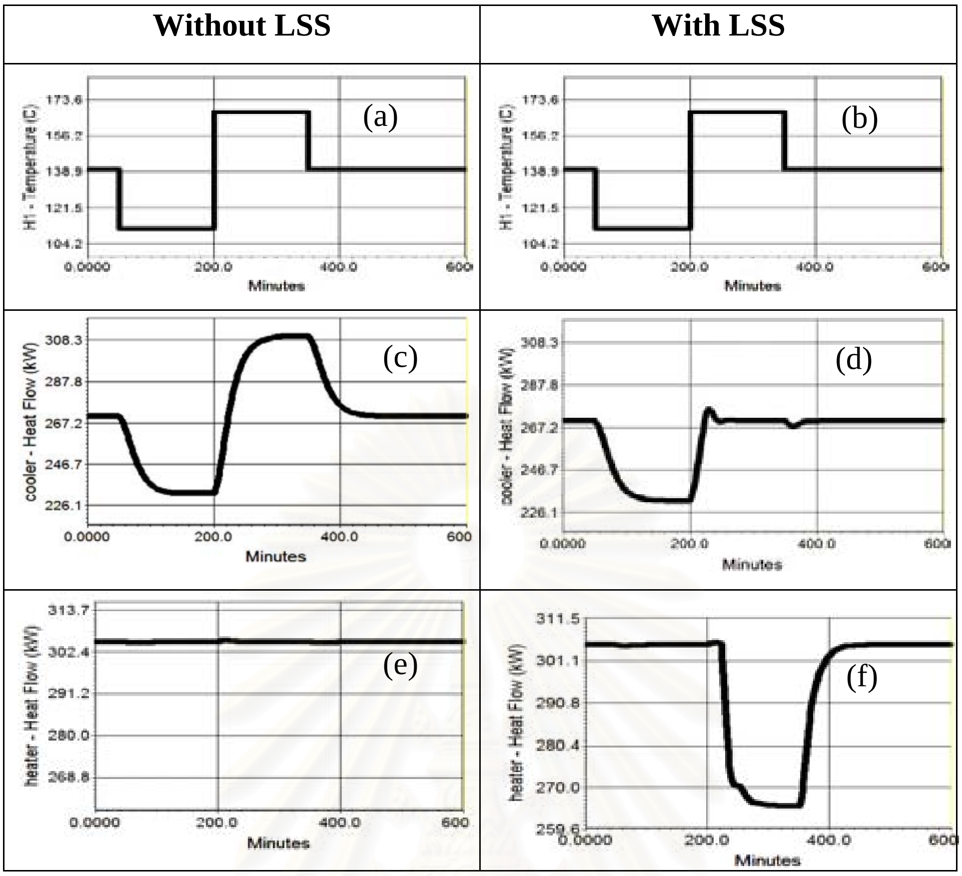


Figure 4.9 Dynamic responses of duty for HEN in Example 4.1 to a change in the disturbance load of H1.

As can be seen, first the hot stream inlet temperature (H1) decreases. That is to say negative disturbances, (D^-). Heat pathway is exhibited as in Figure 4.6(b). As a result, the cold outlet of FEHE3 temperature decreases below its minimum value, the LSS takes an action to control the cold outlet temperature of FEHE3. Therefore, the cooler duty decreases. Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of FEHE3. Consequently, following Figure 4.6(a), the Heater duty will be decreased (Figure 4.9).

4.6.1.2 Change in the Disturbance Load of Hot Stream H2 Temperature for Example 4.1

Figure 4.10 and 4.11 show the dynamic responses of the HEN with and without LSS in example 4.1 to a change in the disturbance load of H2. In order to make these disturbances, first the fresh feed (i.e. H2 in Figure 4.10(a)) temperature decreases from 160°C to 140°C at time equals 50 minutes, and the temperature increases from 140°C to 180°C at time equals 200 minutes, then its temperature returns to its nominal value of 160°C at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figures 4.10 and 4.11.

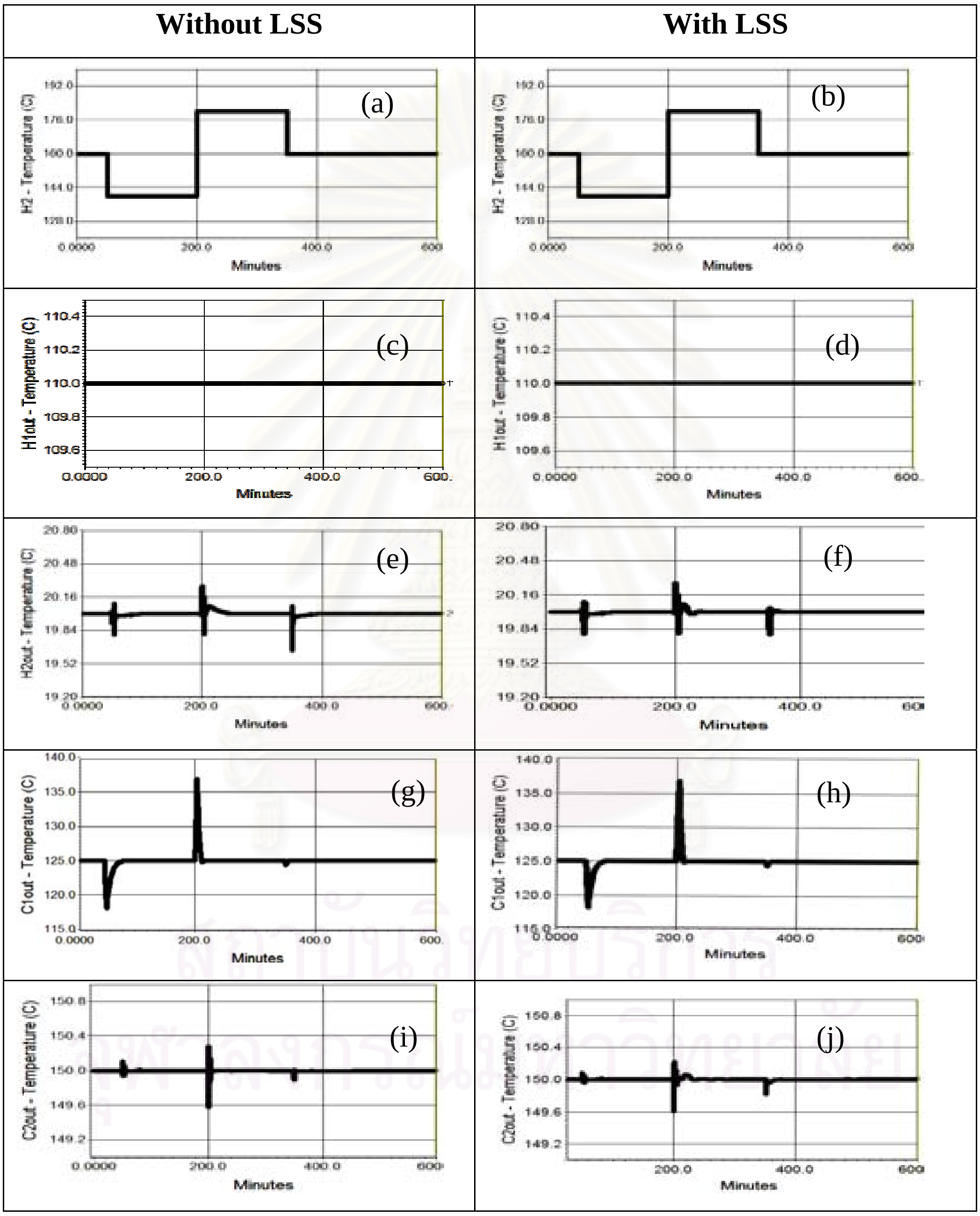


Figure 4.10 Dynamic responses of streams of HEN in Example 4.1 to a change in the disturbance load of H2.

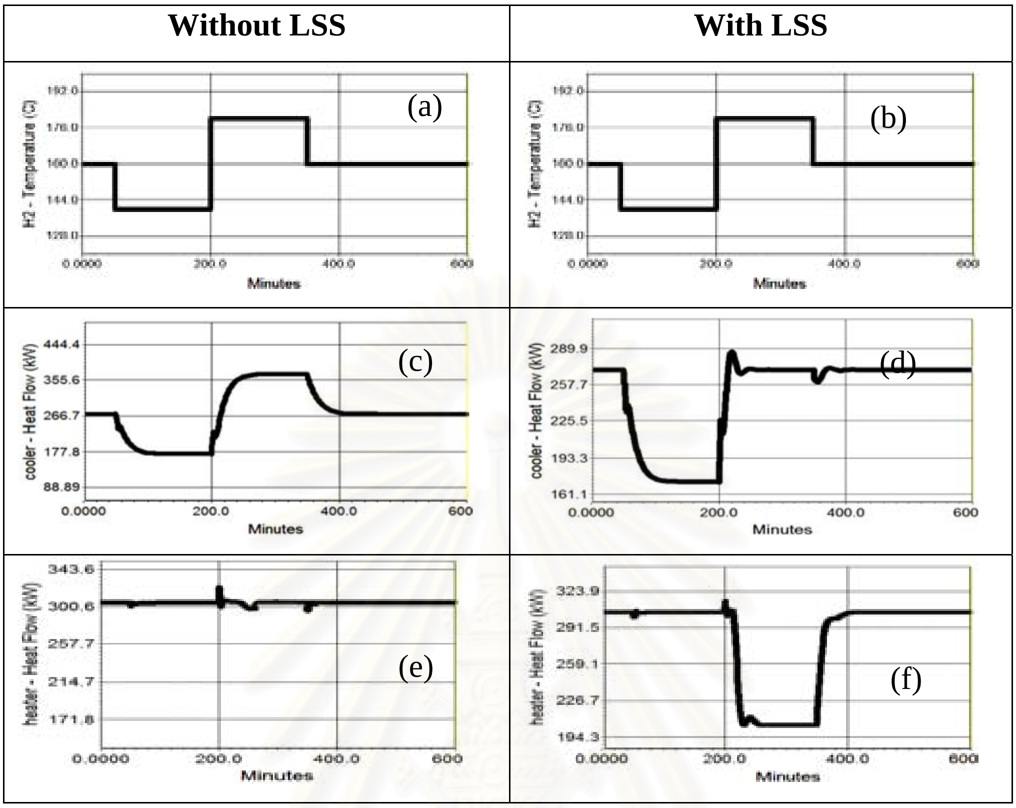


Figure 4.11 Dynamic responses of duty for HEN in Example 4.1
to a change in the disturbance load of H2.

As can be seen, first the hot stream inlet temperature (H1) decreases. That is to say negative disturbances, (D^-). Heat pathway is exhibited as in Figure [4.10(d)]. As a result, the cold outlet of FEHE3 temperature decreases below its minimum value, the LSS takes an action to control the cold outlet temperature of FEHE3. Therefore, the cooler duty decreases from 270.7 kW to 172.3 kW. Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of FEHE3. Consequently, following Figure 4.10(c), the Heater duty will be decreased from 305.1 to 204 kW (Figure 4.11(f).

4.6.1.3 Change in the Disturbance Load of Cold Stream C1 Temperature for Example 4.1

Figure 4.12 and 4.13 show the dynamic responses of the HEN with and without LSS in example 4.1 to a change in the disturbance load of C1. In order to make these disturbances, first the fresh feed (i.e. C1 in Figure 4.12(a)) temperature decreases from 90 °C to 80°C at time equals 50 minutes, and the temperature increases from 80°C to 100°C at time equals 200 minutes, then its temperature returns to its nominal value of 90°C at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figures 4.12 and 4.13.

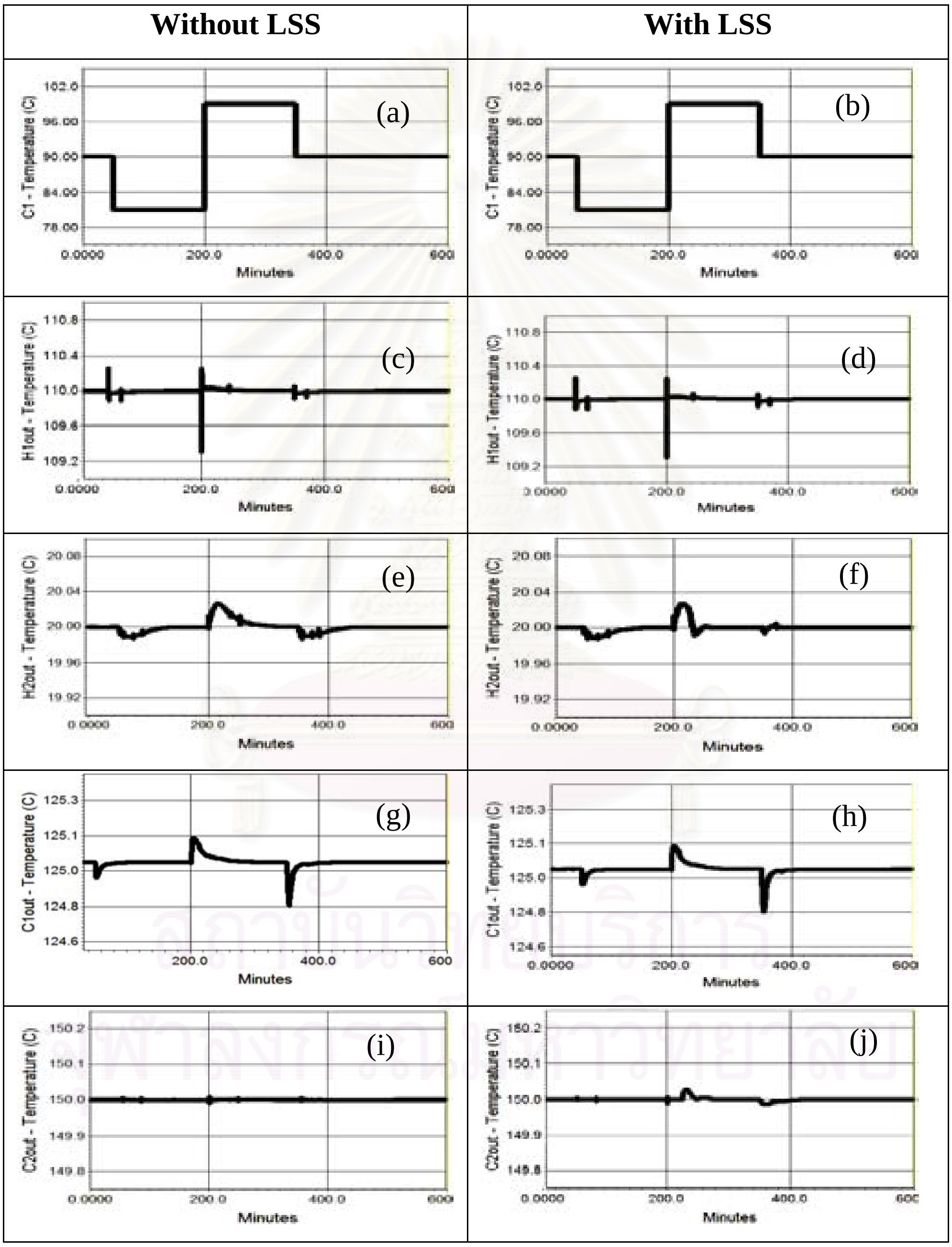


Figure 4.12 Dynamic responses of streams of HEN in Example 4.1 to a change in the disturbance load of C1.

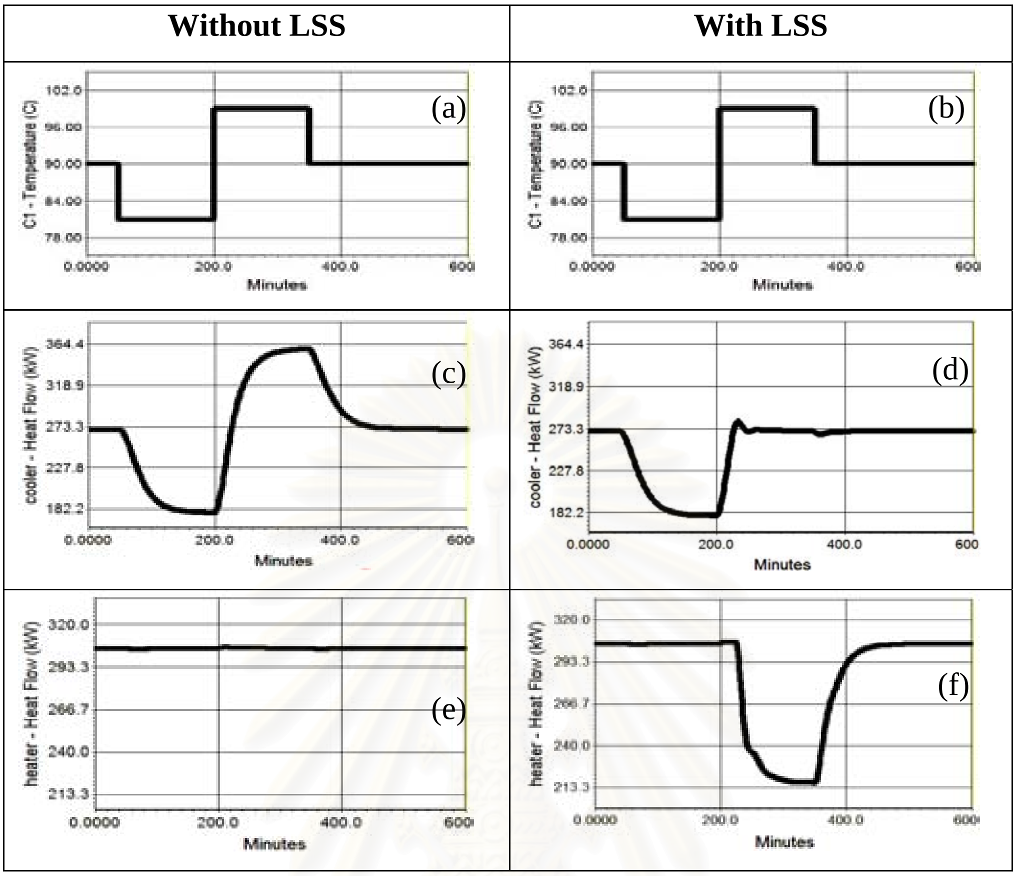


Figure 4.13 Dynamic responses of duty for HEN in Example 4.1 to a change in the disturbance load of C1.

When C1 temperature decreases, thus it results in decrease of the hot inlet and outlet temperature of FEHE3. The LSS will take an action to control the cold outlet temperature of FEHE3. Namely, the positive disturbance load of cold stream should be shifted to a cooler utility. Therefore, the cooler duty decreases from 270.7 kW to 182.1 kW (Figure 4.13(d)). Then the negative disturbance load of cold stream shifts to furnace utility by controlling the hot outlet temperature of FEHE3. As a result, the furnace duty decreases from 305.1 kW to 217 kW (Figure 4.13(f)).

4.6.1.4 Change in the Disturbance Load of Cold Stream C2 Temperature for Example 4.1

Figure 4.14 and 4.15 show the dynamic responses of the HEN with and without LSS in Example 4.1 to a change in the disturbance load of C2. In order to make these disturbances, first the fresh feed (i.e. C2 in Figure 4.14(a)) temperature decreases from 20 °C to 16.5 °C at time equals 50 minutes, and the temperature increases from 16.5 °C to 23.5°C at time equals 200 minutes, then its temperature returns to its nominal value of 20°C at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figures 4.14 to 4.15.

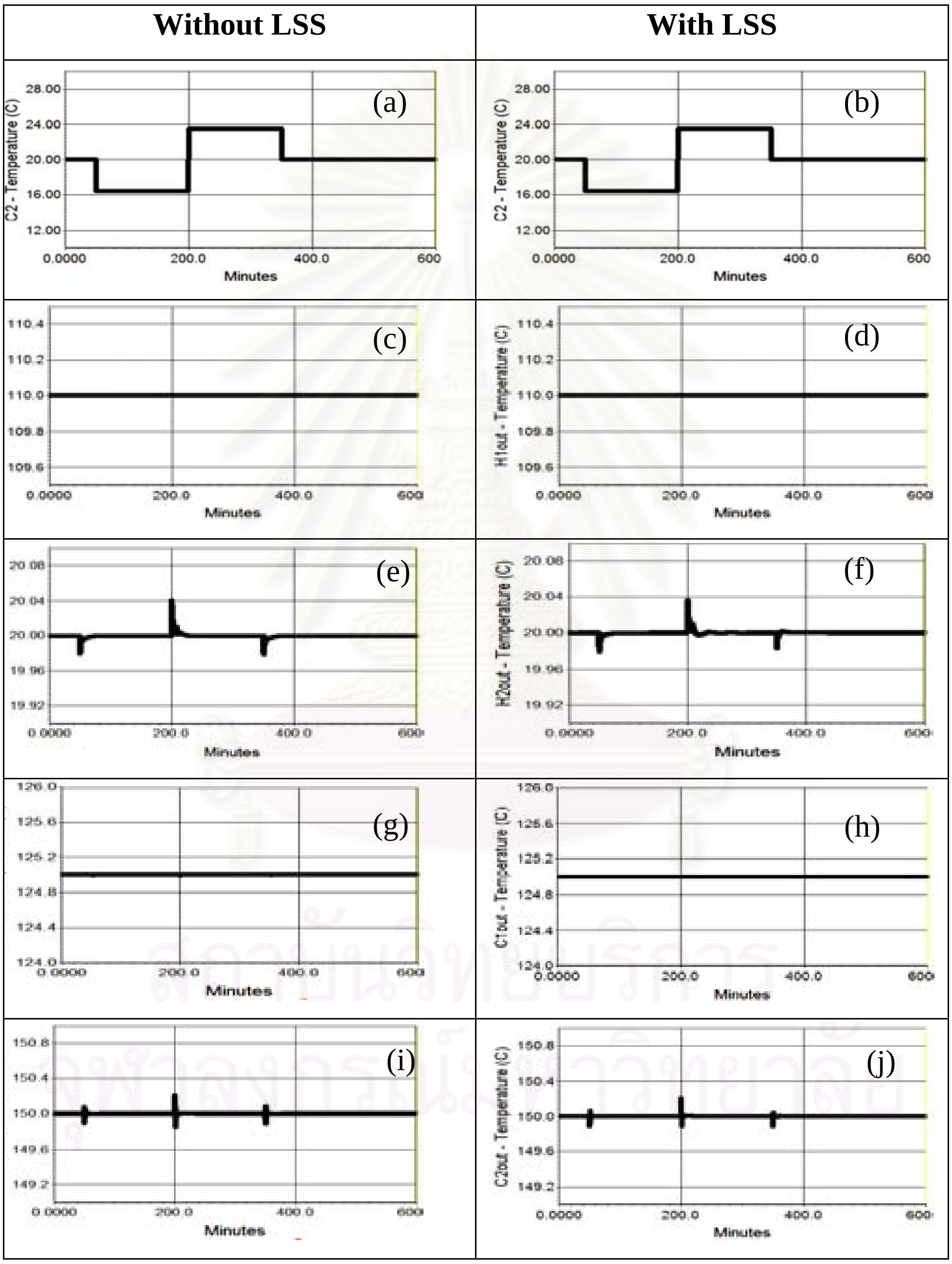


Figure 4.14 Dynamic responses of streams of HEN in Example 4.1 to a change in the disturbance load of C2.

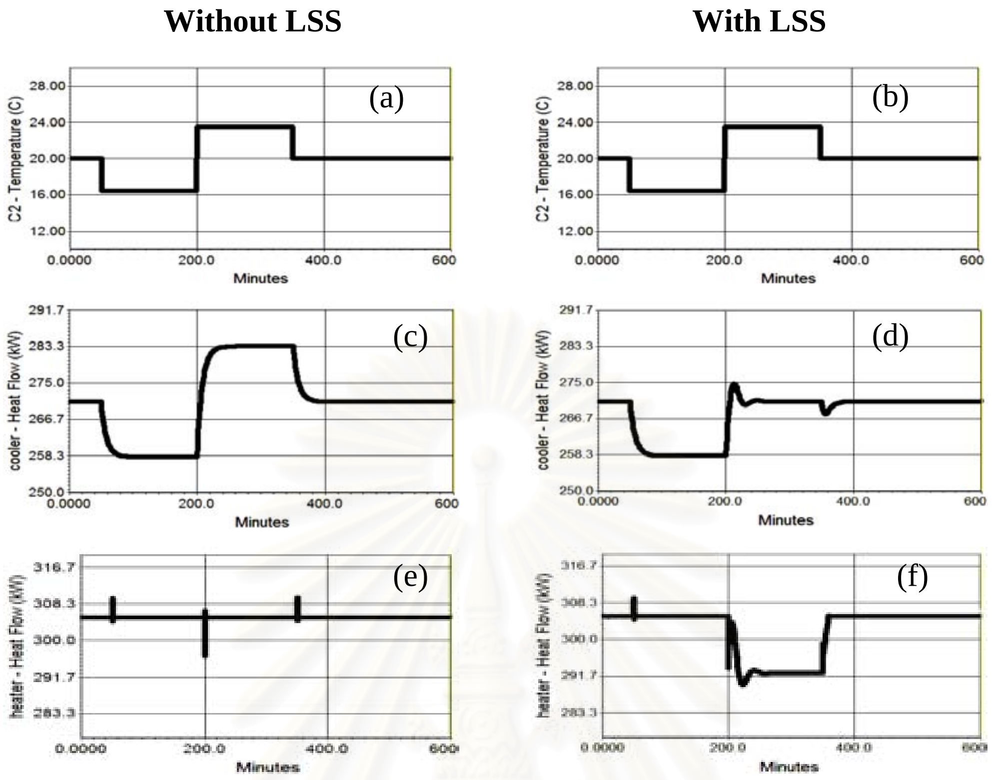


Figure 4.15 Dynamic responses of duty for HEN in Example 4.1 to a change in the disturbance load of C2.

When C2 temperature decreases, thus it results in decrease of the hot outlet temperature of FEHE3. The LSS will take an action to control the cold outlet temperature of FEHE3. Namely, the positive disturbance load of cold stream should be shifted to a cooler utility. Therefore, the cooler duty decreases from 270.7 kW to 258.1 kW (Figure 4.15(d)). Then the negative disturbance load of cold stream is shifted to furnace utility by controlling the hot outlet temperature of FEHE3. As a result, the furnace duty decreases from 305.1 kW to 292.4 kW (Figure 4.15(f)).

Table 4.3 Comparison of the energy consumption of control structure with and without LSS in the case of Example 4.1 (temperature changed).

Stream	**Type of Disturbances**	**Cooler Utility, kW**		**Heater Utility ,kW**	
Temperature Variation		**With out LSS**	**With LSS**	**With out LSS**	**With LSS**
H1					
	Negative Disturbances	232.1	232.1	305.1	305.1
	Positive Disturbances	310.0	270.7	305.1	265
H2					
	Negative Disturbances	123.6	172.3	305.1	305.1
	Positive Disturbances	370.9	270.7	305.1	204
C1					
	Negative Disturbances	358.0	270.7	305.1	217
	Positive Disturbances	182.1	182.1	305.1	305.1
C2					
	Negative Disturbances	283.4	270.7	305.1	292.4
	Positive Disturbances	258.1	258.1	305.1	305.1

4.6.1.5 Change in the Disturbance Load of Hot Stream H1 Flow Rate for Example 4.1

Figure 4.16 and 4.17 show the dynamic responses of the HEN with and without LSS in example 4.1 to a change in the disturbance load of H1. In order to make these disturbances, first the fresh feed (i.e. H1 in Figure 4.16(a)) flow rate decreases from 15 kgmol/h to 12 kgmol/h at time equals 50 minutes, and the flow rate increases from 12 kgmol/h to 18 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 15 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figures 4.16 and 4.17.

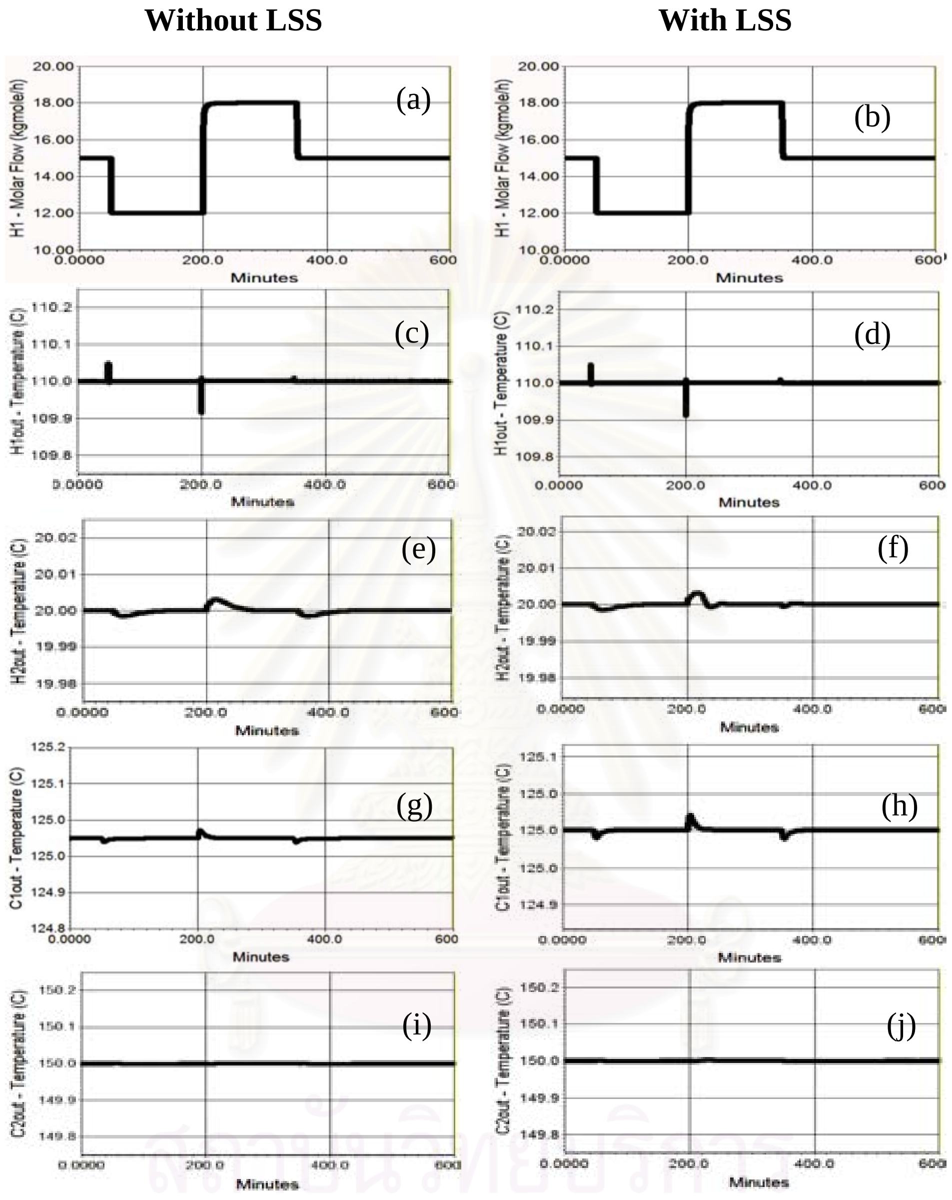


Figure 4.16 Dynamic responses of streams of HEN in Example 4.1 to a change in the disturbance load of H1.

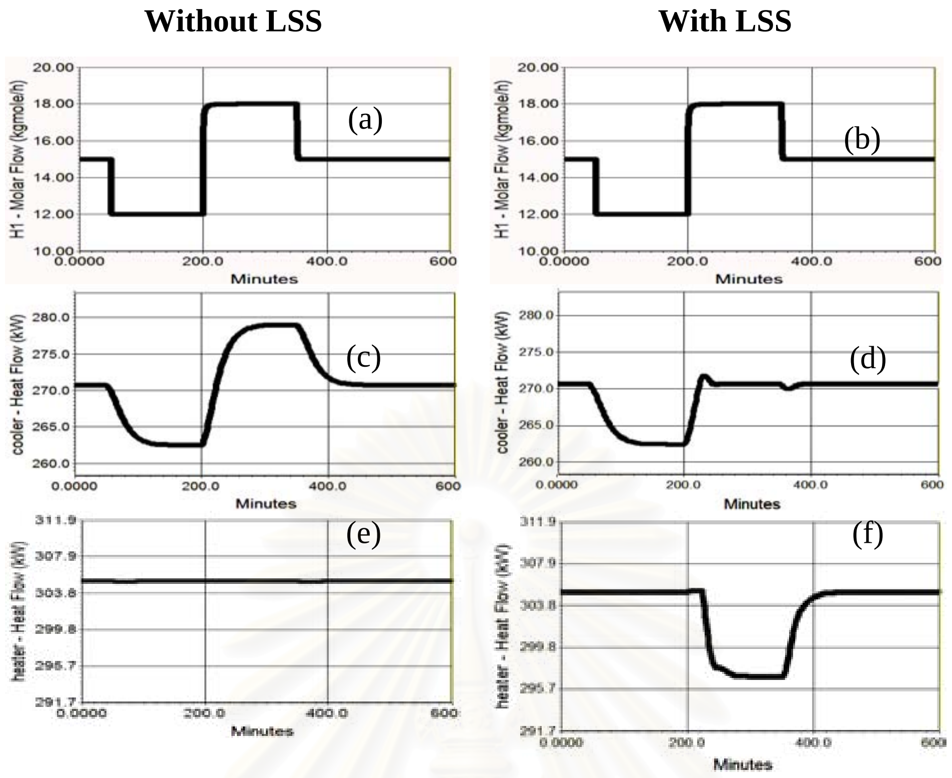


Figure 4.17 Dynamic responses of duty for HEN in Example 4.1 to a change in the disturbance load of H1.

As can be seen, first the hot stream inlet flow rate (H1) decreases. That is to say negative disturbances, (D^-). Heat pathway is exhibited as in Figure 4.6(b). As a result, the LSS takes an action to control the cold outlet temperature of FEHE3. Therefore, the cooler duty decreases from 270.7 kW to 262.5 kW. Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of FEHE3. Consequently, following Figure 4.6(c), the Heater duty will be decreased from 305.1 kW to 296.9 kW (Figure 4.17).

4.6.1.6 Change in the Disturbance Load of Hot Stream H2 Flow Rate for Example 4.1

Figure 4.18 and 4.19 show the dynamic responses of the HEN with and without LSS in example 4.1 to a change in the disturbance load of H1. In order to make these disturbances, first the fresh feed (i.e. H2 in Figure 4.18(a)) flow rate decreases from 48.6 kgmol/h to 38.88 kgmol/h at time equals 50 minutes, and the flow rate increases from 38.88 kgmol/h to 58.32 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 48.6 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figures 4.18 and 4.19.

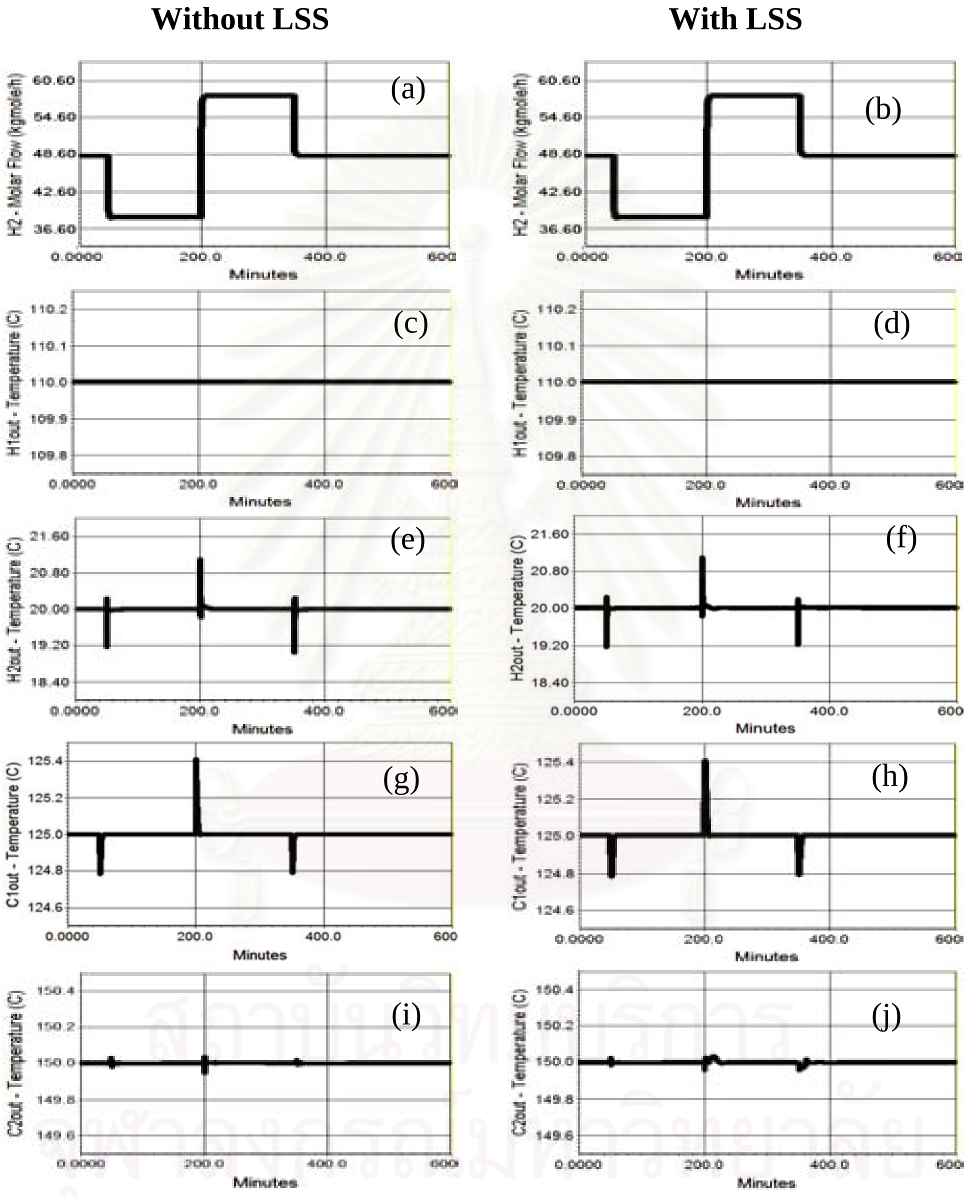


Figure 4.18 Dynamic responses of streams of HEN in Example 4.1 to a change in the disturbance load of H2.

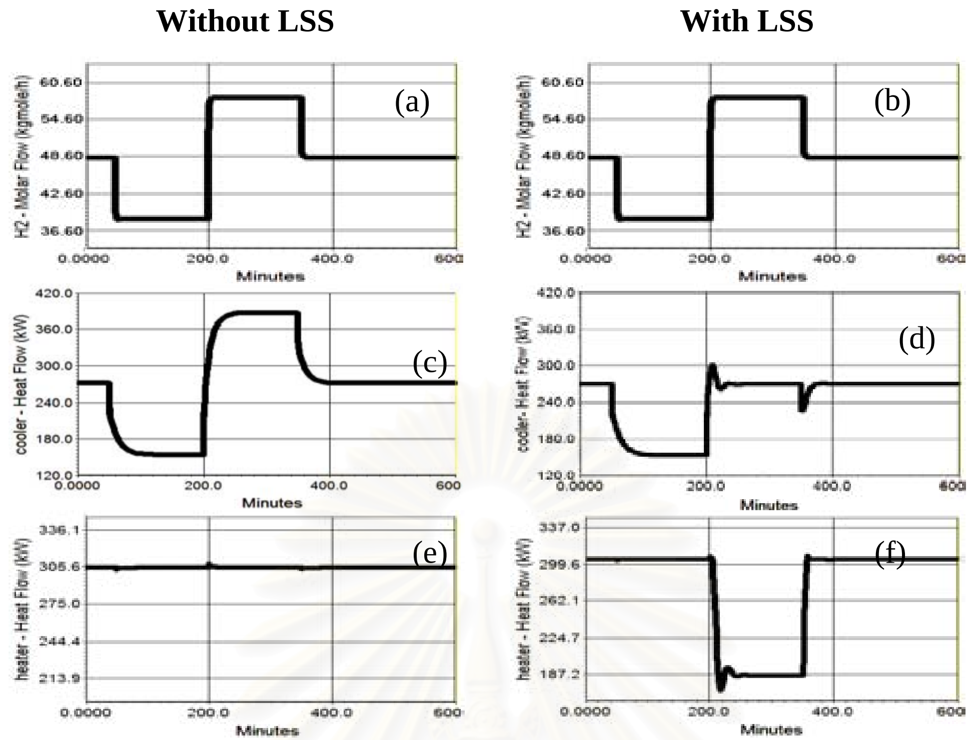


Figure 4.19 Dynamic responses of duty for HEN in Example 4.1 to a change in the disturbance load of H2.

As can be seen, first the hot stream inlet flow rate (H2) decreases. That is to say negative disturbances, (D^-). It should be shifted to a cooler utility. As a result, the cold outlet of FEHE3 temperature decreases below its minimum value, the LSS takes an action to control the cold outlet temperature of FEHE3. Therefore, the cooler duty decreases from 270.7 kW to 159.5 kW. Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of FEHE3. Consequently, following Figure 4.6(c), the Heater duty will be decreased from 305.1 kW to 187.2 kW (Figure 4.19f).

4.6.1.7 Change in the Disturbance Load of Cold Stream C1 Flow Rate for Example 4.1

Figure 4.20 and 4.21 show the dynamic responses of the HEN with and without LSS in example 4.1 to a change in the disturbance load of C1. In order to make these disturbances, first the fresh feed (i.e. C1 in Figure 4.21(a)) flow rate decreases from 60.0 kgmol/h to 51.0 kgmol/h at time equals 50 minutes, and the flow rate increases from 51.0 kgmol/h to 66.0 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 60.0 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figures 4.20 to 4.21.

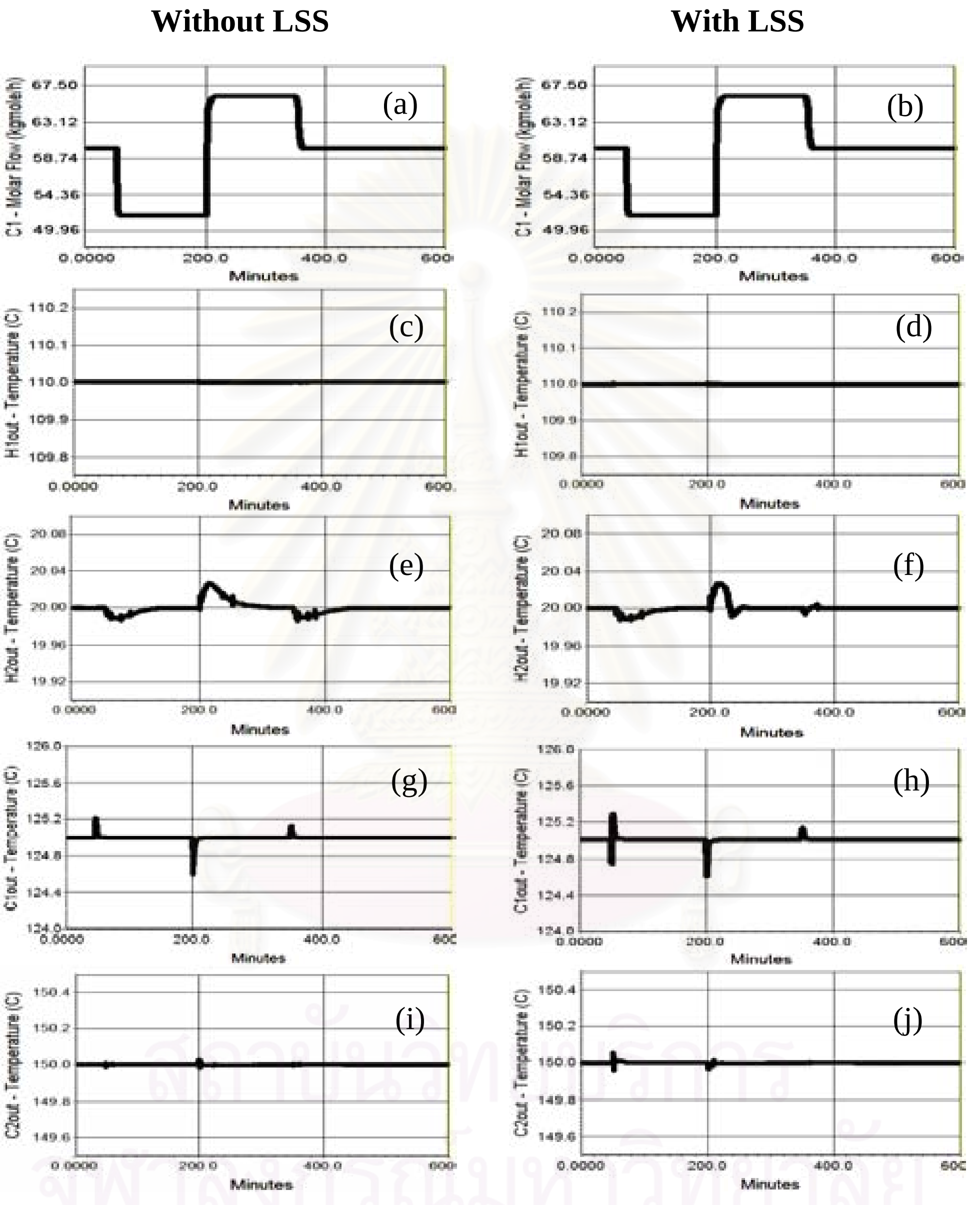


Figure 4.20 Dynamic responses of streams of HEN in Example 4.1 to a change in the disturbance load of C1.

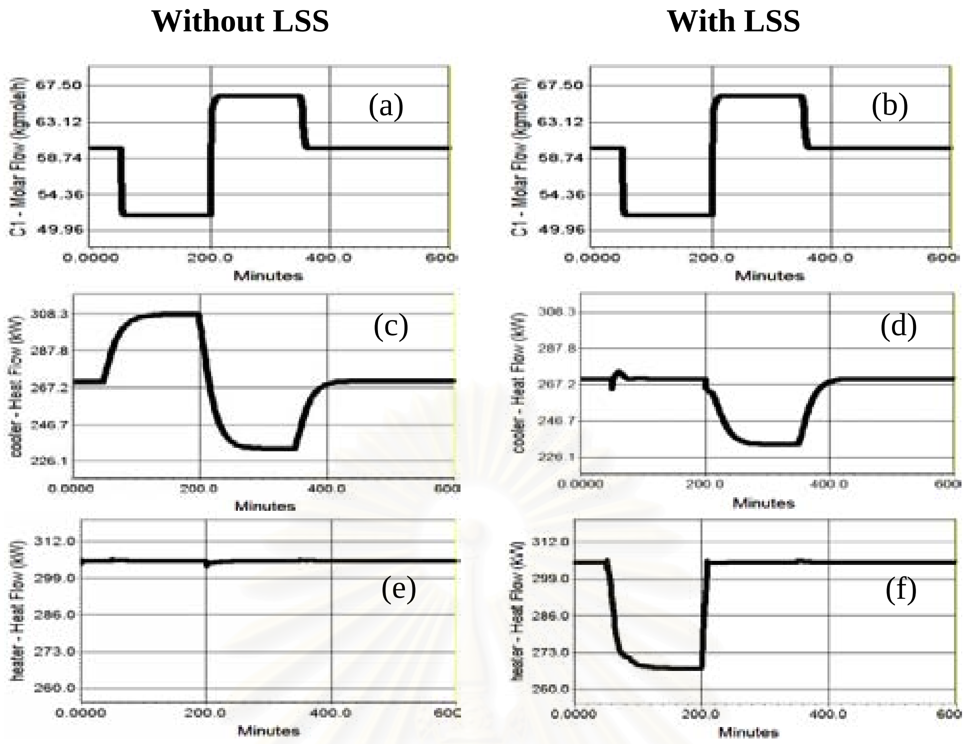


Figure 4.21 Dynamic responses of duty for HEN in Example 4.1 to a change in the disturbance load of C1.

As can be seen, first the cold stream inlet flow rate (C1) decreases. That is to say negative disturbances, (D^-). Heat pathway is exhibited as in Figure 4.6(f). As a result, the hot outlet of FEHE3 temperature decreases below its minimum value, the LSS takes an action to control the hot outlet temperature of FEHE3. Therefore, the Heater duty will be decreased from 305.1 kW to 267.6 kW. Then, the positive disturbance load, (D^+) of cold stream is shifted to a cold utility by controlling the hot outlet temperature of FEHE3. As a result, the cooler duty decreases from 270.7 kW to 179.8 kW (Figure 4.21(f)).

4.6.1.8 Change in the Disturbance Load of Cold Stream C2 Flow Rate for Example 4.1

Figure 4.22 and 4.23 show the dynamic responses of the HEN with and without LSS in example 4.1 to a change in the disturbance load of C2. In order to make these disturbances, first the fresh feed (i.e. C2 in Figure 4.20(a)) flow rate decreases from 42 kgmol/h to 33.6 kgmol/h at time equals 50 minutes, and the flow rate increases from 33.6 kgmol/h to 50.4 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 42 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figure 4.22 and 4.23.

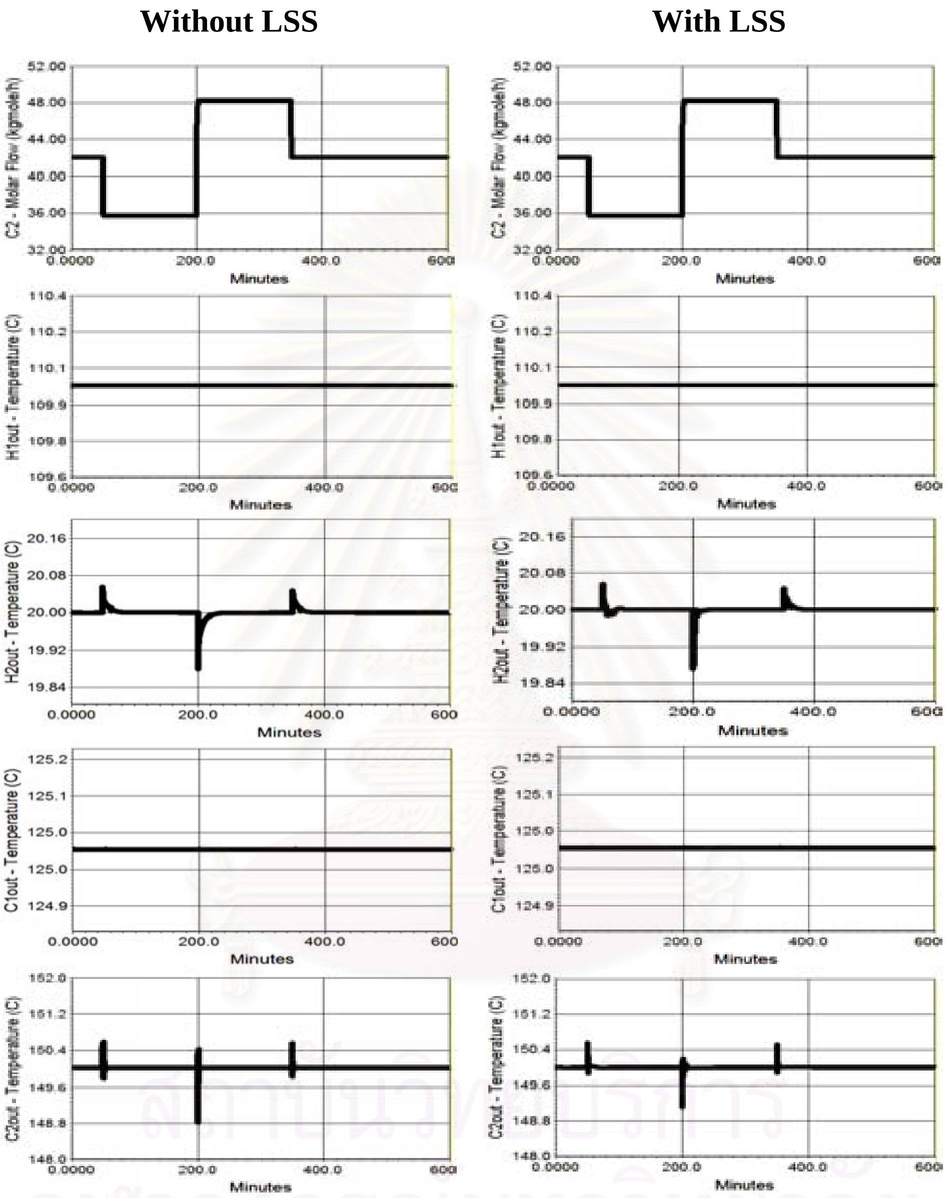


Figure 4.22 Dynamic responses of streams of HEN in Example 4.1 to a change in the disturbance load of C2.

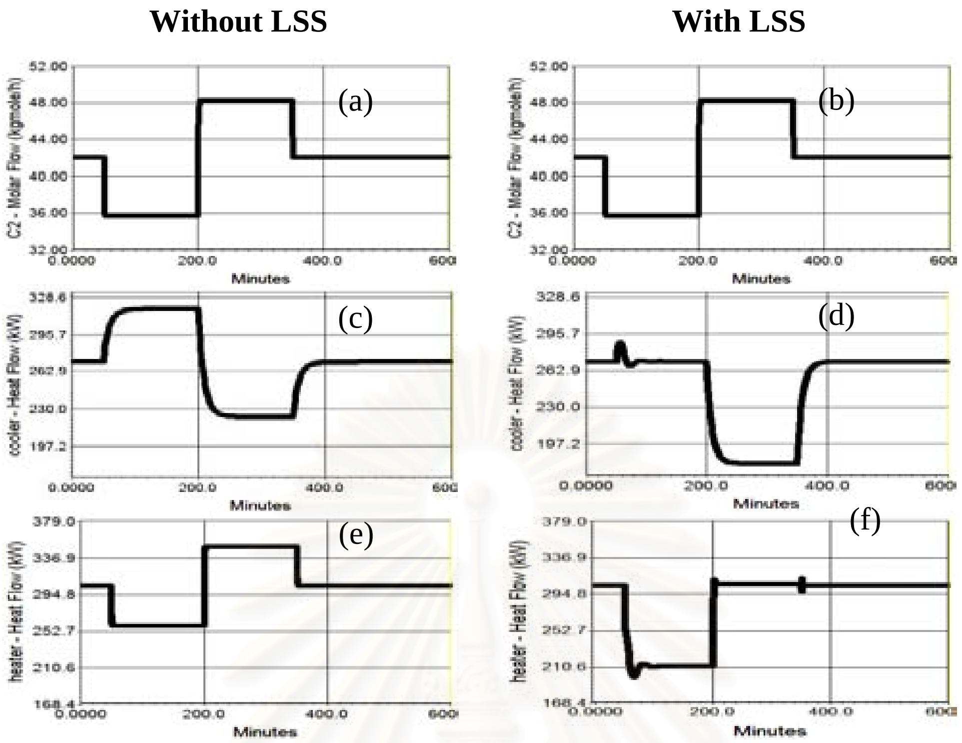

Without LSS **With LSS**

Figure 4.23 Dynamic responses of duty for HEN in Example 4.1 to a change in the disturbance load of C2.

As can be seen, first the cold stream inlet flow rate (C2) decreases. That is to say negative disturbances, (D^-). Heat pathway is exhibited as in Figure 4.6(h). As a result, the hot outlet of FEHE3 temperature decreases below its minimum value, the LSS takes an action to control the hot outlet temperature of FEHE3. Therefore, the Heater duty will be decreased from 305.1 kW to 211.6 kW. Then, the positive disturbance load, (D^+) of cold stream is shifted to a cold utility by controlling the hot outlet temperature of FEHE3. As a result, the cooler duty decreases from 270.7 kW to 189.2 kW (Figure 4.23(f)).

Table 4.4 Comparison of the energy consumption of control structure with and without LSS in the case of Example 4.1 (Flow rate variation).

Stream	**Type of Disturbances**	**Cooler Utility, kW**		**Heater Utility, kW**	
Flow rate Variation		**Without LSS**	**With LSS**	**With out LSS**	**With LSS**
H1					
	Negative Disturbances	262.5	262.5	305.1	305.1
	Positive Disturbances	279.1	270.7	305.1	296.9
H2					
	Negative Disturbances	159.5	159.5	305.1	305.1
	Positive Disturbances	387.9	270.7	305.1	187.2
C1					
	Negative Disturbances	307.9	270.7	305.1	267.6
	Positive Disturbances	229.4	229.4	305.1	305.1
C2					
	Negative Disturbances	318.4	270.7	259.3	211.6
	Positive Disturbances	223.9	187.0	350.89	305.1

From the result it is found that using LSS is likely an effective way to handle with disturbance come along with class I problem, pinch is not be changed or continuous vary. It brings about control structure of HEN that give dynamic maximum energy recovery.

4.7 Example 4.2: Class II problem (Temperature Variation Cause Pinch Jump)

The HEN synthesis problem is adapted from Calandranis and Stephanopoulos (1986) presenting a single pinch jump. The four-stream HEN synthesis problem is shown in Table 4.5. At the temperature of H2 of 120^{o}C, the network pinch is 90/80 ^{o}C. (see Table 4.6). When temperature goes up to 132^{o}C, the new pinch is located at 132/122 ^{o}C. (see Table 4.7)

Table 4.5 Data for pinch temperature calculating.

Stream	W (kW/ °C)	Tin(°C)		Tout (°C)
		Max	Min	
H1	4	-	220	70
H2	6	150	120	15
C1	5	-	20	220
C2	7	-	80	110

From Table 4.5, it can be applied to the problem table (see Table 4.6 to 4.8).

Table 4.6 Problem table for minimum heat load.

W				T hot	T cold	W	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	°C	°C	kW/ °C	°C	kW	kW	kW
0	0	0	0	230	220					Qh=210
0	0	-5	0	220	210	-5	10	-50	-50	160
4	0	-5	0	170	160	-1	50	-50	-100	110
4	0	-5	0	132	122	-1	38	-38	-138	72
4	0	-5	0	120	110	-1	12	-12	-150	60
4	6	-5	-7	90	80	-2	30	-60	-210	0
4	6	-5	0	70	60	5	20	100	-110	100
0	6	-5	0	30	20	1	40	40	-70	140
0	6	0	0	15	5	6	15	90	20	Qc=230

Table 4.7 Problem table for T_{H2} =132°C.

W				T hot	T cold	W	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	°C	°C	kW/°C	°C	kW	kW	kW
0	0	0	0	230	220					Qh=138
0	0	-5	0	220	210	-5	10	-50	-50	88
4	0	-5	0	170	160	-1	50	-50	-100	38
4	0	-5	0	132	122	-1	38	-38	-138	0
4	6	-5	0	120	110	5	12	60	-78	60
4	6	-5	-7	90	80	-2	30	-60	-138	0
4	6	-5	0	70	60	5	20	100	-38	100
0	6	-5	0	30	20	1	40	40	2	140
0	6	0	0	15	5	6	15	90	92	Qc=230

When the inlet temperature of H2 increases from 132°C, the pinch temperature will be tied to the T_{H2} through the upper bound of T_{H2}.

Table 4.8 Problem table for maximum heat load.

W				T hot	T cold	W	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	°C	°C	kW/ °C	°C	kW	kW	kW
0	0	0	0	230	220					Qh=138
0	0	-5	0	220	210	-5	10	-50	-50	88
4	0	-5	0	150	140	-1	88	-88	-138	0
4	6	-5	0	132	122	5	30	150	12	150
4	6	-5	0	120	110	5	12	60	72	210
4	6	-5	-7	90	80	-2	30	-60	12	150
4	6	-5	0	70	60	5	20	100	112	250
0	6	-5	0	30	20	1	40	40	152	290
0	6	0	0	15	5	6	15	90	242	Qc=380

Wongsri (1990) used heuristic approaches involving disturbance propagation method and match patterns to design network. The final match structure of this problem is shown in Figure 4.24.

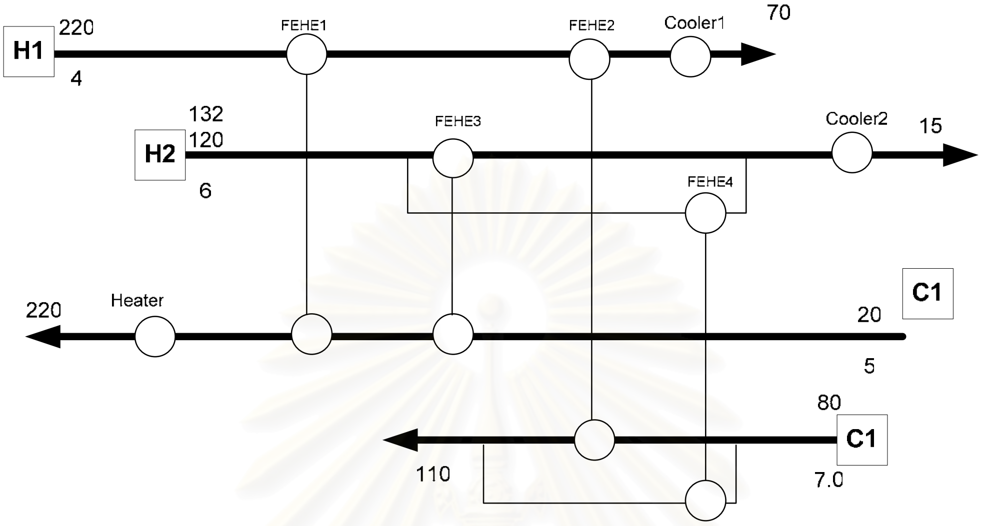


Figure 4.24 Resilient network structures for Example 4.2.

Based on the pinch position from the problem table, network is explicated as follows:

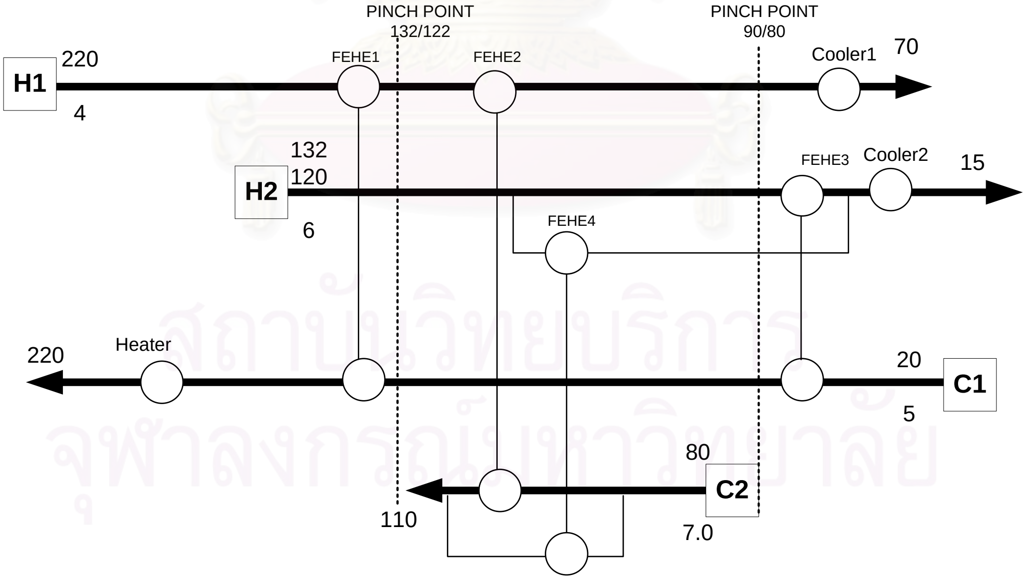


Figure 4.25 HEN for network of Example 4.2.

From the procedure in 4.5, it can be used to design control structure as follows:

Step 1. Identify heat link to find the minimum number of LSS.

As can be seen from Figure 26, there is one possible heat link so one LSS should be settled. However, at the end of heat link is target temperature it should, therefore, be considered to set LSS at the former unit (FEHE 1) and control at the outlet stream of both hot and cold stream as displayed in Figure 4.27.

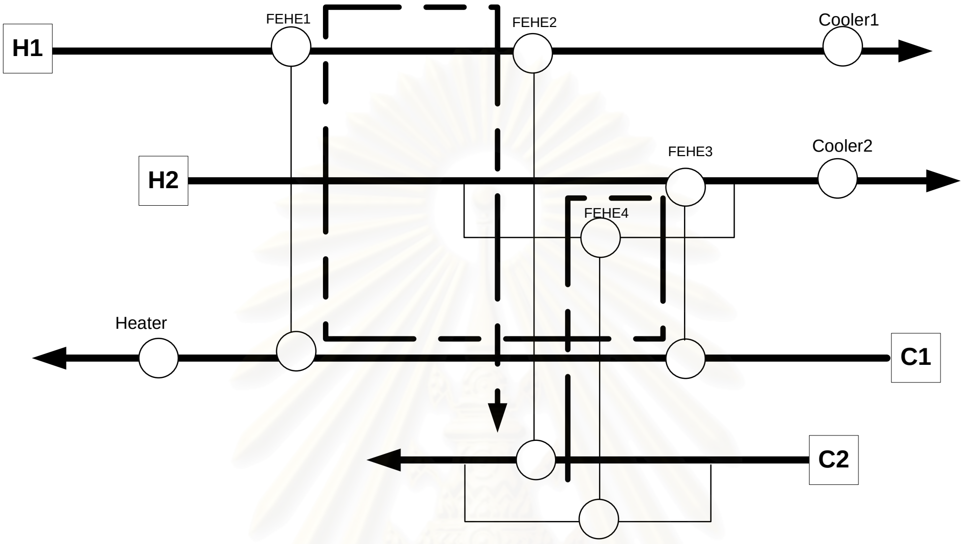


Figure 4.26 heat link of Example 4.2

Step 2. Set up LSS in the network

In this case, heat can not be transferred through cold stream of C2 inconsequence of no heat path way to heater. So it should set LSS at the former FEHE which is FEHE 1. Regarding to W of hot stream is less than that of cold stream, therefore bypass is equipped at hot stream and control both outlet temperature of FEHE1 as illustrated in Figure 4.27

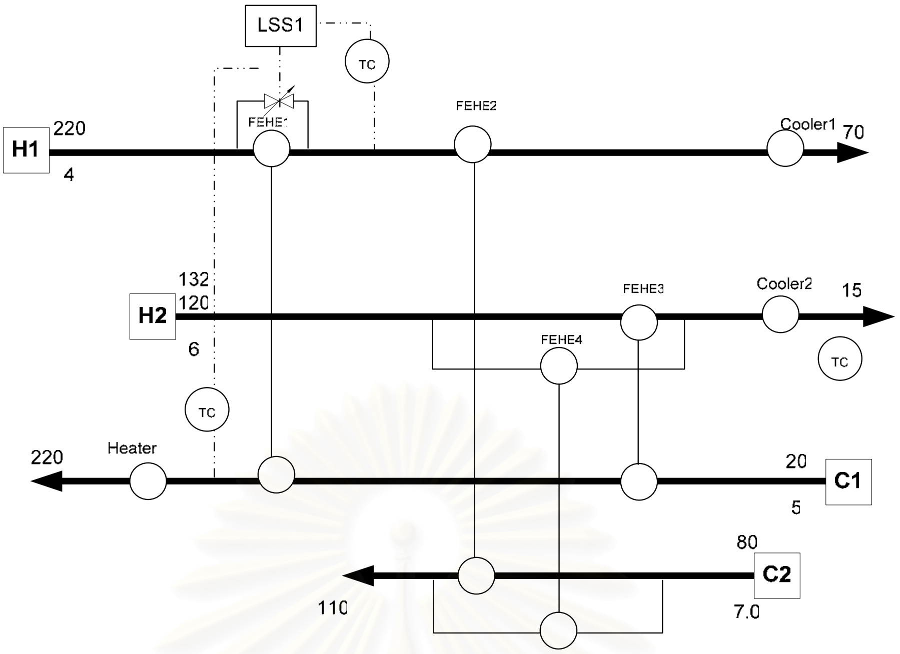


Figure 4.27 Set up LSS for example 4.2

. **Step 3.** Design control structure with regard to the law of control structure design no. 1-15 as aforementioned in Chapter III. It is not necessary to consider the factor in consequence so the order can be changed to the appropriate condition.

To begin with determination of set up control loop at utility of any stream in order to maintain target temperature. Consider FEHE 1 and C2 stream which have to maintain target temperature without utility. The temperature at this point is from the combination of splitting stream. From the fifteenth law it is claimed that bypass should be settled on heat exchanger which is spitted for control and because of this is class C problem so upstream should be used to transfer heat. Moreover, these two splitting stream is exchanged heat with another FEHE so heat can be transferred though these upstream. According to the tenth law, bypass and control loop should be settled at cold stream of FEHE 2 due to its higher heat transfer capacity.

As can be seen from Figure 4.26, at FEHE 4 heat is transferred to upstream. It is evident that there have a necessary to control outlet temperature of cold stream of FEHE 4. It is, moreover, found that splitting ratio of H2 stream should be used instead of setting up bypass to control exchanged stream referring to the fourteenth law and this disturbance is propagated though FEHE 3. Based on heat sink, it should control inlet temperature of cooler2 in order to transfer disturbance to FEHE 1 so bypass is selected to set at hot stream of FEHE 3 to control temperature which is a temperature of combination stream from splitting stream as in FEHE2. Control structure and heat path way are shown in Figure 28 and Figure 30.

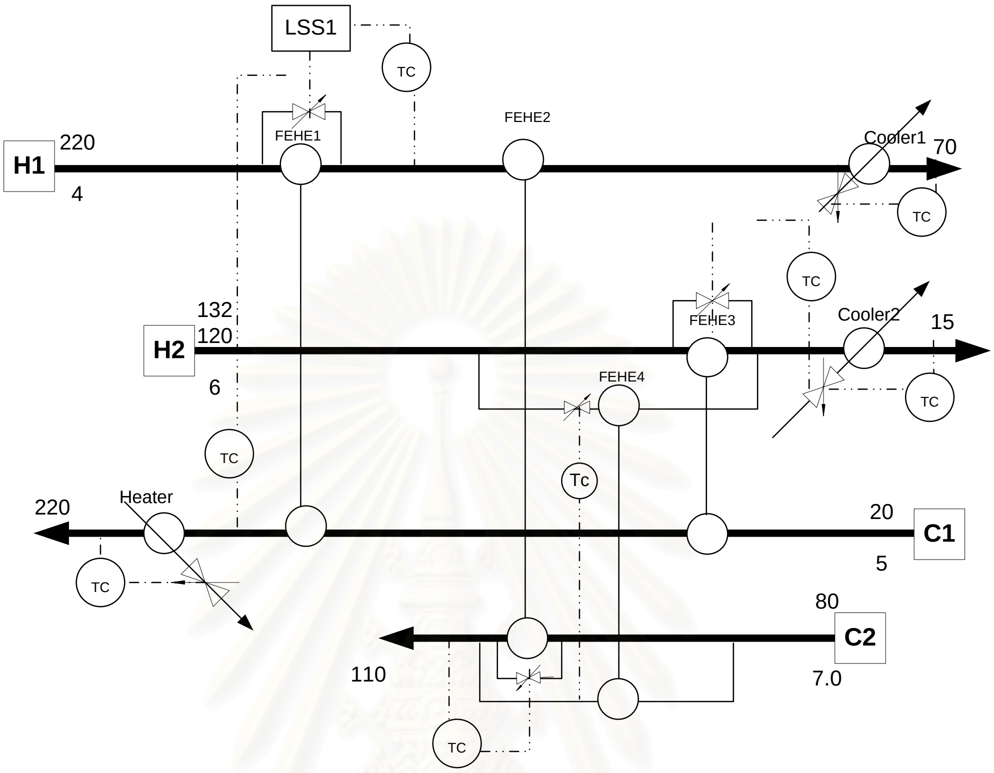


Figure 4.28 Control structure of network equipped with LSS of example 4.2

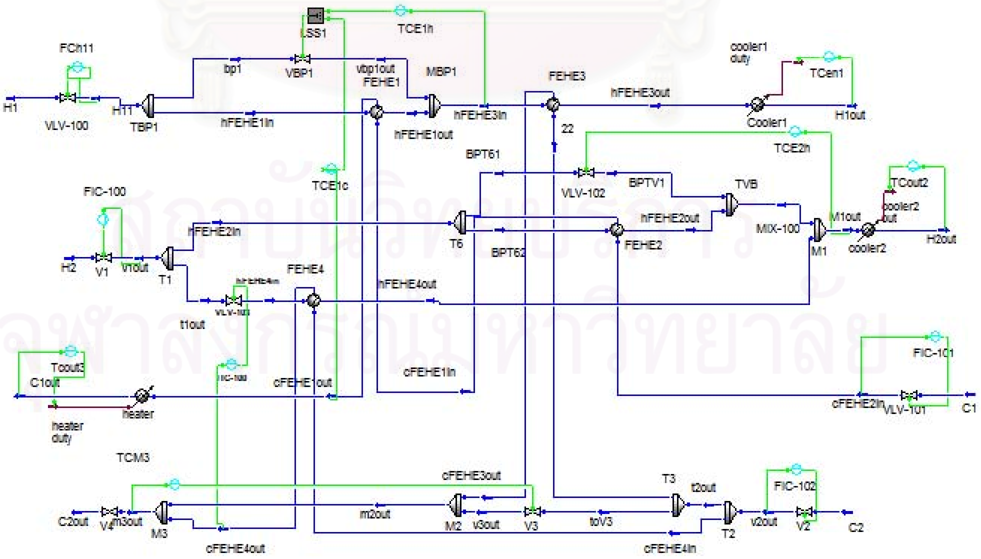


Figure 4.29 HEN from HYSYS flow sheet of example 4.2 HEN from HYSYS

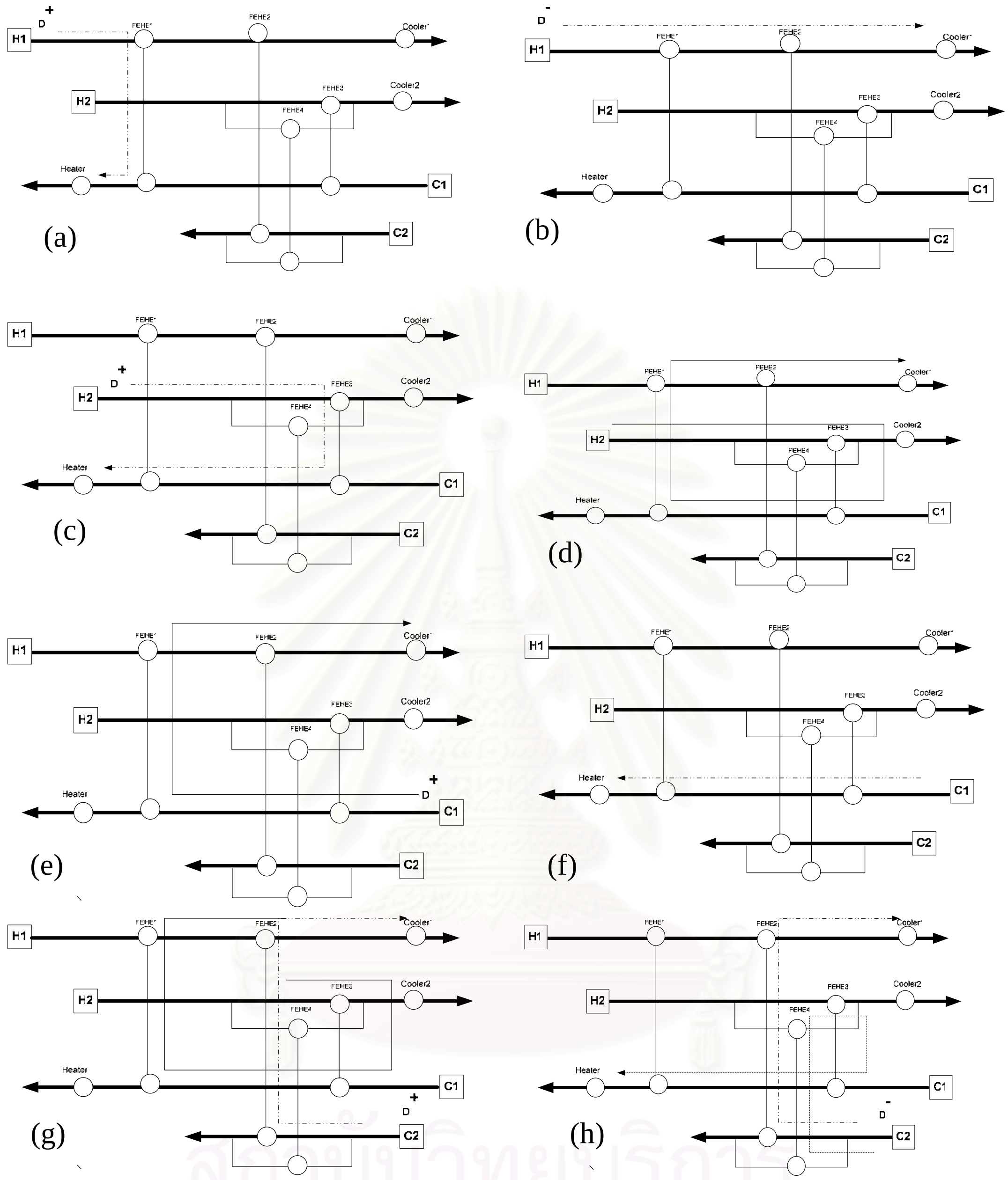
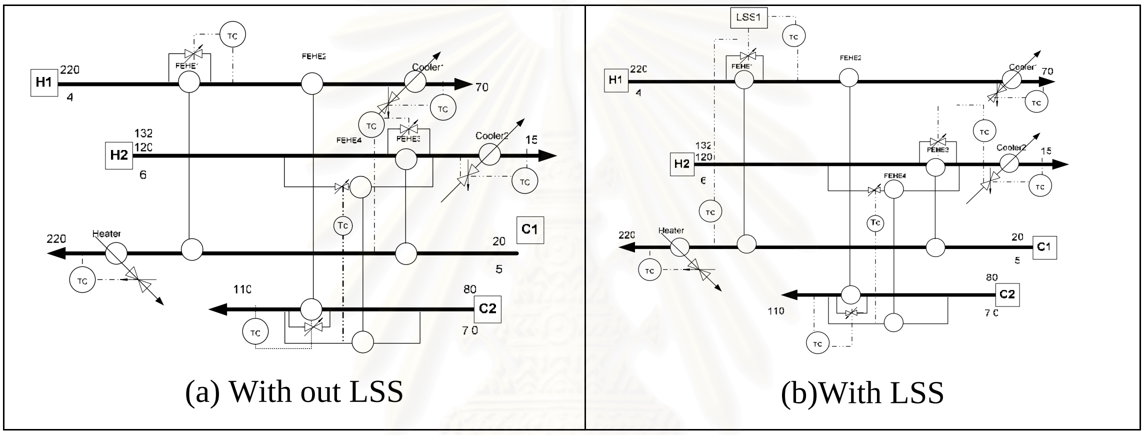


Figure 4.30 Heat pathway of control structure of network equipped with LSS of example 4.2. a) D$^+$ presented at H1, b) D$^-$ presented at H1, c) D$^+$ presented at H2, d) D$^-$ presented at H2, e) D$^+$ presented at C1 , f) D$^-$ presented at C2, g) D$^+$ presented at H1, h) D$^-$ presented at C2.

4.7.1 Dynamic Simulation Results for HEN in Example 4.2

In order to evaluate the dynamic behaviors of HEN in Example 4.1 and the control performance of LSS, the comparison between control structure with and without LSS (Figure 4.31a and b) is addressed. Then several disturbance loads is made (ie H1, H2, C1, C2), the dynamic responses of the control systems are shown in Figures 4.32 to 4.41 . Left side shows dynamic behavior of system without LLS. On the other hand, right side presents the dynamic behavior of the new control system using the LSS to select appropriate heat pathway through the network.



(a) With out LSS

(b)With LSS

Figure 4.31 Control structure of network equipped; (a) With out LSS, (b)With LSS

4.7.1.1 Change in the Disturbance Load of Hot Stream H1 Temperature for Example 4.2

Figure 4.32 and 4.33 show the dynamic responses of the HEN with and without LSS in example 4.2 to a change in the disturbance load of H1 .In order to make these disturbances, first the fresh feed H1 temperature decreases from 220^{o}C to 209^{o}C at time equals 50 minutes, and the temperature increases from 209^{o}C to 231^{o}C at time equals 200 minutes, then its temperature returns to its nominal value of 220°C at time equals 350 minutes. The dynamic responses of the control system with and without are shown in Figures 4.32 to 4.33.

As can be seen, first the hot stream inlet temperature (H1) decreases. This is negative disturbances. LSS1 will take an action to control the cold outlet temperature of FEHE1. This disturbances load is continued to FEHE2 and cooler. Therefore, the cooler1 duty will be decreases from 709.6 kW to 300.6 kW. Whenever D^+ is originated from stream H1, LSS1 will switch the control action to control the hot outlet temperature of FEHE1. As a result the heater duty will be decreased to 2430 kW, (Figure 4.33(h)).

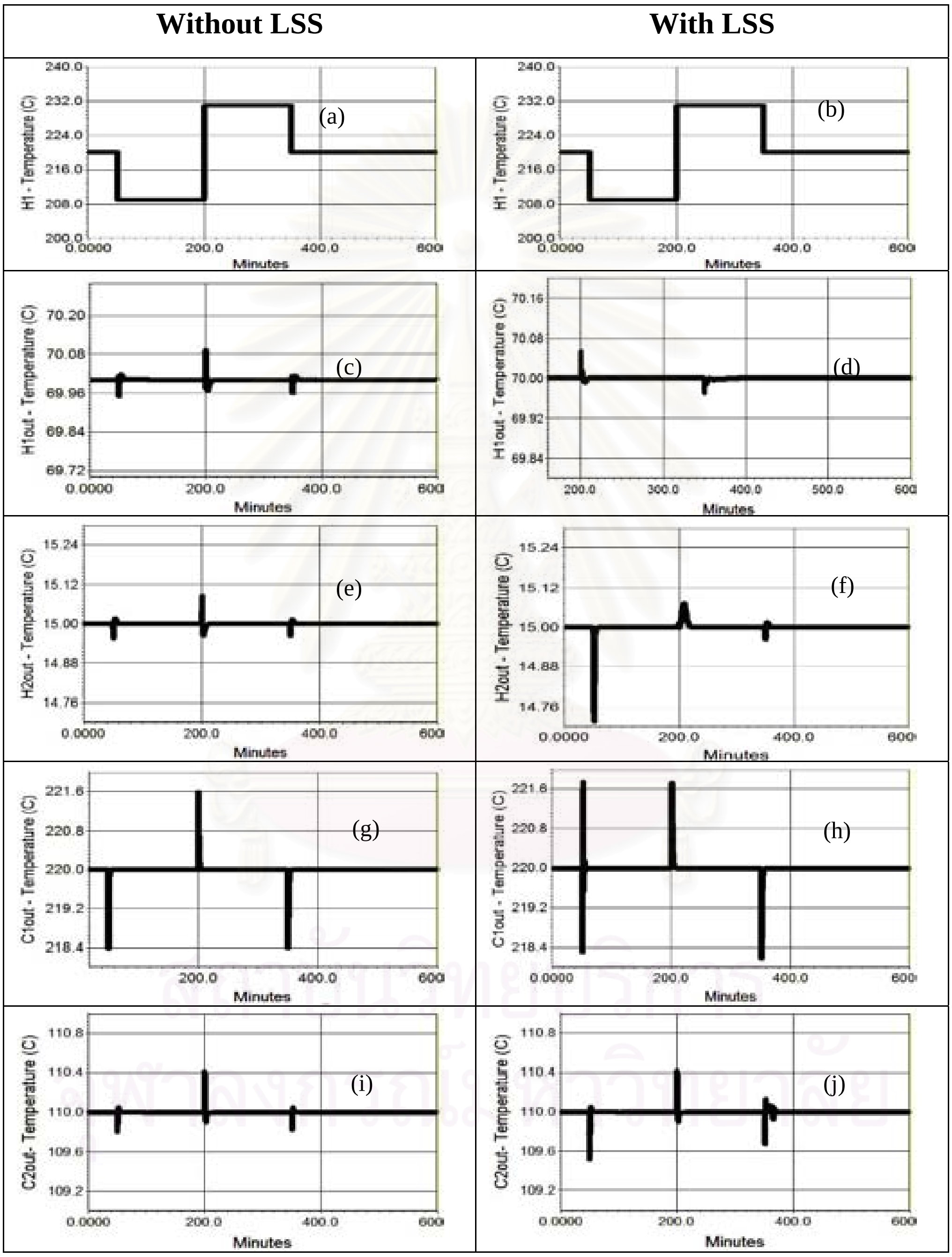


Figure 4.32 Dynamic responses of streams of HEN in Example 4.2 to a change in the disturbance load of H1.

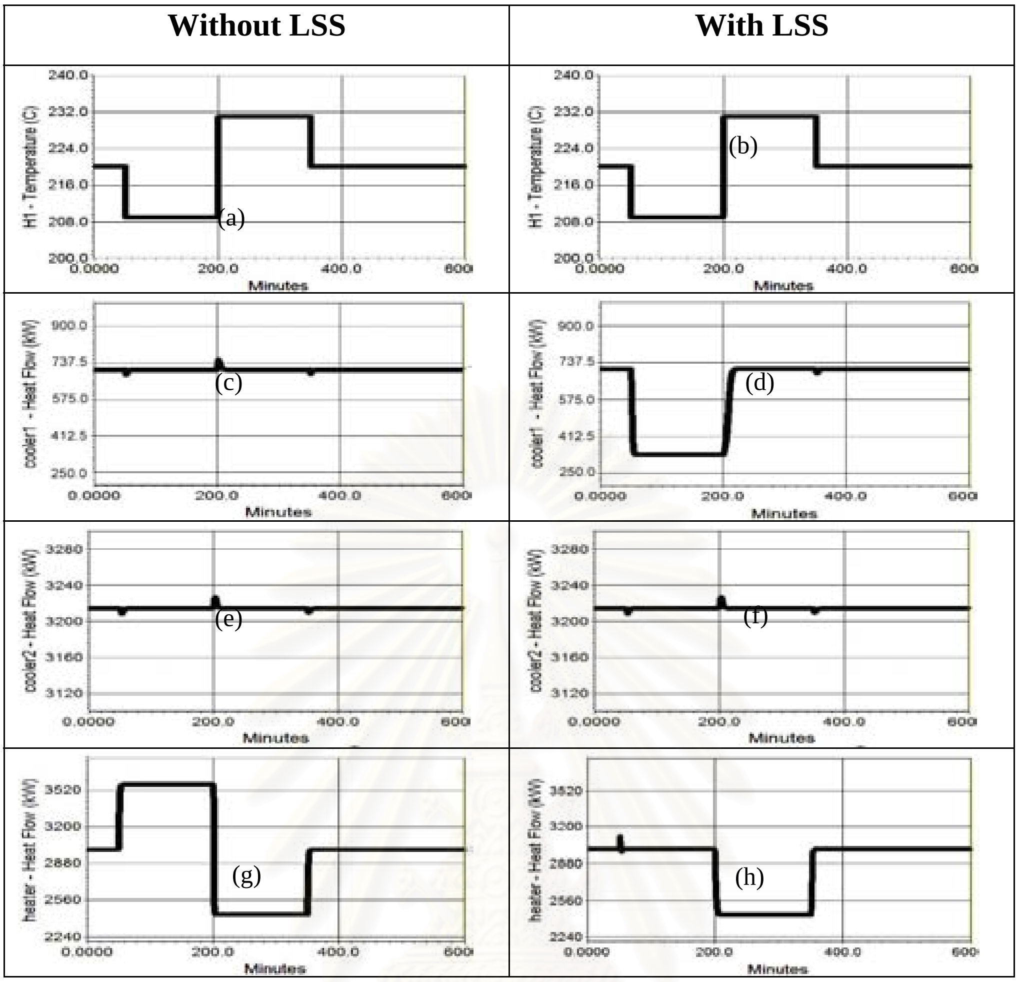


Figure 4.33 Dynamic responses of duty for HEN in Example 4.2 to a change in the disturbance load of H1.

4.7.1.2 Change in the Disturbance Load of Hot Stream H2 Temperature for Example 4.2

Figure 4.34 and 4.35 show the dynamic responses of the HEN with and without LSS in example 4.2 to a change in the disturbance load of H2 .In order to make these disturbances, first the H2 temperature decreases from 120 ^{o}C to 111.5^{o}C at time equals 50 minutes, and the temperature increases from 111.5^{o}C to 128.5 ^{o}C at time equals 200 minutes, then its temperature returns to its nominal value of 120°C at time equals 350 minutes. The dynamic responses of the control system with and without LLS are shown in Figures 4.34 and 4.35.

Without LSS	With LSS

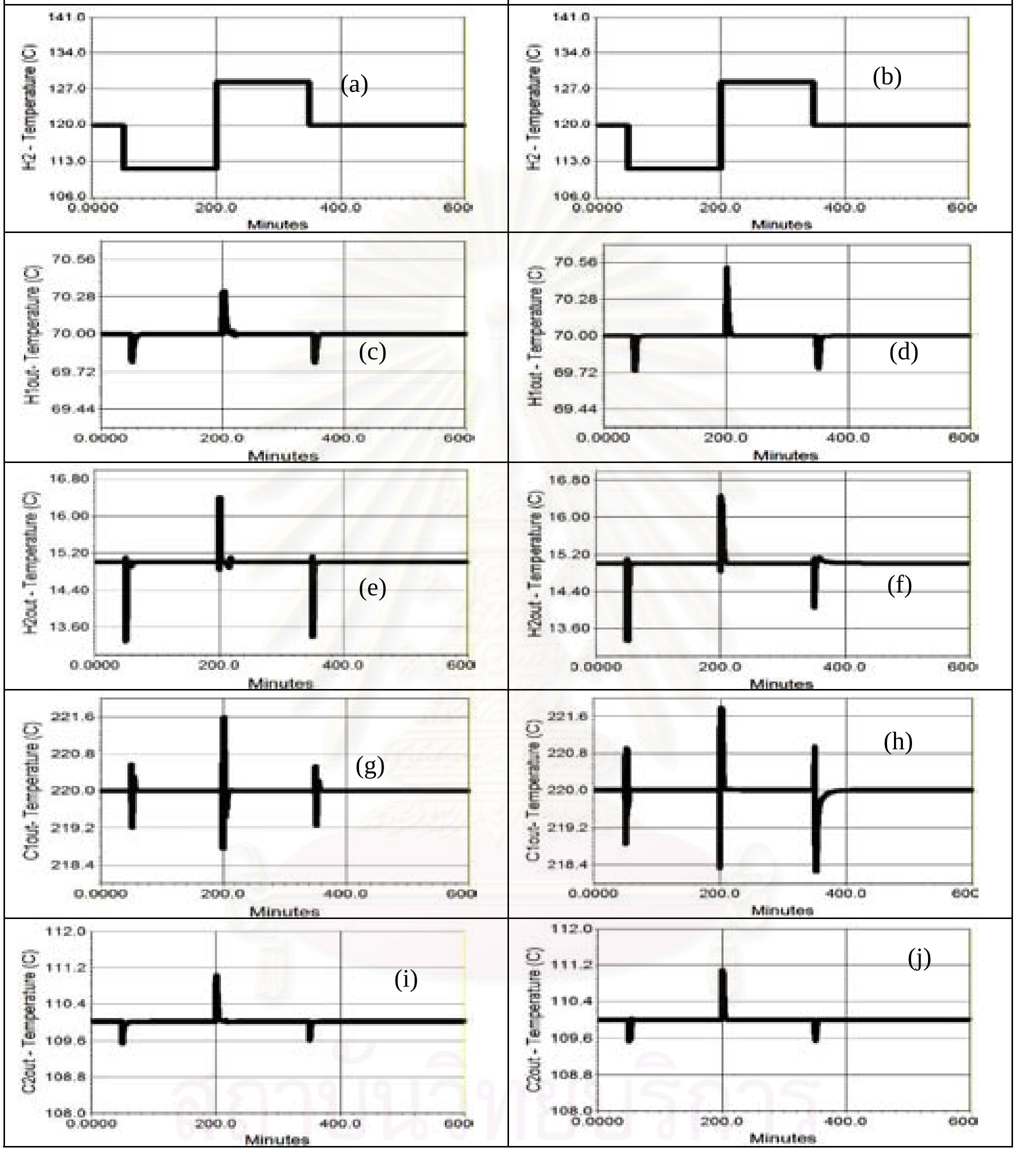


Figure 4.34 Dynamic responses of streams of HEN in Example 4.2 to a change in the disturbance load of H2.

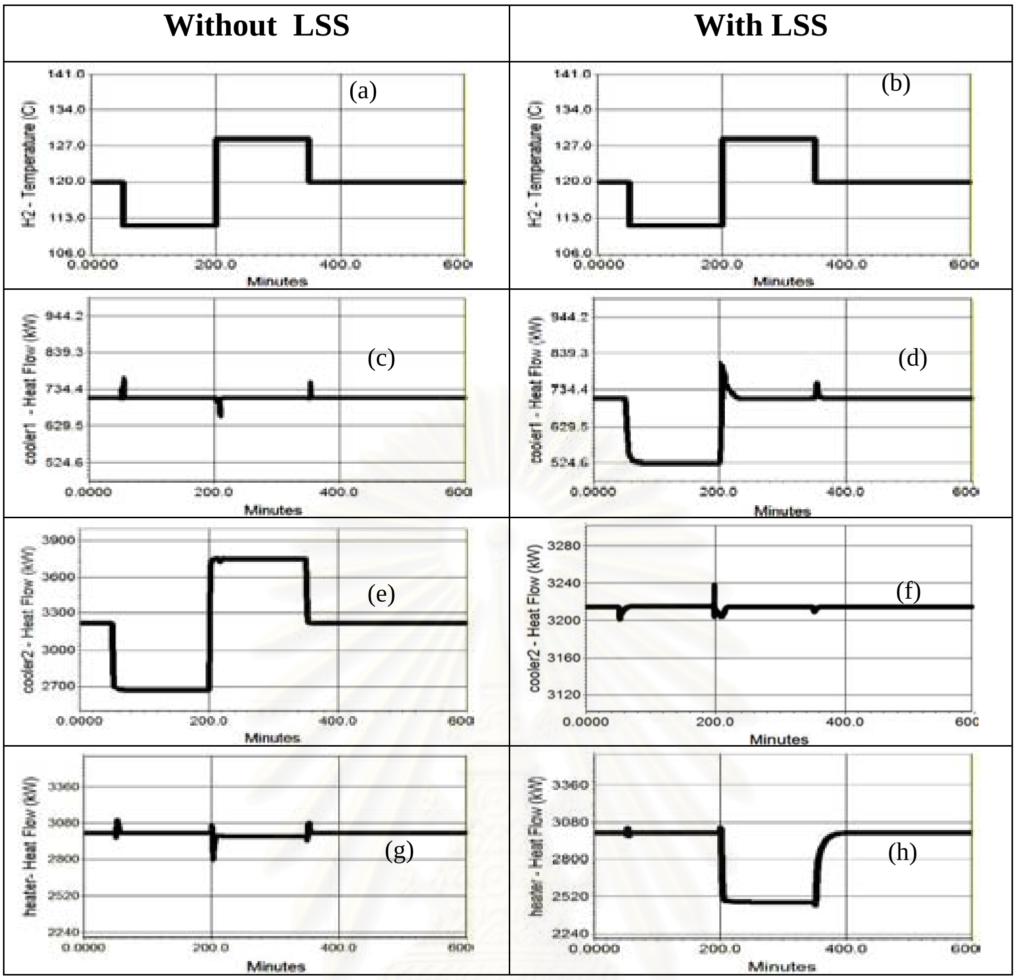


Figure 4.35 Dynamic responses of duty for HEN in Example 4.2 to a change in the disturbance load of H2.

As can be seen, first the hot stream inlet temperature (H2) decreases. The LSS takes an action to control the cold outlet temperature of FEHE3. Therefore, the cooler1 duty decreases from 709.6 kW to 524.8 kW. Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of FEHE1. The LSS1 will take action to hot outlet temperature of FEHE1. Hence, the Heater duty will be decreased from 3002 kW to 2476 kW (Figure 4.35(h)).

4.7.1.3 Change in the Disturbance Load of Hot Stream H2 Temperature for Example 4.2 Base on condition (Table 4.5).

Figure 4.36 and 4.37 show the dynamic responses of the HEN with and without LSS in example 4.2 to a change in the disturbance load of H2. In order to make these disturbances , first the fresh H2 temperature increases from 120^{o}C to 132^{o}C at time equals 50 minutes (pinch jump position), and the temperature increases from 132^{o}C to 170^{o}C at time equals 200 minutes, then its temperature returns to its nominal value of 120°C at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figures 4.36 to 4.37

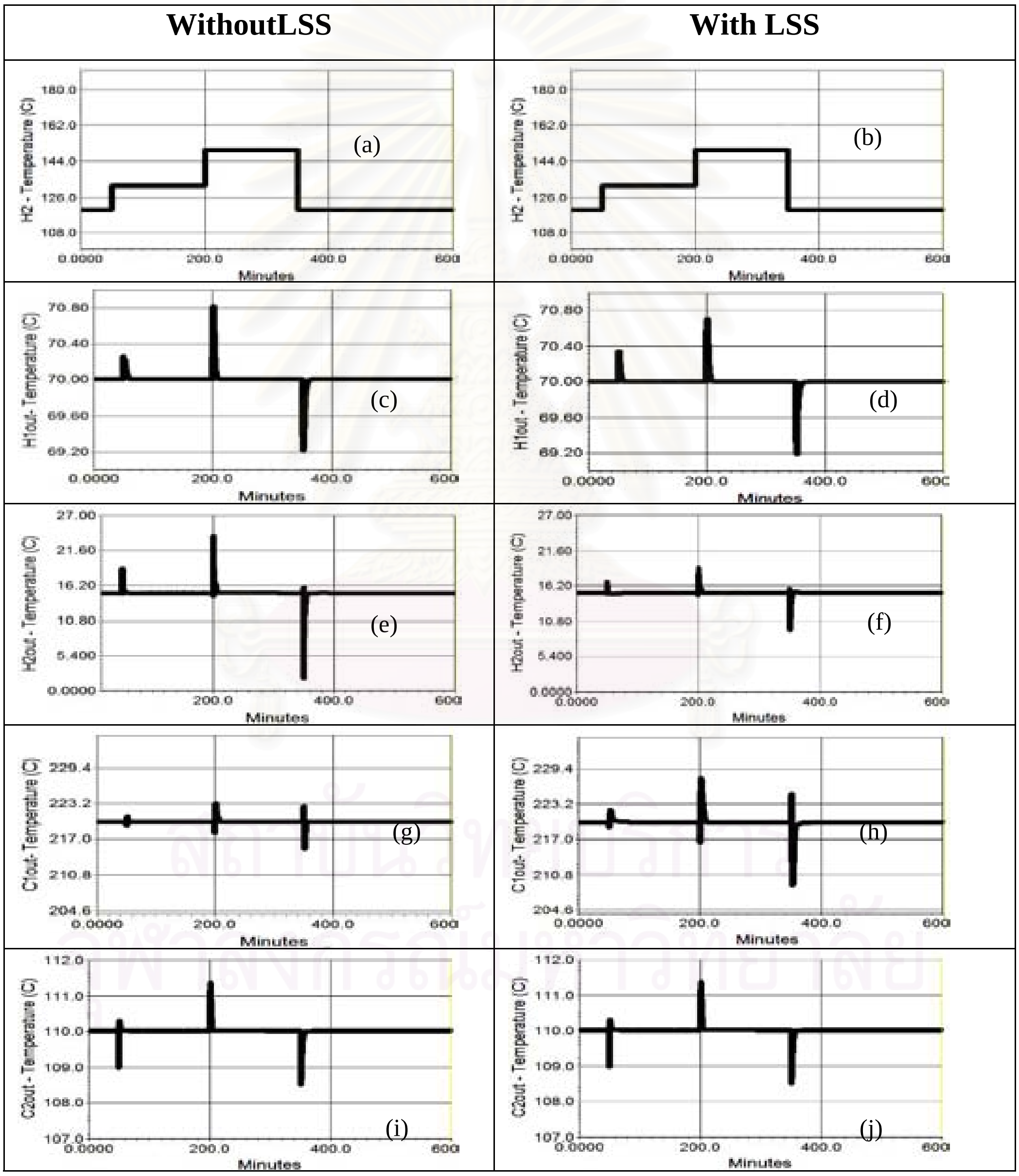


Figure 4.36 Dynamic responses of streams of HEN in Example 4.2 to a change in the disturbance load of H2.

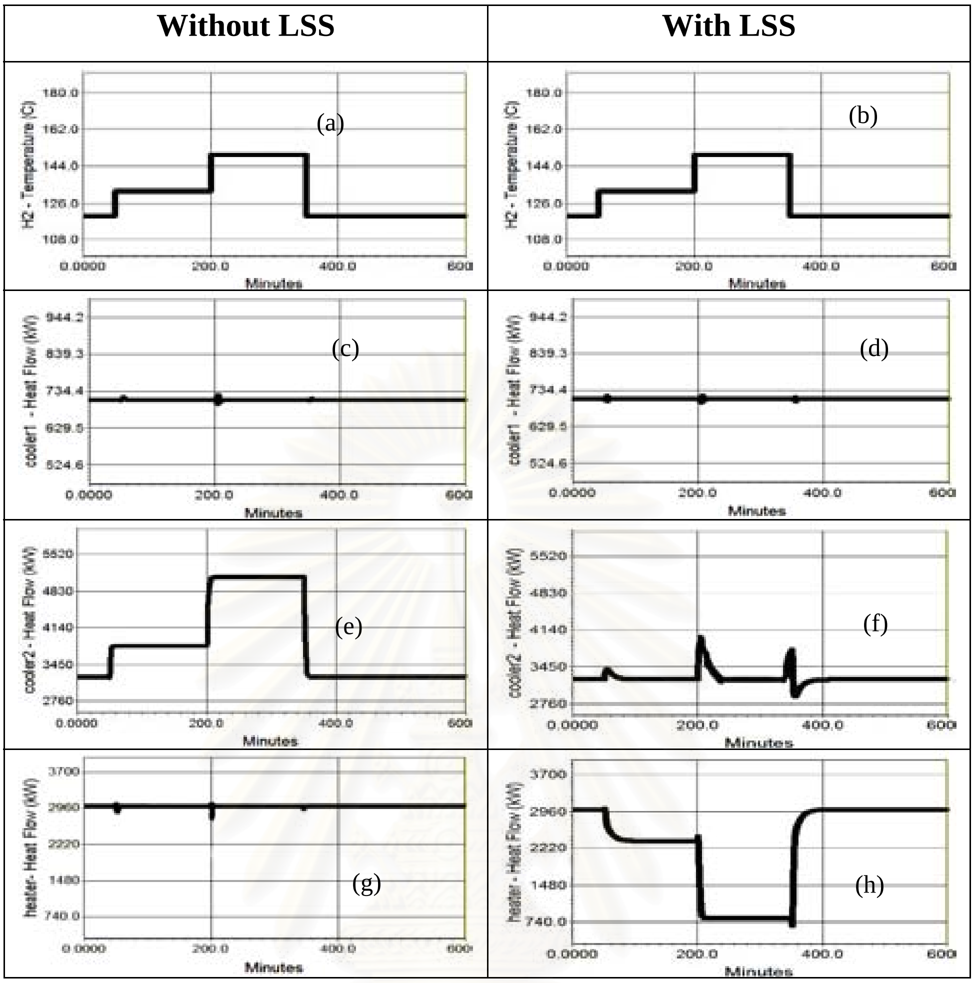


Figure 4.37 Dynamic responses of duty for HEN in Example 4.2 to a change in the disturbance load of H2.

As can be seen, first the hot stream inlet temperature (H2) increases to 132°C. As a result, the LSS1 takes an action to control the hot outlet temperature of FEHE1. The LSS1 will take an action to control the hot outlet temperature of FEHE1. Therefore, the heater duty decreases from 3002 kW to 2363.7 kW. Then, more positive disturbance load is entered. LSS1 still action to control the hot outlet temperature of FEHE1, the heater duty will be decreased from 2363.7 to 814 kW (Figure 4.37(h)).

4.7.1.4 Change in the Disturbance Load of Cold Stream C1 Temperature for Example 4.2

Figure 4.38 and 4.39 show the dynamic responses of the HEN with and without LSS in example 4.2 to a change in the disturbance load of C1 .In order to make these disturbances, first the C1 temperature decreases from 20^{o}C to 10^{o}C at time equals 50 minutes, and the temperature increases from 10^{o}C to 30^{o}C at time equals 200 minutes, then its temperature returns to its nominal value of 20°C at time equals 350 minutes.

When C1 temperature decreases. Namely, the positive disturbance load of cold stream should be shifted to a cooler utility. The LSS1 will take an action to control the cold outlet temperature of FEHE1. Therefore, the cooler 1 duty decreases from 709.6 kW to 223.6 kW (Figure 4.39(f)). Then the negative disturbance load of cold stream shifts to furnace utility by controlling the hot outlet temperature of FEHE1 with LSS1. As a result, the furnace duty decreases from 3002 kW to 2490 kW (Figure 4.39(h).

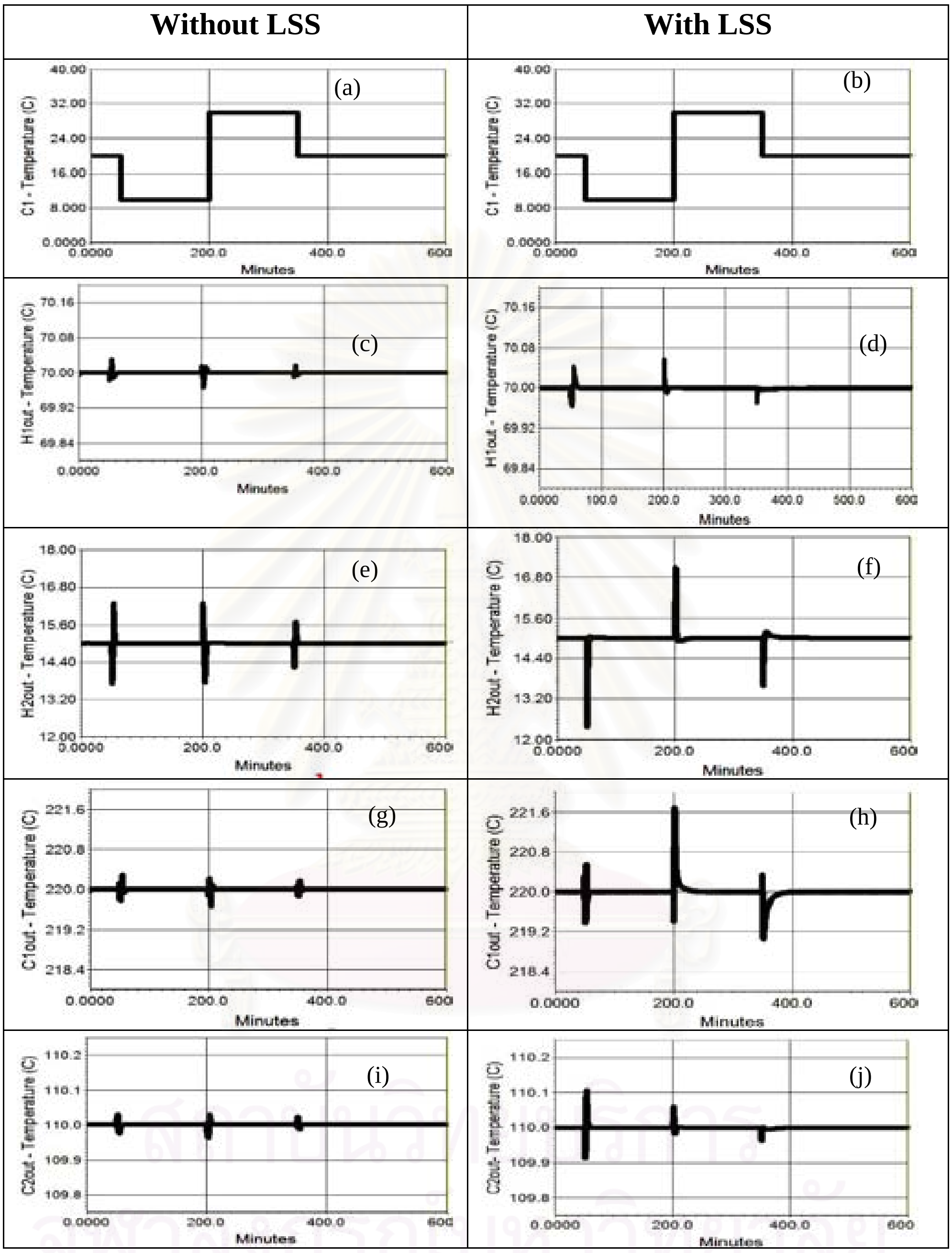


Figure 4.38 Dynamic responses of streams of HEN in Example 4.2 to a change in the disturbance load of C1.

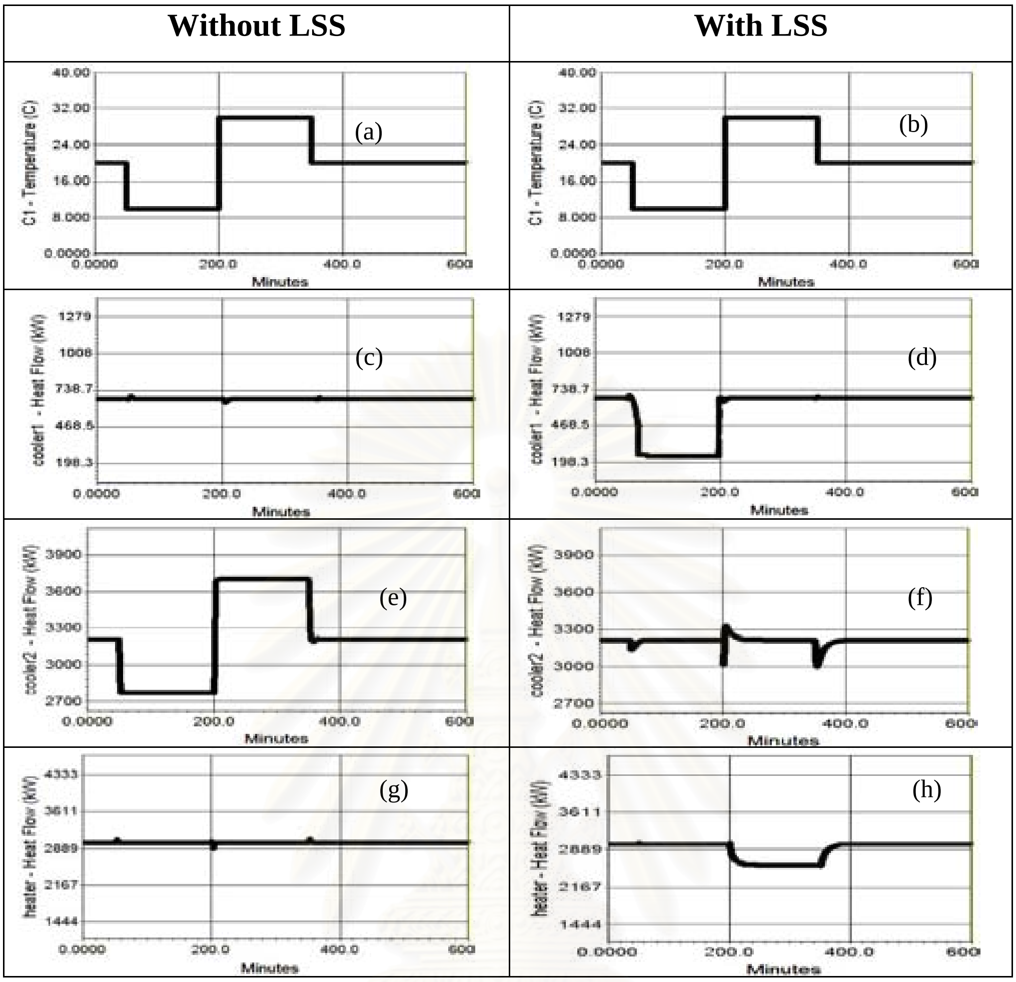


Figure 4.39 Dynamic responses of duty for HEN in Example 4.2 to a change in the disturbance load of C1.

4.7.1.5 Change in the Disturbance Load of Cold Stream C2 Temperature for Example 4.2

Figure 4.40 and 4.41 show the dynamic responses of the HEN with and without LSS in example 4.2 to a change in the disturbance load of C2 .In order to make these disturbances, first the fresh feed C2 temperature decreases from 80^{o}C to 72.5^{o}C at time equals 50 minutes, and the temperature increases from 72.5^{o}C to 87.5^{o}C at time equals 200 minutes, then its temperature returns to its nominal value of 80°C at time equals 350 minutes. The dynamic responses of the control system with and without LLS are shown in Figures 4.40to 441.

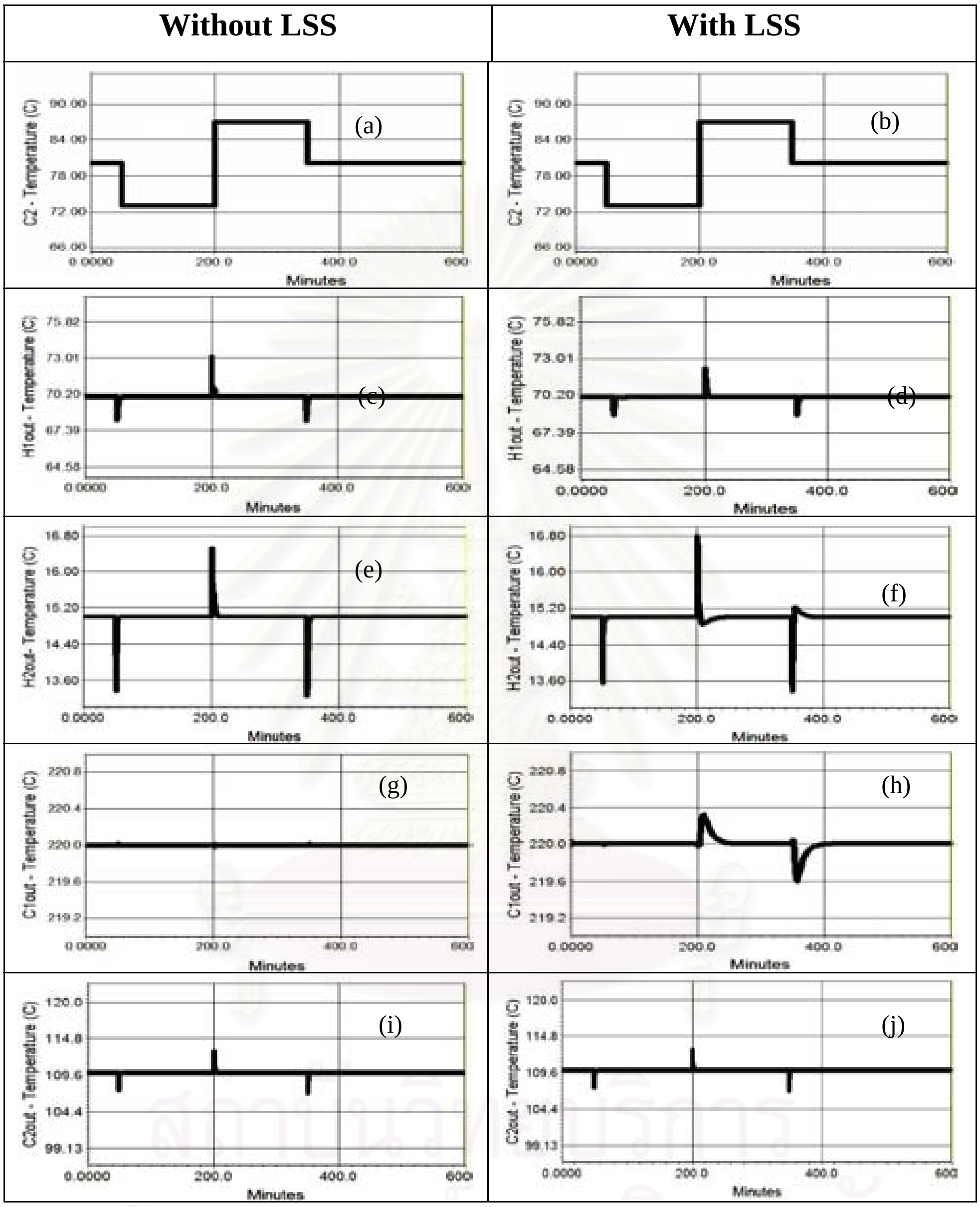


Figure 4.40 Dynamic responses of streams of HEN in Example 4.2 to a change in the disturbance load of C2.

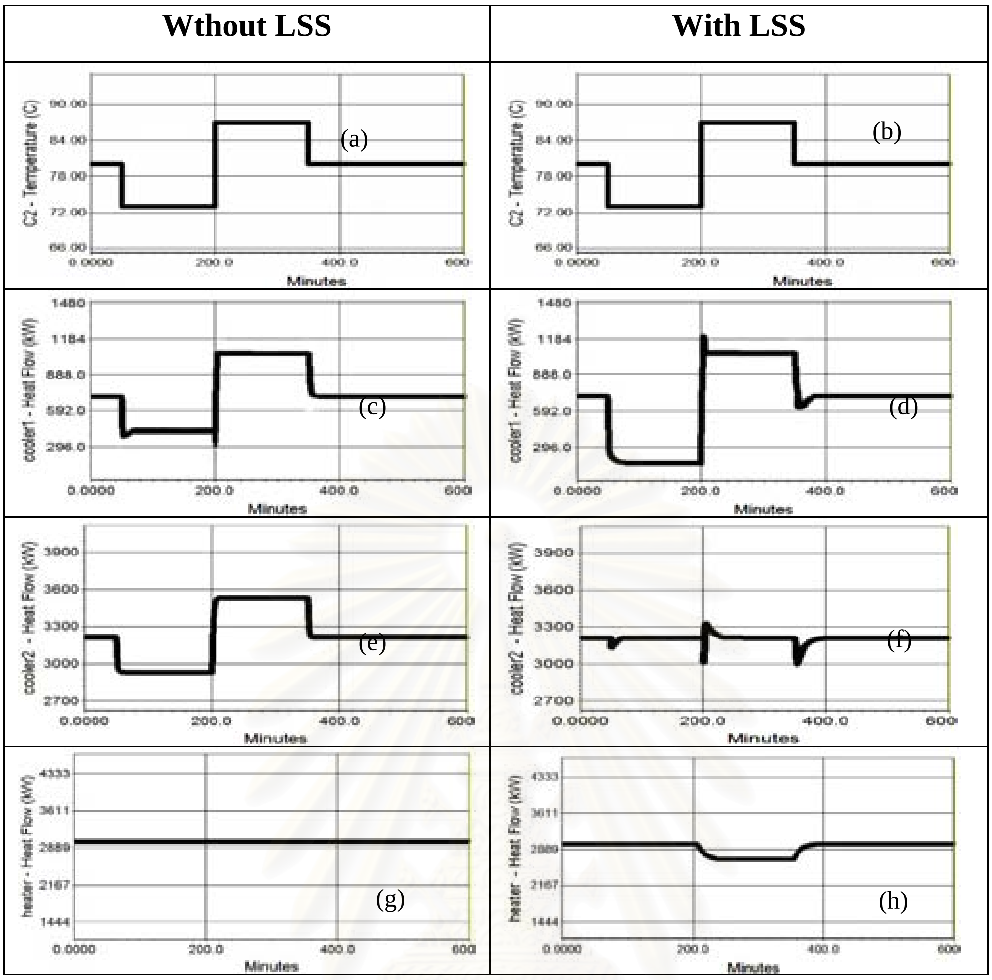


Figure 4.41 Dynamic responses of duty for HEN in Example 4.2 to a change in the disturbance load of C2.

When C2 temperature decreases resulted in decrease of the hot outlet temperature of FEHE1. The LSS1 will take an action to control the cold outlet temperature of FEHE1. The positive disturbance load of cold stream should be shifted to a cooler utility. Therefore, the cooler 1 duty decreases from 709.6 kW to 149.2 kW (Figure 4.41f). Then the negative disturbance load of cold stream shifts to furnace utility by controlling the hot outlet temperature of FEHE1 with LSS1. As a result, the furnace duty decreases from 3002 kW to 2785.1 kW (Figure 4.41h).

Table 4.9 Comparison of the energy consumption of control structure with and without LSS in the case of Example 4.2 (temperature changed).

Stream	**Type of Disturbances**	**Cooler1 Utility, kW**		**Cooler2 Utility, kW**		**Heater Utility, kW**	
Temperature Variation		Without LSS	With LSS	Without LSS	With LSS	Without LSS	With LSS
H1							
	D$^-$	709.6	300.6	3214	3214	3566.6	3002
	D$^+$	709.6	709.6	3214	3214	2430	2430
H2							
	D$^-$	709.6	524.8	2669	3214	3002	3002
	D$^+$	709.6	709.6	3749.9	3214	3002	2476
	At H2=132	709.6	709.6	3801	3214	3002	2363.7
	At H2=150	709.6	709.6	5099	3002	1880	814
C1							
	D$^-$	709.6	709.6	3701	3214	3002	2490
	D$^+$	709.6	223.6	2776.3	3214	3002	3002
C2							
	D$^-$	950	950	3527	3214	3002	2785.1
	D$^+$	339.2	149.2	2932	3214	3002	3002

From the result it is found that using LSS is likely an effective way to handle with disturbance come along with class 2 problem in case of temperature variation cause pinch jump. It brings about control structure of HEN that give dynamic maximum energy recovery.

4.8 Example 4.3: Class II problem (Flow Rate Variation Cause Pinch Jump)

In the following example, a stream H2 its heat capacity flow rate vary from 2-4 kJ/°C·min. The stream data are shown in Table 4.10. At the heat capacity flow rate of H2 of 2 kJ/°C·min, the network at pinch 70/60 °C. (see Table 4.11). When heat capacity goes up to 2.4625 kJ/°C·min. The new pinch is locate at 150/140 °C.
(see Table 4.12)

Table 4.10 Data for pinch temperature calculating.

Stream No.	Stream type	Start temperature (Ts),^{o}C	Target Temperature (Tt),^{o}C	Heat capacity flow rate (CP), kJ/^{o}C·min	
				Max	Min
1	Hot	180	20	-	2
2	Hot	150	40	4	2
3	Cold	60	220	-	3
4	Cold	30	105	-	2.6

From Table 4.5, it can be applied to the problem table (see Table 4.11 to 4.13).

Table 4.11 Problem Table for Example 4.3.

W				T hot	T cold	ΣW	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	(°C)	(°C)	(kW/°C)	(°C)	(kW)	(kW)	(kW)
0	0	-3	0	220	210					187
2	0	-3	0	180	170	-3	0	-120	-120	67
2	2	-3	0	150	140	-1	0	-30	-150	37
2	2	-3	-2.6	115	105	1	0	35	-115	72
2	2	0	-2.6	70	60	-1.6	-2.6	-72	-187	0
2	0	0	0	40	30	1.4	-2.6	42	-145	42
0	0	0	0	20	10	2	0	40	-105	82

It is obvious that when the heat capacity flow rate (CP) is 2 kJ/^{o}C·min, the pinch temperature is located at 70/60.

Table 4.12 problem table for W=2.4625.

W				T hot	T cold	ΣW	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	(°C)	(°C)	(kW/°C)	(°C)	(kW)	(kW)	(kW)
0	0	-3	0	220	210					150
2	0	-3	0	180	170	-3	40	-120	-120	30
2	2.49	-3	0	150	140	-1	30	-30	-150	0
2	2.49	-3	-2.6	115	105	1.49	35	52.15	-97.85	52.15
2	2.49	0	-2.6	70	60	-1.11	45	-49.95	-147.8	2.2
2	0	0	0	40	30	1.89	30	56.7	-91.1	58.9
0	0	0	0	20	10	2	20	40	-51.1	98.9

It is apparent that when the heat capacity flow rate (CP) increases from 2 to 2.4625 kJ/^{o}C·min, the pinch temperature is jumped to 150/140.

Table 4.13 problem table for W=4.

W				T hot	T cold	ΣW	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	(°C)	(°C)	(kW/ °C)	(°C)	(kW)	(kW)	(kW)
0	0	-3	0	220	210					150
2	0	-3	0	180	170	-3	40	-120	-120	30
2	4	-3	0	150	140	-1	30	-30	-150	0
2	4	-3	-2.6	115	105	3	35	105	-45	105
2	4	0	-2.6	70	60	0.4	45	18	-27	123
2	0	0	0	40	30	3.4	30	102	75	225
0	0	0	0	20	10	2	20	40	115	265

It is obvious that when the heat capacity flow rate (CP) is 4 kJ/^{o}C·min, the pinch temperature is located at 150/140.

Wongsri(1990) used heuristic approaches involving disturbance propagation method and match patterns to design network. The final match structure of this problem is shown in Figure 4.42.

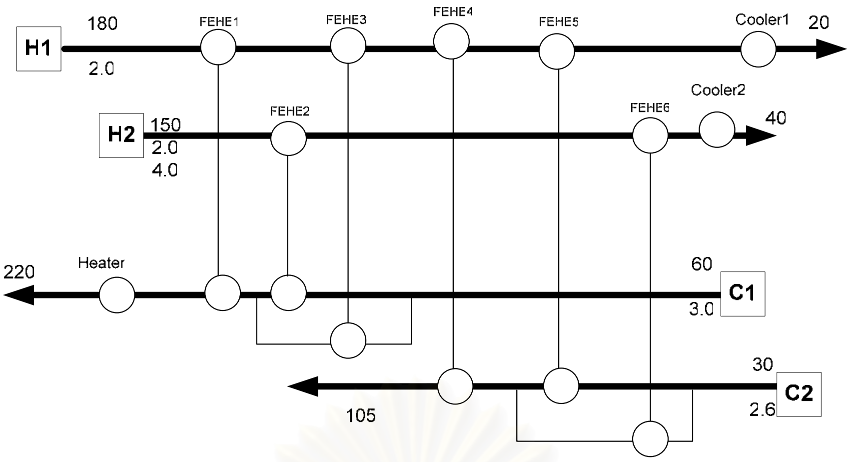


Figure 4.42 Resilient network structure for Example 4.3.

From the procedure in 4.5, it can be used to design control structure as follows:

Step 1.

As can be seen from **Figure** 4.43, there are four possible heat links. However, at the end of heat link of 2 and 3 are target temperature without utility supported. It should, therefore, be considered to set LSS at the former unit which is the same link as heat link 1 . So it means that there are three links similar. The number of LSS can be calculated from the following equation.

Number of LSS = 4-3+1=2

Therefore,LSS should be equipped with FEHE 1 and FEHE 2.

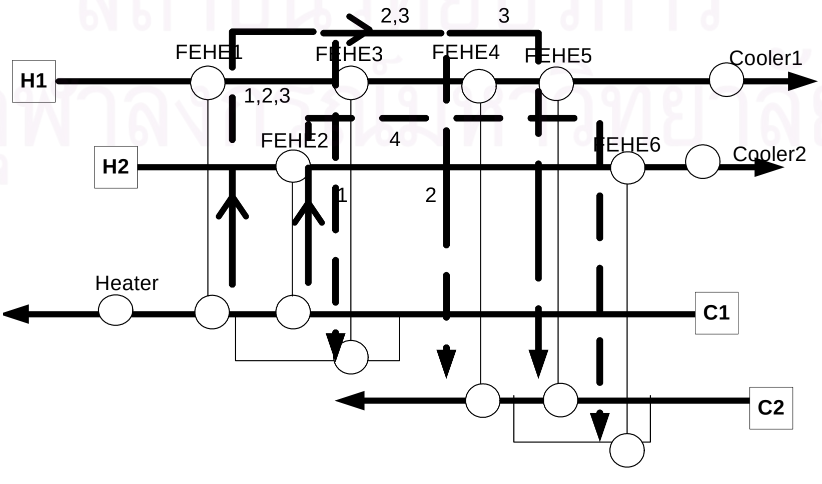


Figure 4.43 heat path way for example 4.3

Step 2. Set up LSS in the network

With considering at FEHE 2, bypass should be settled at cold C1 in order to use LSS to control outlet temperature of FEHE2 in both hot and cold stream which is the temperature of combination of splitting stream. In addition to FEHE1, by pass is equipped at hot stream and also LSS to control outlet temperature of both side (Figure 4.44)

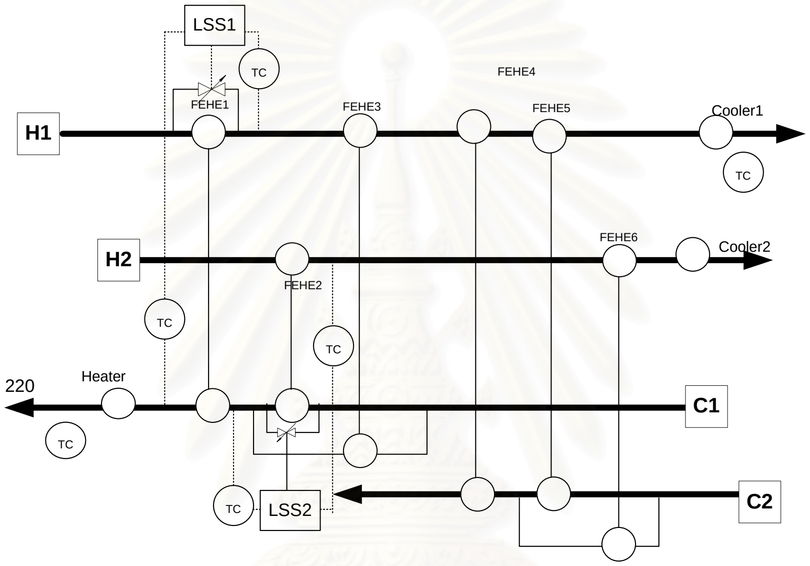


Figure 4.44 Set up LSS of example 4.3

Step 3. Design control structure with regard to the law of control structure design no. 1-15 as aforementioned in Chapter III. It is not necessary to consider the factor in consequence so the order can be changed to the appropriate condition.

To begin with determination of set up control loop at utility of any stream in order to maintain target temperature. Consider C2 stream which have to maintain target temperature without utility. At FEHE 4 heat is transferred to upstream. It is evident that there have a necessary to control outlet temperature of cold stream of FEHE 4 so bypass is selected to set at hot stream of FEHE 4 to control cold outlet temperature.

With considering at FEHE 5 and FEHE6, the temperature at this point is from the combination of splitting stream. From the fifteenth law it is claimed that bypass should be settled on heat exchanger which is spitted for control and because of this is class C problem so upstream should be used to transfer heat. Moreover, these two splitting stream is exchanged heat with another FEHE so heat can be transferred though these upstream. According to the tenth law, bypass and control loop should be settled at cold stream of FEHE 5 due to its higher heat transfer capacity.

The last one is FEHE3 should be used splitting ratio of C1 stream to control hot stream of FEHE3. Control structure and heat path way are shown in Figure 45 and Figure 47.

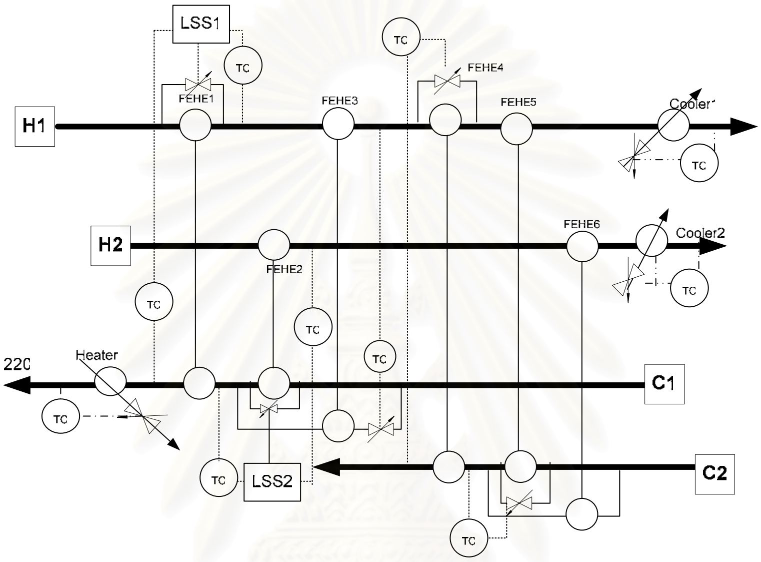


Figure 4.45 Control structure f network equipped with LSS of example 4.3

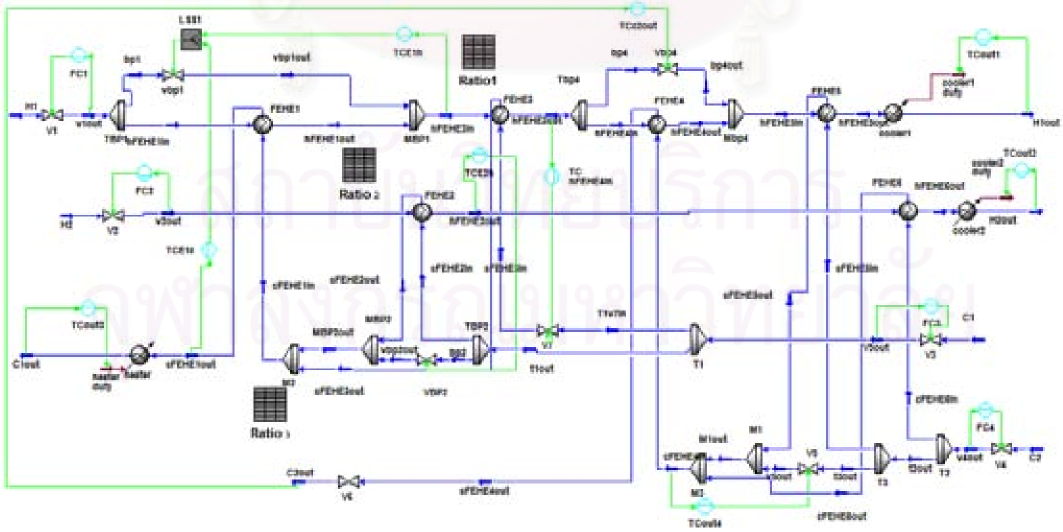


Figure 4.46 HYSYS flow sheet of HEN.

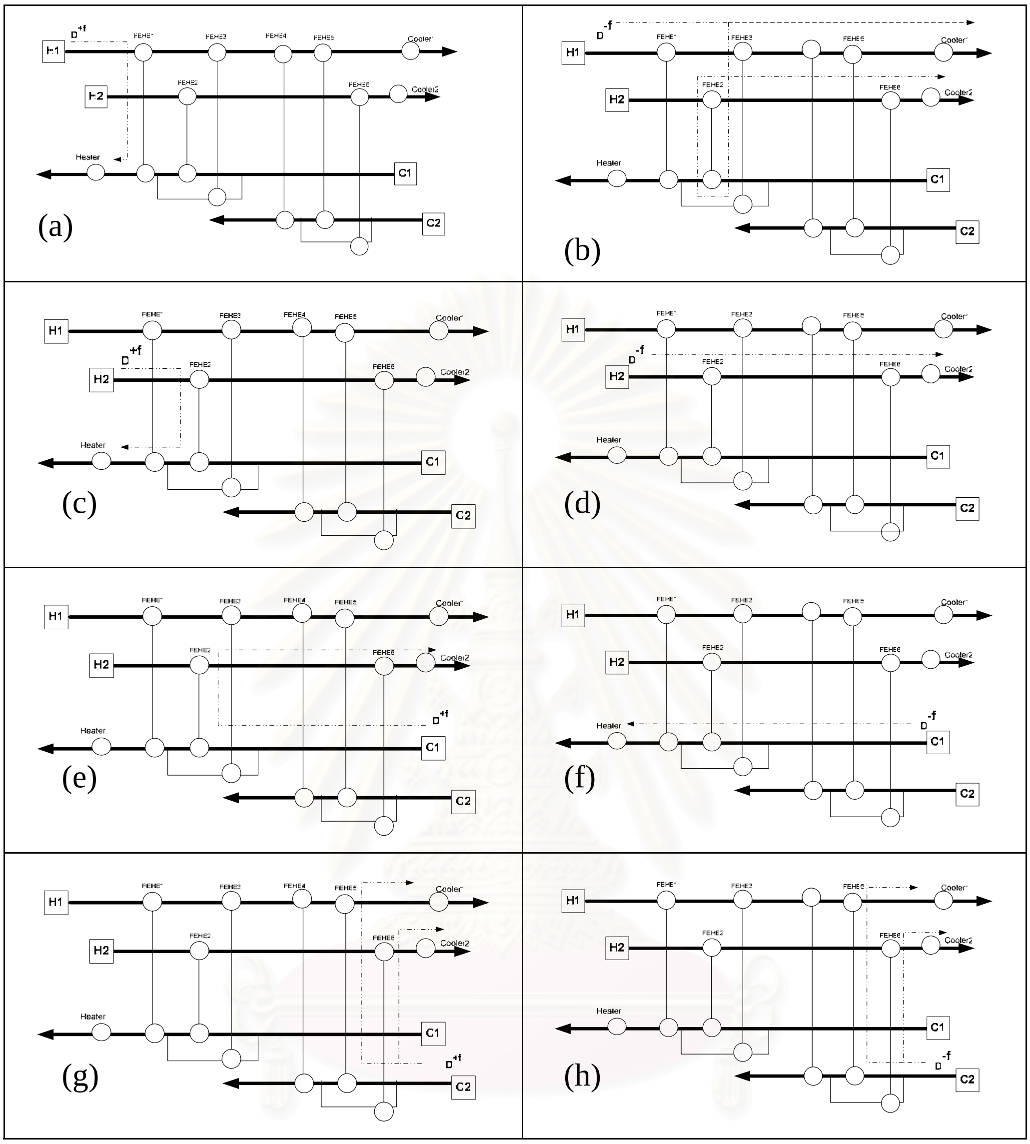
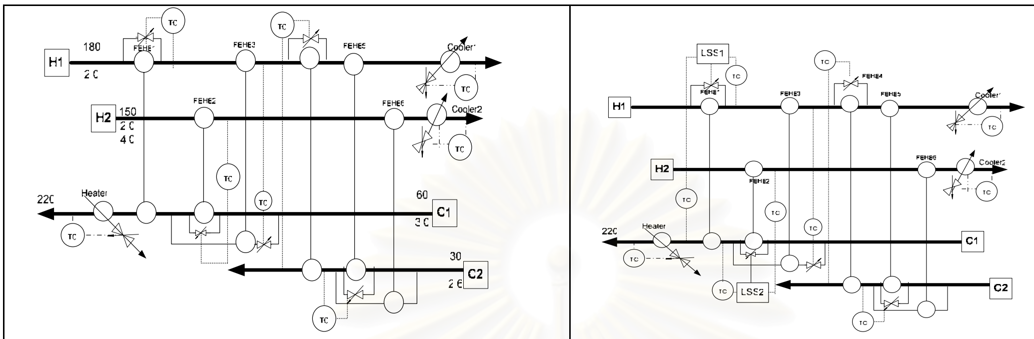


Figure 4.47 Heat path way for example 4.3.

4.8.1 Dynamic Simulation Results for HEN in Example 4.3

4.8.1 Dynamic Simulation Results for HEN in Example 4.3

In order to evaluate the dynamic behaviors of HEN in Example 4.3 and the control performance of LSS, the comparison between control structure with and without LSS (Figure 4.48a and b) is addressed. Then several disturbance loads is made (ie H1, H2, C1, C2), the dynamic responses of the control systems are shown in Figures 4.49 to 4.57. Left side shows dynamic behavior of system without LLS. On the other hand, right side presents the dynamic behavior of the new control system using the LSS to select appropriate heat pathway through the network.



(a)Without LSS

(b) With LSS

Figure 4.48 Control structure of network equipped; (a) With out LSS, (b)With LSS

4.8.1.1 Change in the Disturbance Load of Hot Stream H1 Flow Rate for Example 4.3

Figure 4.49 and 4.50 show the dynamic responses of the HEN with and without LSS in Example 4.3 to a change in the disturbance load of H1. In order to make these disturbances, first the fresh feed (i.e. H1 in Figure 4.49) flow rate decreases from 28.8 kgmol/h to 25.9 kgmol/h at time equals 50 minutes, and the flow rate increases from 25.9 kgmol/h to 31.7 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 28.8 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figure 4.49 and 4.50**.**

As can be seen, first the hot stream inlet flow rate (H1) decreases. That is to say negative disturbances, (D^-). As a result, the LSS1,LSS2 take an action to control the cold outlet temperature of FEHE1 and FEHE2. Therefore, the cooler1 duty decreases from 58.4 kW to 22.9 kW. Then, the positive disturbance load (D^+) of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of FEHE1 and FEHE2. The Heater duty will be decreased from 259.5 kW to 242.6 kW (Figure 4.50(h)).

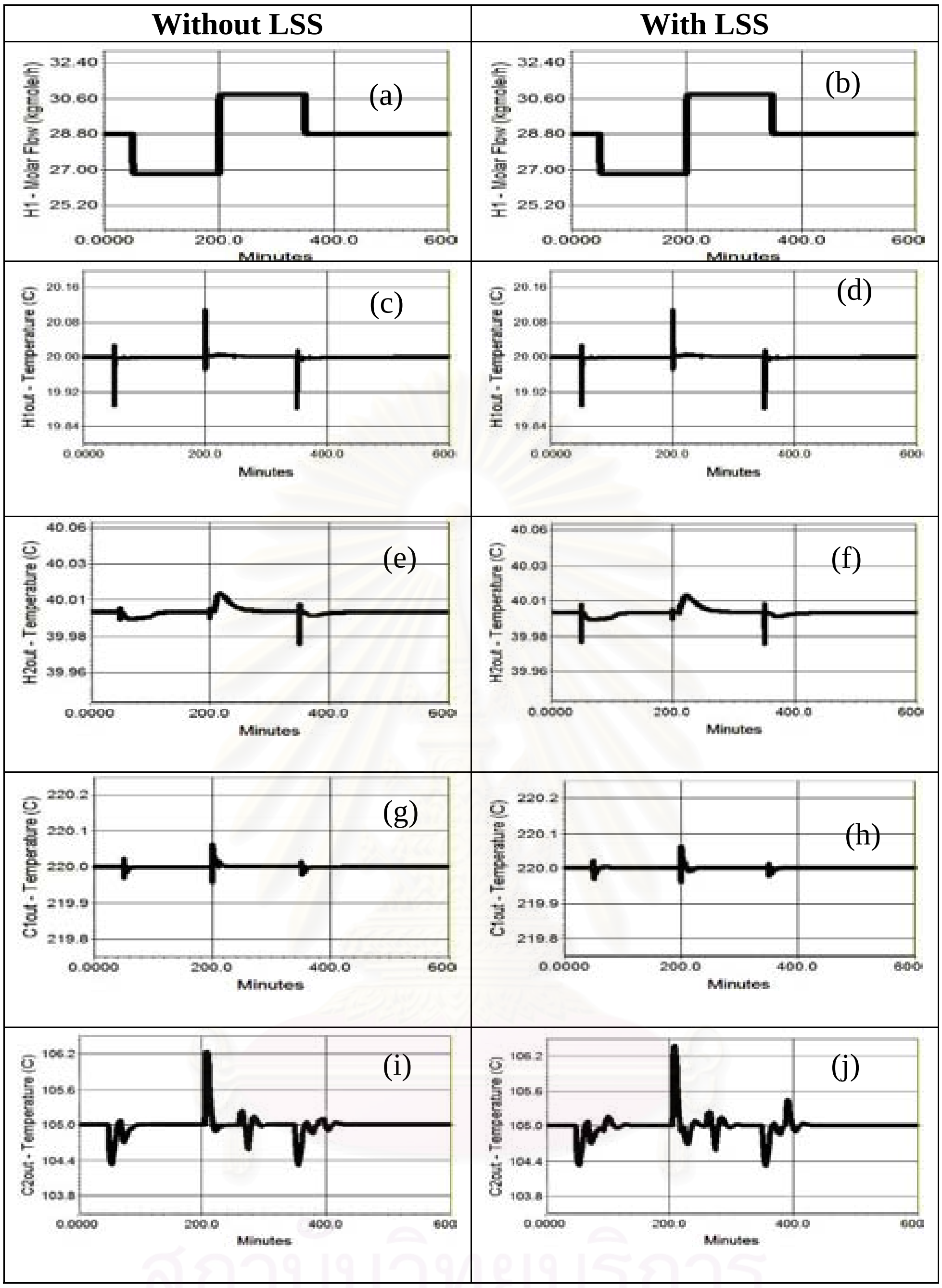


Figure 4.49 Dynamic responses of streams of HEN in Example3 to a change in the disturbance load of H1.

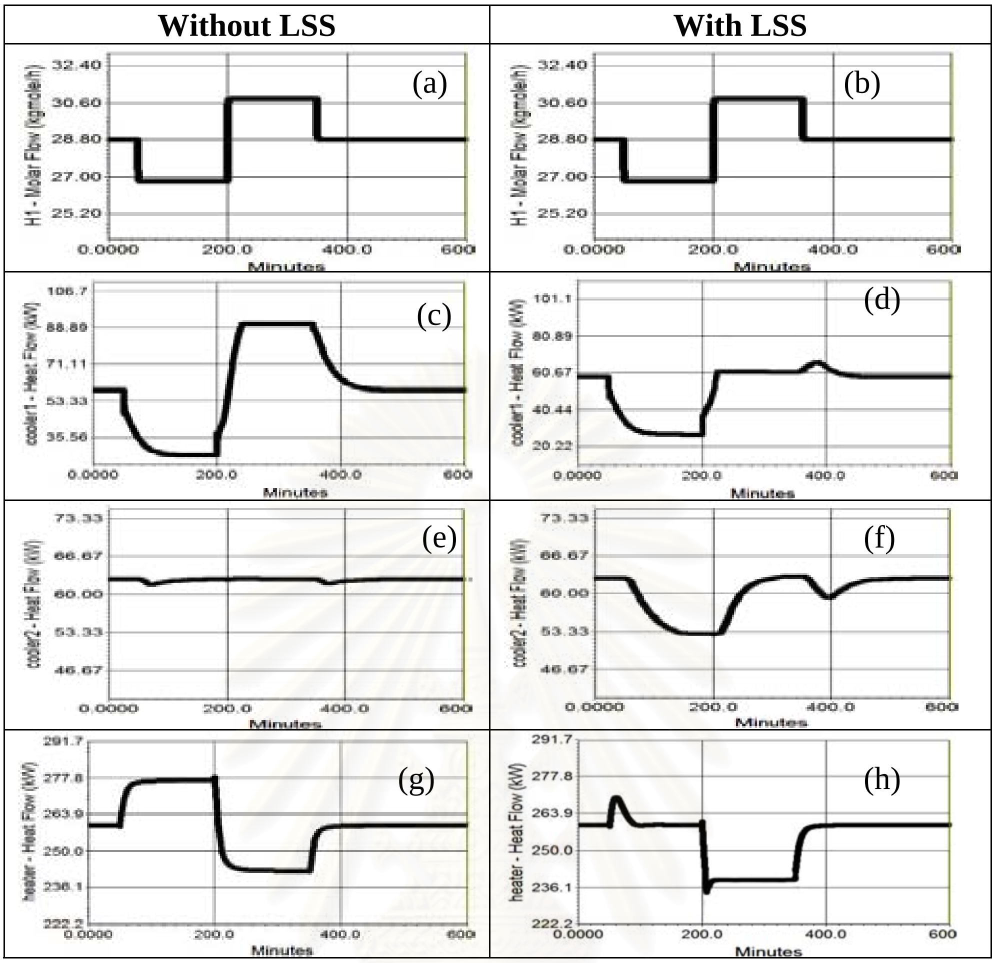


Figure 4.50 Dynamic responses of duty for HEN in Example 4.3 to a change in the disturbance load of H1.

4.8.1.2 Change in the Disturbance Load of Hot Stream H2 Flow Rate for Example 4.3

Figure 4.51 and 4.52 shows the dynamic responses of the HEN with and without LSS in Example 4.3 to a change in the disturbance load of H2. In order to make these disturbances, first the fresh feed (i.e. H2 in Figure 4.51) flow rate decreases from 25.2 kgmol/h to 22.7 kgmol/h at time equals 50 minutes, and the flow rate increases from 22.7 kgmol/h to 27.7 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 25.2 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figure 4.51 and 4.52.

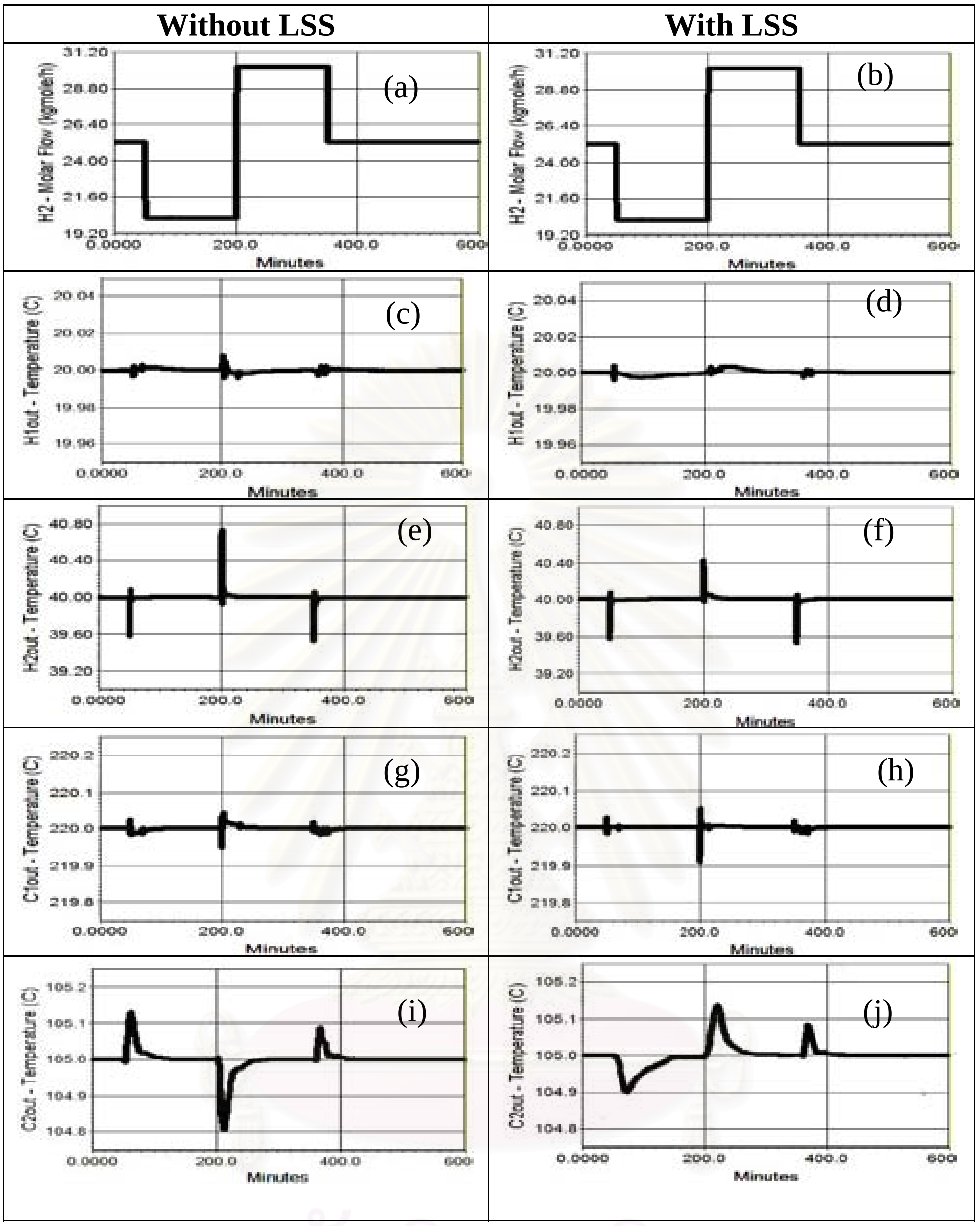


Figure 4.51 Dynamic responses of streams of HEN in Example 4.3 to a change in the disturbance load of H2.

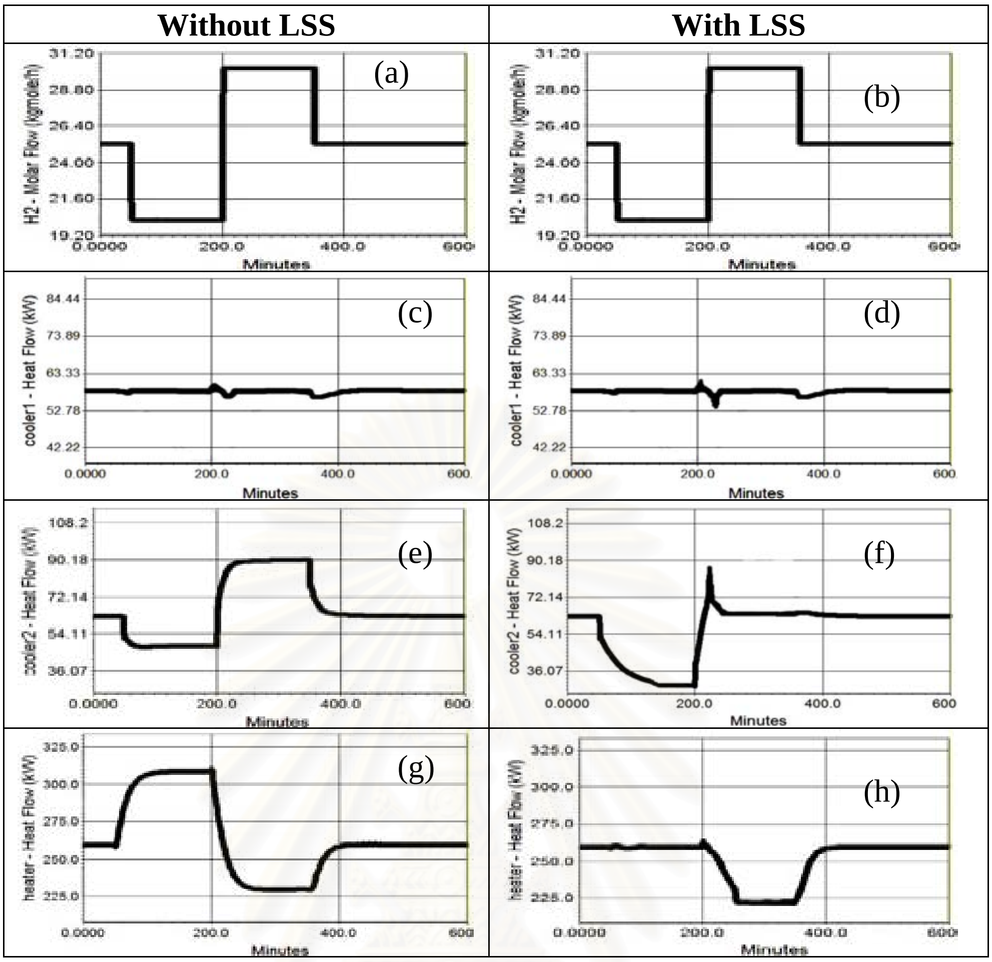


Figure 4.52 Dynamic responses of duty for HEN in Example 4.3 to a change in the disturbance load of H2.

As can be seen, first the hot stream inlet flow rate (H2) decreases. That is to say negative disturbances, (D^-). It should be shifted to a cooler utility. The LSS2 takes an action to control the mixed stream of cold outlet temperature of FEHE2.Therefore, the cooler 2 duty decreases from 62.7 kW to 29.1 kW. Then, the positive disturbance load of hot stream is shifted to a furnace utility by controlling the hot outlet temperature of FEHE2. Consequently, following Figure 4.10(c), the Heater duty will be decreased from 259.5 kW to 213.4kW (Figure 4.52(h)).

4.8.1.3 Change in the Disturbance Load of Hot Stream H2 Flow Rate for Example 4.3 base on condition

Figure 4.53 and 4.54 show the dynamic responses of the 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 fresh feed (i.e. C2 in Figure 4.66) flow rate decreases from 25.2 kgmol/h to 31.8 kgmol/h at time equals 50 minutes, and the flow rate increases from 31.8 kgmol/h to 50.4 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 25.2 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figure 4.53 and 4.54**.**

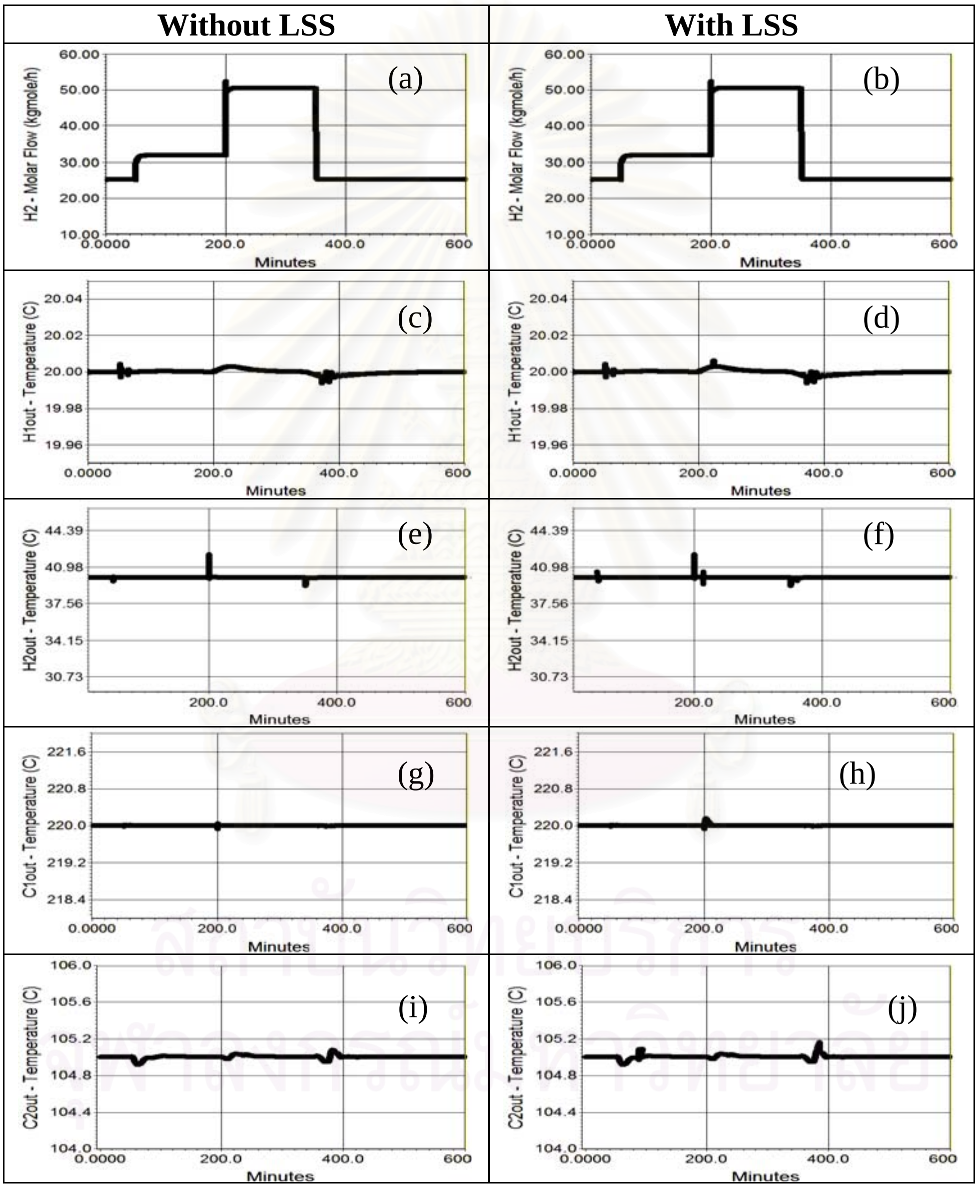


Figure 4.53 Dynamic responses of streams of HEN in Example 4.3 to a change in the disturbance load of H2(base on condition)..

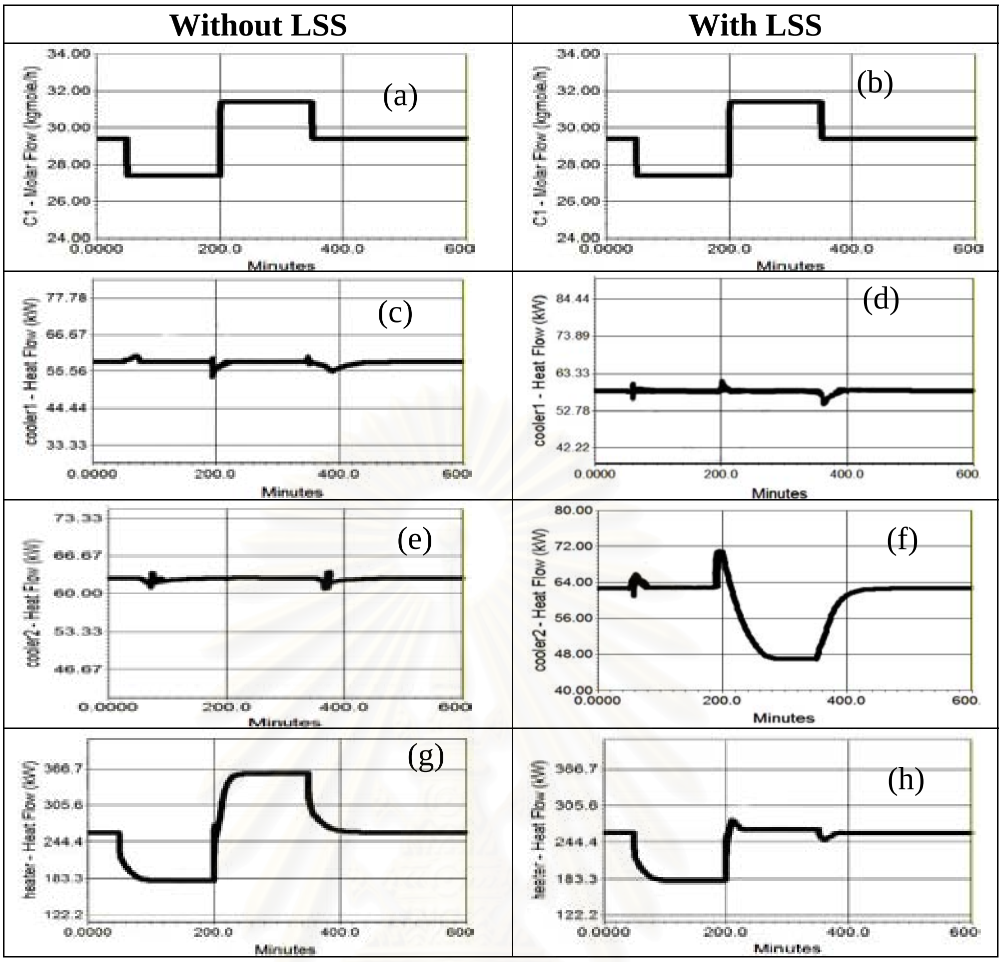


Figure 4.54 Dynamic responses of duty for HEN in Example 4.3 to a change in the disturbance load of H2(base on condition).

As can be seen, first the hot stream inlet flow rate (H2) is 31.8 kgmol/h. The LSS1, LSS2 take an action to control the hot outlet temperature. Therefore, the Heater duty will be decreased from 259.5 kW to 227.7 kW and cooler1 duty is 61.8 kW,cooler2 duty is 124.1. Then, the flow rate (H2) is 50.4 kgmol/h. As a result, Heater duty will be decreased from 227.7 kW to 224.5 kW.

4.8.1.4 Change in the Disturbance Load of Cold Stream C1 Flow Rate for Example 4.3

Figure 4.55 and 4.56 show the dynamic responses of the 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 fresh feed (i.e. C1 in Figure 4.55) flow rate decreases from 29.4 kgmol/h to 26.5 kgmol/h at time equals 50 minutes, and the flow rate increases from 26.5 kgmol/h to 32.3 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 29.4 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figure 4.55 and 4.56**.**

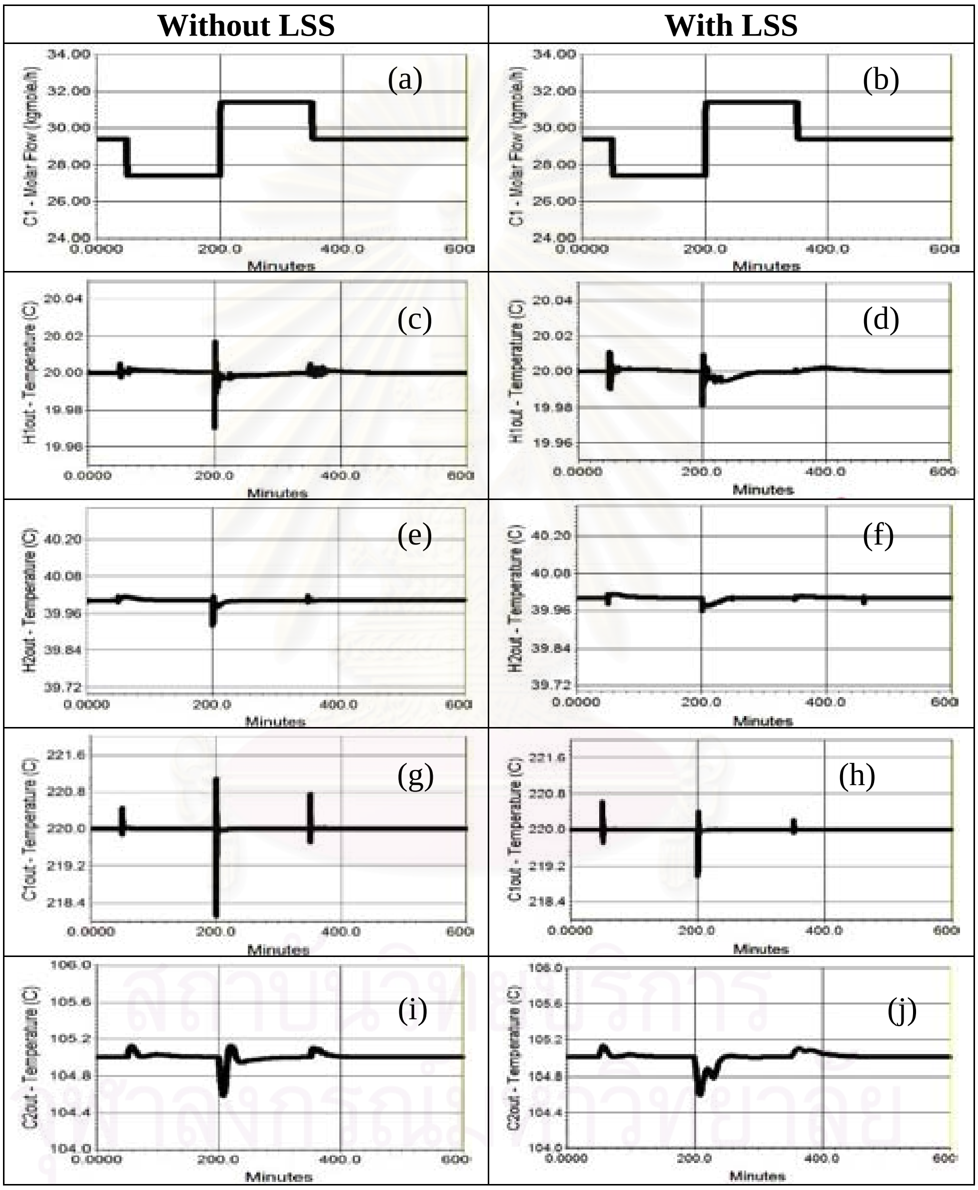


Figure 4.55 Dynamic responses of streams of HEN in Example 4.3 to a change in the disturbance load of C1.

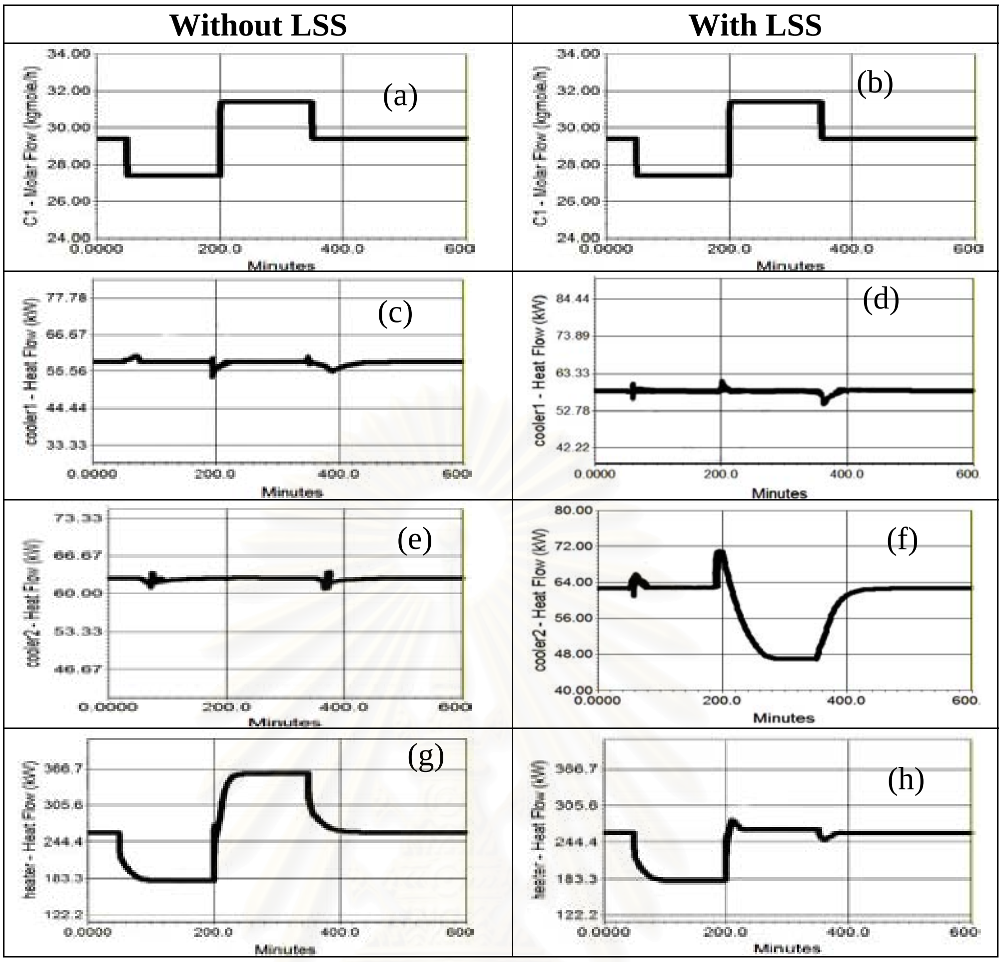


Figure 4.56 Dynamic responses of duty for HEN in Example 4.3 to a change in the disturbance load of C1.

As can be seen, first the cold stream inlet flow rate (C1) decreases. That is to say negative disturbances, (D^-). The LSS takes an action to control the hot outlet temperature of FEHE1 and FEHE2. Therefore, the Heater duty will be decreased from 259.4 kW to 180 kW. Then, the positive disturbance load, (D^+) of cold stream is shifted to a cold utility by controlling mixed stream of the cold outlet temperature of FEHE 2. the cold outlet temperature of FEHE1 and FEHE3. As a result, the cooler2 duty decreases from 61.8 kW to 49.3 kW (Figure 4.56(f)).

4.8.1.5 Change in the Disturbance Load of Cold Stream C2 Flow Rate for Example 4.3

Figure 4.57and 4.58 shows the dynamic responses of the 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 fresh feed (i.e. C2 in Figure 4.57) flow rate decreases from 39.5 kgmol/h to 35.5 kgmol/h at time equals 50 minutes, and the flow rate increases from 35.5 kgmol/h to 43.4 kgmol/h at time equals 200 minutes, then its flow rate returns to its nominal value of 39.5 kgmol/h at time equals 350 minutes. The dynamic responses of the control system with and without LSS are shown in Figure 4.57 and 4.58.

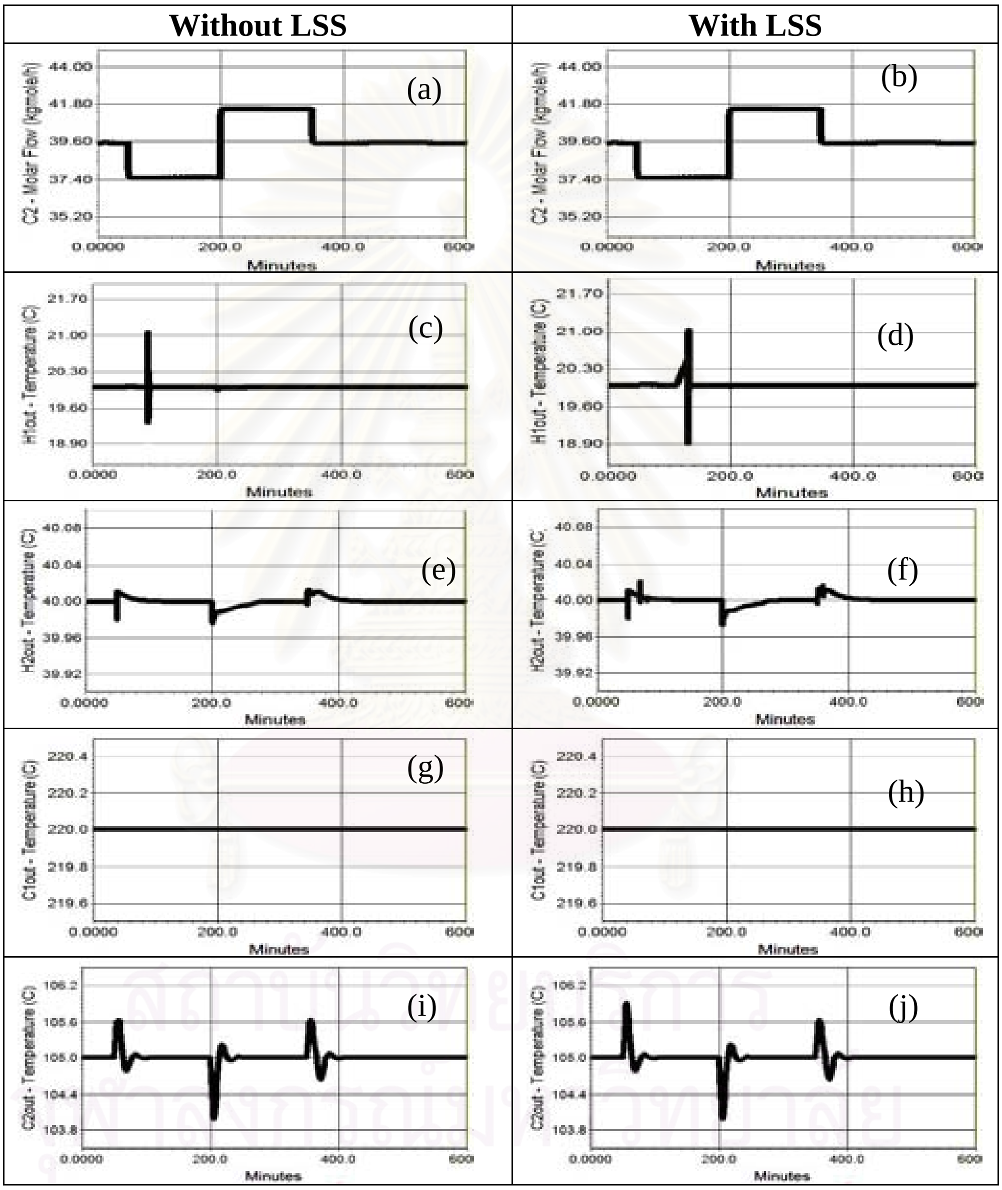


Figure 4.57 Dynamic responses of streams of HEN in Example 4.3 to a change in the disturbance load of C2.

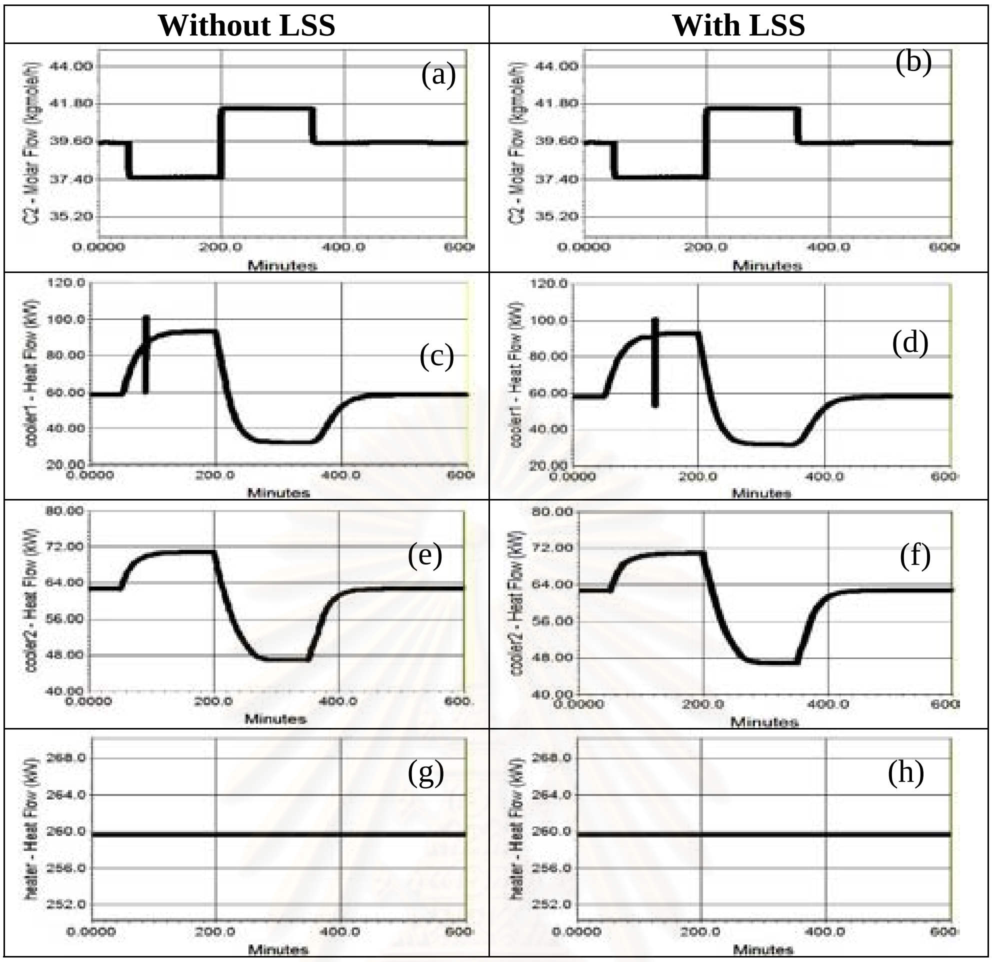


Figure 4.58 Dynamic responses of duty for HEN in Example 4.3 to a change in the disturbance load of C2.

As can be seen from the described results, in this case there is no utility consumption difference between using and without using LSS because the heat transferring path of C2 is directed via cooler only. So when flow rate of cold stream decreases, the so-called negative disturbances (D^-), it can bring about an increase in cooler duty and in the opposite way if that flow rate get rising, namely positive disturbance (D^+), it is found to decrease cooler duty (Figure 4.58).

Table 4.14 Comparison of the energy consumption of control structure with and without LSS in the case of Example 4.3 (Flow rate variation).

Stream	Type of Disturbances	Cooler1 Utility,kW		Cooler2 Utility,kW		Heater Utility,kW	
Flow Rate Variation		Without LSS	With LSS	Without LSS	With LSS	Without LSS	With LSS
H1							
	D^-	26.9	22.9	61.8	52.9	277.8	259.5
	D^+	90.8	61.6	61.8	61.8	242.6	238.4
H2							
	D^-	58.4	58.4	47.9	29.1	308.23	259.5
	D^+	58.4	58.4	89.9	68.8	229.4	213.4
	H2=31.8 kgmol/h	58.4	58.4	124.1	77.5	227.7	179.4
	H2=50.4 kgmol/h	58.4	58.4	383.7	280	224.5	123.2
C1							
	D^-	58.4	58.4	61.8	61.8	180	180
	D^+	58.4	58.4	61.8	49.3	359.3	263.1
C2							
	D^-	93.1	93.1	70.8	70.8	259.5	259.5
	D^+	32.2	32.2	46.9	46.9	259.5	259.5

From the result it is found that using LSS is likely an effective way to handle with disturbance come along with class 2 problem in case of flow rate variation cause pinch jump. It brings about control structure of HEN that give dynamic maximum energy recovery.

4.9 Conclusion

From the result it is found that using A selective controller, i.e. a low selector switch (LSS) is likely an effective way to handle with disturbance come along with Class I problem, pinch is not be changed or continuous vary and Class II problem, pinch jump. Several typical HEN examples are considered to describe the implementation of the design procedure for HEN control. Finally, by following this design procedure, a workable HEN control configuration for dynamic maximum energy recovery.

CHAPTER V

SUMMARY AND CONCLUSIONS

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**.**

5.1 Heuristic Approach for Control Structure Design

The consideration for control structure design by considering its existed control structure is listed below.

The first law: The stream which comprises of only one heat exchanger is the first priority to consider in process design.

The second law: The heat exchanger used for controlling stream temperature can not be used to control another exchanged stream.

The third law: It should always set bypass and control loop at the last unit to maintain target temperature.

The fourth law: The utility flow rate is used to control the stream equipped with utility.

The fifth law: Network consisted of class A and B for heat transfer can use only feed back control.

The sixth law: Network comprised of class C and D must use up stream unit for controlling purpose.

The seventh law: The up stream used must transfer the disturbance to the utility.

The eighth law: Network comprised of class C and D containing type 1 and 2 must use both feed back control and feed forward control for controlling purpose.

The ninth law: In the case of overload disturbance, It must be transfer to another utility in network which further equipped with control loop and bypass stream for improving disturbance propagation.

The tenth law: The great heat transfer exchanger unit must be selected for settling bypass and control loop.

The eleventh law: Control loop must be settled for reducing the disturbance load path.

The twelfth law: Bypass stream should be settled in the lower flow rate side

The thirteenth law: If two streams are equal in flow rate, bypass stream should be settled on the temperature controlling side.

The fourteenth laws: 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.

The fifteenth law: If the controlling temperature is the temperature of aggregated stream, bypass should be settled on heat exchanger at split stream to control that temperature.

The sixteenth laws: Set up selector switch in network in order to support the operation of heat pathway management to achieve the requirement of maximum energy recovery.

5.2 The Procedure for Designing Control Structure of Heat Exchanger Network

Step 1. Identify heat link in order to find the minimum number of LSS.

Step 2. Set up LSS in the network based on the sixteenth law in order to maintain DMER.

Step 3. Design control structure with regard to the law of control structure design no. 1-15 as aforementioned in Chapter III. It is not necessary to consider the factor in consequence so the order can be changed to the appropriate condition.

5.3 The number of LSS to be used in particular case can be determined as follows:

5.3.1 Identify the heat like in HEN that can be used for the propagation of disturbance load, note that the propagation is co-curerent with the process stream

5.3.2 If there is only one heat link the only one LSS is employed and placed on the last heat exchanger unit used in the heat link.

5.3.3 If there are more than one heat link

5.3.3.1 Design the heat links so that all of them will end up at same heat exchanger unit in order to reduce the number of LSS.

5.3.3.2 If all heat links end up at the different heat exchanger units, so the number of LSS is equal to the number of heat link.

5.3.3.3 If there are some heat links, which end up at the same heat exchanger unit , the number of LOS can be determined following the equation below:

$$\mathrm{NLOS} = \text{Number of LOS} = N_H - N_s + 1$$

where NH is defined as the total number of heat links and NS is defined as the number of heat links, which end up at the same heat exchanger unit.

5.3.4. If the end of heat link is target temperature at which heat cannot transfer through the utility, it means that this position cannot equip with LSS so the former position should be consider instead. By following these steps, a workable HEN control configuration for dynamic maximum energy recovery (DMER) can be obtained.

5.4 Conclusion

The design procedure of control structure earned from this research can be applied to the usual network in the presence of variation from changing in flow rate and inlet temperature(Class I and II) 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.

5.5 Recommendations

The procedure of control structure design previously proposed gives more convenient step and guidance to configure network system control of heat exchanger. Because of this procedure was developed from the control rules covering various main factors involved in network structure and disturbance propagation it shorten time consume to find the suitable control structure of network and take more easy for application use.

However, this step can be applied to resolve the network problem without changing in material state condition. That is, the substance in this research work is only liquid state. So it is important to take the change in state condition of material into consideration due to the fact that the dynamic behavior of heat exchange between gas phase and liquid phase is typically different in consequence to the variation in heat exchanger behavior.

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APPENDICES

Appendix A

Problem Table for Example

In this research, HYSYS program is used to simulate control structure and Cp of materials is changed with temperature. Therefore, problem table obtained have various number of energy consumption according to the type of problem and its control structure.

A.1 Problem Table for Example 4.1

Table A.1 Problem table for Example 4.1

W				T hot	T cold	ΣW	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	(°C)	(°C)	kJ/kgmol.°C	°C	kJ/min	kJ/min	kJ/min
0	499.2	0	-367.9	160	150					18249
161.0	486.2	0	-350.6	140	130	131.3	20	2626.0	2626.0	20875
141.9	479.2	-8724	-344.3	135	125	296.6	5	1483.0	4109.0	22358
121.8	468.1	-8694	-331.1	130	120	-595.6	5	-2978.0	1131.0	19380
0	460.3	-8554	-321.7	110	100	-610.6	20	-12212.0	-11081.0	7168
0	451.4	0	-302.2	100	90	-716.8	10	-7168.0	-18249.0	0
0	442.5	0	-291.1	90	80	149.2	10	1492.0	-16757.0	1492
0	437.0	0	-272.9	70	60	151.4	20	3028.0	-13729.0	4520
0	399.3	0	0	30	20	164.1	40	6564.0	-7165.0	11084
0	0	0	0	20	10	399.3	10	3993.0	-3172.0	15077

When Hot utility = 18,249 kJ/min (304.15 kW)

Cold utility =15,077 kJ/min (251.28kW)

A.2 Problem Table for Example 4.2

Table A.2 problem table for Example 4.2 at T_{H2} =120^{o}C

W				T hot	T cold	W	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	°C	°C	kJ/kgmol.°C	°C	kJ/min	kJ/min	kJ/min
0	0	0	0	230	220					186958
0	0	-5314	0	220	210	-5314	10	-53140	-53140	133818
4379	0	-5278	0	170	160	-899	50	-44950	-98090	88868
4268	0	-5103	0	132	122	-835	38	-31730	-129820	57138
4158	0	-4947	0	120	110	-789	12	-9468	-139288	47670
3894	6422	-4905	-7000	90	80	-1589	30	-47670	-186958	0
3821	6283	-4802	0	70	60	5302	20	106040	-80918	106040
0	5942	-4714	0	30	20	1228	40	49120	-31798	155160
0	5899	0	0	15	5	5899	15	88485	56687	243645

When Hot utility = 186,958 kJ/min (3115.96 kW)

Cold utility = 243,645kJ/min (4060.75kW)

Table A.3 Problem table for Example 4.2 at T_{H2} =132^{o}C

W				T hot	T cold	W	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	°C	°C	kJ/kgmol.°C	°C	kJ/min	kJ/min	kJ/min
0	0	0	0	230	220					129820
0	0	-5314	0	220	210	-5314	10	-53140	-53140	76680
4379	0	-5278	0	170	160	-899	50	-44950	-98090	31730
4268	0	-5103	0	132	122	-835	38	-31730	-129820	0
4158	6489	-4947	0	120	110	5700	12	68400	-61420	68400
3894	6422	-4905	-7000	90	80	-1589	30	-47670	-109090	20730
3821	6283	-4802	0	70	60	5302	20	106040	-3050	126770
0	5942	-4714	0	30	20	1228	40	49120	46070	175890
0	5899	0	0	15	5	5899	15	88485	134555	264375

When Hot utility = 129,820 kJ/min (2163.667kW)

Cold utility = 264,375 kJ/min (4406.25kW)

Table A.4 Problem table for maximum heat load

W				T hot	T cold	W	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	°C	°C	kJ/kgmol.°C	°C	kJ/min	kJ/min	kJ/min
0	0	0	0	230	220					116070
0	0	-5314	0	220	210	-5314	10	-53140	-53140	62930
4379	0	-5278	0	150	140	-899	70	-62930	-116070	0
4268	6603	-5103	0	132	122	6139	18	233282	-12246	103824
4158	6489	-4947	0	120	110	5700	12	68400	56154	172224
3894	6422	-4905	-7000	90	80	-1589	30	-47670	8484	124554
3821	6283	-4802	0	70	60	5302	20	106040	114524	230594
0	5942	-4714	0	30	20	1228	40	49120	163644	279714
0	5899	0	0	15	5	5899	15	88485	252129	368199

When Hot utility = 116,070 kJ/min (1,934.5 kW)

Cold utility = 368,199 kJ/min (6,136.65 kW)

A.3 Problem Table for Example 4.3

Table A.5 Problem table for Example 4.3

W				T hot	T cold	ΣW	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	(°C)	(°C)	kJ/kgmol.°C	°C	kJ/min	kJ/min	kJ/min
0	0	-3205.5	0	220	210					16578.2
2244.4	0	-3132.6	0	180	170	-3205.6	40.0	-128222.1	-128222.1	3756.0
2193.4	2192.6	-2905.0	0	150	140	-888.3	30.0	-26648.1	-154870.2	1091.2
2100	2076.2	-2812.8	-2757.8	115	105	1481.1	35.0	51838.2	-103032.0	6275.0
1952.7	1975.4	0	-2631.8	70	60	-1394.5	45.0	-62750.4	-165782.4	0
1864.7	0	0	0	40	30	1296.4	30.0	38891.1	-126891.3	3889.1
0	0	0	0	20	10	1864.8	20.0	37295.0	-89596.3	7618.6

When Hot utility = 16578.2kJ/min (276.3 kW)

Cold utility = 7618.6kJ/min (126.9kW)

Table A.5 Problem table for W=2.4625

W				T hot	T cold	ΣW	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	(°C)	(°C)	kJ/kgmol.°C	(°C)	kJ/min	kJ/min	kJ/min
0	0	-3205.5	0	220	210					15487.0
2244.4	0	-3132.6	0	180	170	-3205.6	40.0	-128222.1	-128222.1	2664.8
2193.4	2606.4	-2905.0	0	150	140	-888.3	30.0	-26648.1	-154870.2	0.0
2100	2401.0	-2812.8	-2757.8	115	105	1894.9	35.0	66320.8	-88549.4	6632.0
1952.7	2398.0	0	-2631.8	70	60	-1069.7	45.0	-48134.3	-136683.7	1818.6
1864.7	0	0	0	40	30	1718.9	30.0	51567.5	-85116.2	6975.4
0	0	0	0	20	10	1864.8	20.0	37295.0	-47821.2	10704.9

When Hot utility = 15,487.0 kJ/min (258.1 kW)

Cold utility = 10,704.9kJ/min (178.4 kW)

Table 4.13 problem table for W=4

W				T hot	T cold	ΣW	ΔT	Net heat	Require heat	Cascade heat
H1	H2	C1	C2	°C	°C	kJ/kgmol.°C	(°C)	kJ/min	kJ/min	kJ/min
0	0	-3205.5	0	220	210					15487.0
2244.4	0	-3132.6	0	180	170	-3205.6	40.0	-128222.1	-128222.1	2664.8
2193.4	4285.3	-2905.0	0	150	140	-888.3	30.0	-26648.1	-154870.2	0.0
2100	4012.5	-2812.8	-2757.8	115	105	3573.8	35.0	125081.6	-29788.6	12508.1
1952.7	3725.0	0	-2631.8	70	60	541.8	45.0	24380.9	-5407.7	14946.2
1864.7	0	0	0	40	30	3045.9	30.0	91375.8	85968.2	24083.8
0	0	0	0	20	10	1864.8	20.0	37295.0	123263.2	27813.3

When Hot utility = 15487.0 kJ/min (258.1 kW)

Cold utility = 7618.6kJ/min (463.5kW)

VITA

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