การออกแบบและควบคุมข่ายงานเครื่องแลกเปลี่ยนความร้อนแบบยืดหยุ่น ในกรณีที่มีการเปลี่ยนแปลงอุณหภูมิขาเข้าและอัตราการไหล

นายเอกรัตน์ ภูริมาภรณ์

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DESIGN AND CONTROL OF RESILIENT HEAT EXCHANGER NETWORK: INPUT TEMPERATURE AND FLOW RATE VARIATION CASE

Mr.Ekkarat Purimaporn

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By	Mr.Ekkarat Purimaporn
Field of study	Chemical Engineering
Advisor	Assistant Professor Montree Wongsri, D.Sc.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree.

.... Dean of the Faculty of Engineering

(Associate Professor Boonsom Lerdhirunwong, Dr.Ing.)

THESIS COMMITTEE

.... Chairman

(Professor Piyasan Praserthdam, Dr.Ing.)

.... Advisor

(Assistant Professor Montree Wongsri, D.Sc.)

.... Examiner

(Soorathep Kheawhom, Ph.D.)

.... External Examiner

(Phisit Jaisathaporn, Ph.D.)

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วิธีการนำพลังงานความร้อนจากกระบวนการการผลิตในอุตสาหกรรมกลับมาใช้อย่างมีประสิทธิภาพวิธีหนึ่งคือข่ายงานเครื่องแลกเปลี่ยนความร้อน อย่างไรก็ตามการแลกเปลี่ยนพลังงานจะทำให้เกิดผลกระทบต่อหน่วยอื่นๆ ภายในกระบวนการและอาจมีการเปลี่ยนแปลงอุณหภูมิขาเข้าที่เกิดจากสิ่งแวดล้อมหรือเพื่อให้ได้ผลิตภัณฑ์ตามต้องการ ทำให้เกิดปัญหาในการควบคุมเพื่อให้ได้อุณหภูมิเป้าหมายตามที่กำหนด และให้ข่ายงานได้การนำกลับคืนพลังงานสูงสุด งานวิจัยนี้ได้นำวิธีการออกแบบข่ายงานเครื่องแลกเปลี่ยนความร้อนแบบยืดหยุ่นมาจัดการกับความแปรปรวนที่เกิดขึ้นโดยนำวิธีการออกแบบของ Wongsri (1990) มาดัดแปลงเพื่อให้สามารถรองรับความแปรปรวนของอุณหภูมิขาเข้าได้ โดยอาศัยแนวทางฮิวริสติกต่างๆ ได้แก่ กระสวนการจับคู่ การออกแบบจุดพินช์ การจัดการกับความแปรปรวน การเลือกติดตั้งกระแสบายพาส และการสวิตช์ตำแหน่งที่ควบคุม มาใช้ในการออกแบบเพื่อแก้ไขปัญหาข่ายงานเครื่องแลกเปลี่ยนความร้อน 3 ตัวอย่าง โดยใช้การจำลองบนโปรแกรมไฮซิส (HYSYS) เพื่อทดสอบสมรรถนะโครงสร้างของการควบคุม

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An effective method to recover the energy from production process plants is heat exchanger network (HEN). However, the energy integration can cause interactions to the other units in process and variation input temperature because environment or product specification that cause the problem to maintain the target temperature and achieve maximum energy recovery. This research, the resilient heat exchanger network design method to dispose of disturbance provide by Wongsri (1990) is modified in case input temperature and flow rate variation. This procedure is presented for design control structure of heat exchanger network using heuristic approach such as match patterns, pinch design, disturbance propagation, bypass setting and selector switch setting to solve 3 examples for heat exchanger network problems. The heat exchanger network with control structures are programmed by simulation in HYSYS for evaluation performance of control structure.

Department:.........Chemical Engineering.... Student's Signature: Ekkarat Purimaporn
Field of Study:.....Chemical Engineering.... Advisor's Signature:.....................
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CHAPTER I

INTRODUCTION

This chapter consists of importance and reasons for research, objectives of research, scopes of research, contributions of research and research procedures.

1.1 Importance and Reasons for Research

Many process stream temperatures in production processes of the process industry are increased or decreased by heat exchange between one stream and other stream (heat transfer between heat required stream and heat donated stream) or one stream with the utility (heat transfer between heat required stream and heater or heat donated stream and cooler) for saving operating and energy cost.

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

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

This research is focuses on the design procedure of resilient heat exchanger networks and their control structures by Wongsri (1990) in case of input temperature and flowrate changed to maintain target temperatures. The commercial process simulator-HYSYS is chosen to evaluate performance of the heat exchanger networks and their control structures by steady state and dynamic simulations.

1.2 Research Objective

To design resilient heat exchanger network for the case of input temperature and flowrate changed, which based on Wongsri (1990).

1.3 Scopes of research

1. No phase changes in all streams.
2. It is assumed that a utility exchanger can handle all variations of heat load.
3. The heat exchanger network with control structures are simulated using HYSYS for control structure performance tests.
4. All heat exchanger will have enough heat transfer area to support the disturbance of heat loads occur in process streams.
5. The target for develop a resilient heat exchanger network and control structures design procedure changed input temperature and flowrate using network and control configuration design procedure with 2 independent HEN problems and 1 process related HEN problem.

1.4 Contributions of research

Heat exchanger network and control structure can be achieved with the process in the presence of disturbance from the variation of input temperature and flowrate. It could reduce energy consumption, operating cost and keep safety in the operation.

1.5 Research procedures

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

1.6 Research Framework

This thesis matter is classified into six 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 covers some background information and theory of heat exchanger network design.

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

Chapter V describes the design of heat exchanger network and control structure by developing procedure in chapter IV. This step can be applied with general heat exchanger network in the presence of energy disturbance i.e., the variation of inlet condition but still be operated and also achieved the target required.

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

CHAPTER II

LITERATURE REVIEW

2.1 Heat Exchanger Network Design

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

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

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

Calandranis and Stephanopoulos (1988) proposed a new approach to address the following problems: design the configuration of control loops in a network of heat exchangers and sequence the control action of the loops, to accommodate set point changes and reject load disturbances. The approach proposed exploits the structure characteristics of a HEN by identifying routes through the HEN structure that can allocate load (disturbances, or set point changes) to available sinks (external coolers or heaters). They also discussed several design issues such as the placement of bypass lines and the restrictions imposed by the existence of a process pinch. An online, real-time planning of control actions is the essence of implementation strategies generated by an expert controller, which selects path through the HEN is to be used for each entering disturbance or set point change, and what loops should be activated (and in what sequence) to carry the associated load (disturbance or set point change) to a utility unit. Although this study provided the comprehensive summary of work on the design of control loop configuration in HENs, it did not report the control strategy, particularly in selecting and manipulating proper heat pathway. In this current study, we present the control strategy; how to select proper heat pathway to carry the associated load to a utility unit, so its duty will be decreased.

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

Sapsawaipol (2007) presented procedure for design control structure of heat exchanger network using heuristic approach to solve heat exchanger network problems in target temperature variation case that is able to maintain target temperatures at specified values and not violate maximum energy recovery.

2.2 Control Structure Design

The objectives of heat exchanger network control are reaching the target temperature and keeping the minimum utility. There are recently a few research works concerned heat exchanger network control. Marselle et al. (1982) proposed that all heat exchanger in network should be equipped with bypass and 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 set point 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.

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

CHAPTER III

THEORY

3.1 Introduction

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

3.2 Basic Knowledge for Pinch Technology

3.2.1 Pinch Technology

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

3.2.2 Basic Pinch Analysis Concept

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

The necessary thermal data is source, target temperature and heat capacity flow rate for each stream as shown in Table 3.1.

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

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

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

$$CP = C_p * F \tag{3.1}$$

Where CP = heat capacity flow rate (kW/^oC)

Cp = Specific heat capacity of the stream (kJ/^oC·kg)

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

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

Table 3.2 The problem table for data given in Table 3.1

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

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

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

3.3 Heat Exchanger network

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

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

3.3.1 Definition of HEN Resiliency

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

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

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

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

3.3.2 Heuristics

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

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

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

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

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

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

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

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

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

Heuristic E.3 Do not cool above the pinch.

Heuristic E.4 Do not heat below the pinch.

The laws of thermodynamics:

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

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

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

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

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

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

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

3.3.3 Physical Approach

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

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

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

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

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

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

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

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

Definition 3.5 Original Disturbance (D): The original disturbance now includes the heat capacity flowrate disturbance.

$$D_i = D_i^{\theta} + D_i^{\omega} + D_i^{t} \tag{3.3}$$

Definition 3.6 Supply Temperature Disturbance (D_i^{θ}): The original disturbance of a stream is the disturbance entered at the supply temperature.

$$D_i^{\theta} = (T_{i,max}^{supply} - T_{i,min}^{supply}) \times W_i \tag{3.4}$$

Definition 3.7 Target Temperature Disturbance (D_i^t): The original disturbance of a stream is the disturbance at the target temperature.

$$D_i^t = (T_{i,max}^{target} - T_{i,min}^{target}) \times W_i \quad (3.5)$$

Definition 3.8 Flowrate Disturbance (D_i^ω): The flowrate disturbance is the increased heat load due to an increase of heat capacity flowrate from its minimum (design) value to its maximum value over the maximum temperature range of such a stream.

$$D_i^\omega = (W_{i,max} - W_{i,min})(T_{i,max}^1 - T_{i,min}^2) \quad (3.6)$$

Definition 3.9 Utility Exchanger Resiliency (R_U): Utility resilience is the capability of a utility exchanger to handle extra load. The value depend the kind of disturbances: propagated disturbance or own disturbance.

For a positive propagated disturbance, the maximum utility exchanger resiliency is the value of utility exchanger duty at the specified design condition. For an own disturbance or a negative propagated disturbance, utility exchanger resiliency can be unlimited. This is possible if there is a bypass line to direct the unwanted fiowrate to the utility exchanger. Of course, there is a limit for practical realization.

Definition 3.10 Stream Resiliency (R_s): Under the assumption that a bypassed line is a standard feature of every unit. The Stream resiliency is the sum of the resiliencies of the down path units on that stream.

Definition 3.11 Network Resiliency (R_N): Network resiliency is the minimum value of stream resiliencies.

$$R_N = min\{R_{S_i}\} \quad (3.7)$$

3.3.4 Propagated Disturbance

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

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

1. Nominal operating condition

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

2. Maximum heat load condition

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

3. Minimum heat load condition

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

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

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

exchanger within its network.

The principles of the DPD can be summarized as follows:

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

2. The design condition was selected to be the minimum heat load condition. This is a condition where all process streams are at their minimum heat loads. For example the input temperatures of hot streams are the lowest and those of cold stream are the highest.

3. Then only the positive disturbance loads of process streams were considered. Thus, the positive disturbance load originating from the hot stream is shifted to heater, and the positive disturbance load originating from the cold stream is shifted to the cooler.

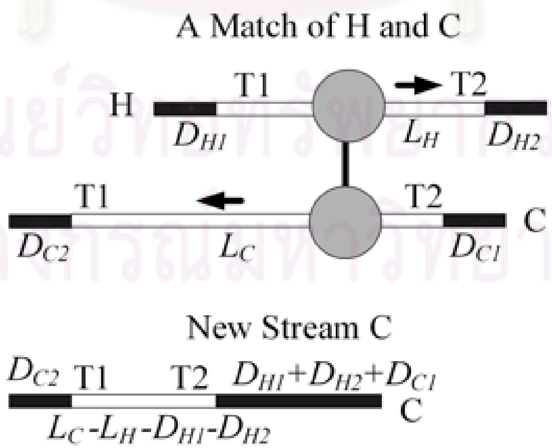


Figure3.1 A concept of propagated disturbance

Note:

D_{H1} : The original disturbance of hot stream from supply temperature

D_{H2} : The original disturbance of hot stream from target temperature

D_{C1} : The original disturbance of cold stream from supply temperature

D_{C2} : The original disturbance of cold stream from target temperature

L_H : The Load of hot stream

L_C : The Load of cold stream

T_1 : The inlet temperature of hot or cold stream at the lowest

T_2 : The inlet temperature of hot or cold stream at the highest

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

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

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

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

1. The inlet and outlet temperatures of the partitioned process streams, by our convention, are subjected to modification within the range of the pinch region. The partition point for a hot end is the lowest pinch temperature in the pinch region and that of a cold end the highest pinch temperature.

2. The minimum cold end temperature, T2 (the target temperature for a hot stream, the supply temperature for a cold stream) for process streams in a heating subproblem is the highest pinch temperature and the minimum

hot end temperature, T1 for process streams in a cooling subproblem is the lowest pinch temperature.

3. The pseudo or pinch-induced disturbances are created to account for the pinch temperature variation.

3.4 Match Pattern

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

3.4.1 Classes of Match Patterns

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

Class A Match Pattern

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

Class B Match Pattern

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

Class C Match Pattern

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

Class D Match Pattern

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

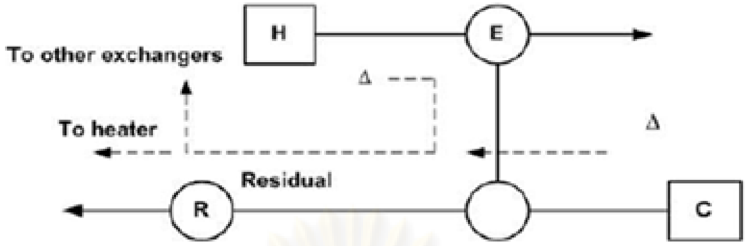


Figure 3.2 Class A Match Pattern.

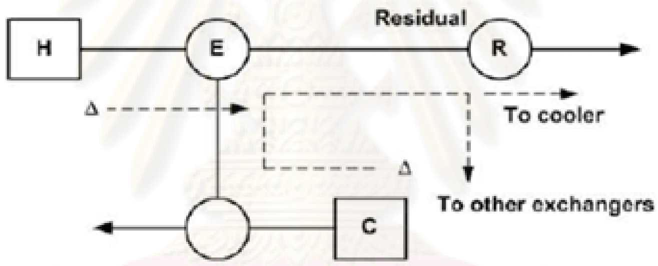


Figure 3.3 Class B Match Pattern.

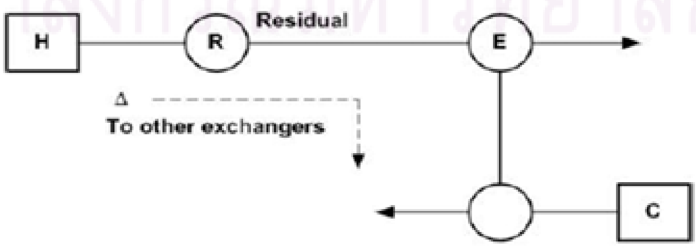


Figure 3.4 Class C Match Pattern.

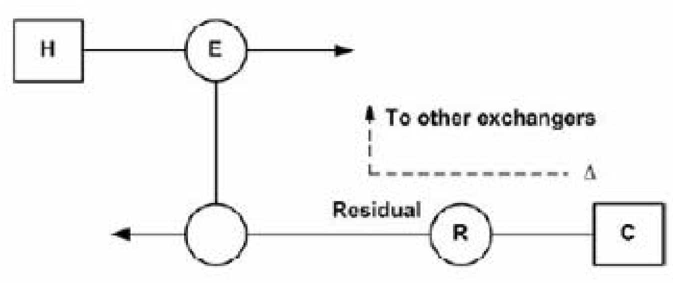
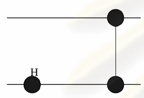
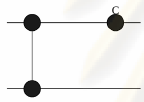
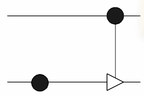
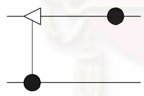
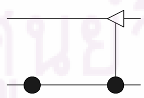
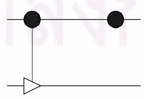


Figure 3.5 Class D Match Pattern

Table 3.3 Match Pattern Operators of Class A and B

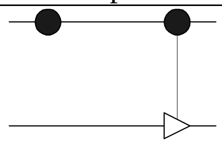
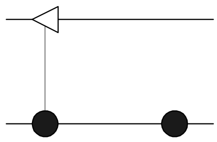
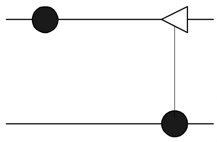
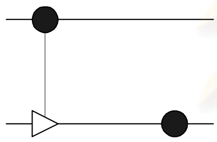
Match Operators	Conditions	Actions
 Pattern AH	$T_H^{s}{}^{*} \ge T_C^{t}{}^{**}$ $L_H \le L_C$ $T_H^s \ge T_C^s + L_H W_C^{-1}$ $L_C - L_H \le Q_{min}^{heating}$	Match H and C Status of H ⇐ Matched*** $T_C^s \Leftarrow T_C^s + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern BK	$T_H^s \ge T_C^t$ $L_C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

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

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

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

Table 3.4 Match Pattern Operators of Class C and D

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

3.5 Resilient Match Patterns

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

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

3.6 Resiliency Requirement Test

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

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

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

$$D_i^{\omega} \leq min\{E_{i,j}, R_{j,i}\} \tag{3.8}$$

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

$$D_i^{\omega} \leq R_{j,i} \tag{3.9}$$

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

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

$$D_i^{\theta}+D_i^{\omega}+D_i^{t} \leq min\{E_{i,j}, R_{j,i}\} \tag{3.10}$$

$$D_i^{\omega} \leq E_{i,j} \tag{3.11}$$

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

o Temperature variation case: The propagated disturbance load.

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

The match test and resiliency test equation of Class A and Class B match patterns are shown in Table 3.5. Those of Class C and Class D are shown in Table 3.6. In the tables, the temperatures of the cold streams and scales up by ΔT_{min}

Table 3.5 Match Operators I

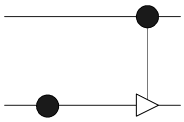
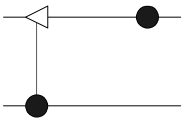
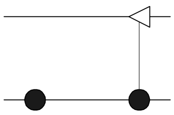
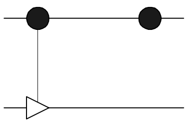
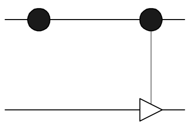
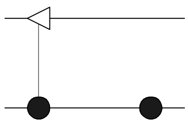
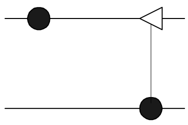
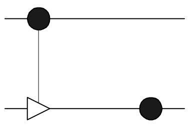
Match Operators	Match Test Equations	Resiliency Test Equations
 Pattern A[H]	$T_H^t \geq T_C^s$ $L_H \leq L_C$ $W_C \geq W_H$	$D^e + D^\omega + D^e_{t,H} \leq R_{C,H}$ $D^\omega \leq E_{C,H} + S_{C,H}$
 Pattern B[C]	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $W_C \leq W_H$	$D^e + D^\omega + D^e_{t,C} \leq R_{H,C}$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

Table 3.6 Match Operators II

Match Operators	Match Test Equations	Resiliency Test Equations
 Pattern C[H]	$T_H^t \ge T_C^s$ $L_H > L_C$ $W_H \le W_C$	$D^e + D^\omega + D^e_{t,H} \le R_{C,H}$ $D^\omega \le E_{C,H} + S_{C,H}$
 Pattern D[C]	$T_H^s \ge T_C^t$ $L_H < L_C$ $W_H \ge W_C$	$D^e + D^\omega + D^e_{t,H} \le R_{H,C}$ $D^\omega \le E_{H,C} + S_{H,C}$
 Pattern C[C]	$T_H^t \ge T_C^s$ $L_H > L_C$ $W_C < W_H$ $T_C^t \le T_H^t + L_C W_H^{-1}$	$D^e + D^\omega + D^e_{t,H} \le \min\{R_{C,H}, E_{C,H}\}$ $D^\omega \le E_{C,H} + S_{C,H}$
 Pattern D[H]	$T_H^s \ge T_C^t$ $L_H \le L_C$ $W_H < W_C$ $T_H^t \ge T_C^t - L_H W_C^{-1}$	$D^e + D^\omega + D^e_{t,H} \le \min\{R_{H,C}, E_{H,C}\}$ $D^\omega \le E_{H,C} + S_{H,C}$

3.7 Design of Heat Pathways for Dynamic MER

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

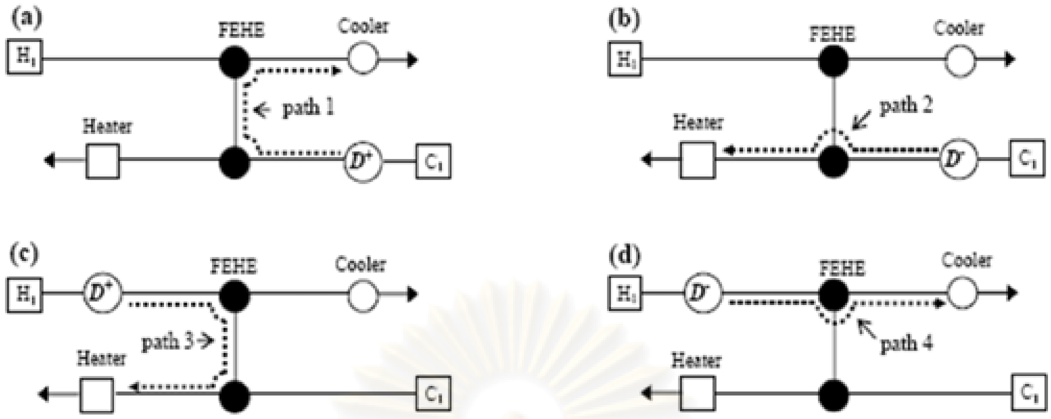


Figure 3.6 Heat pathways in the simplified HEN to achieve the highest possible dynamic MER, where: (a) path 1 is used to shift the positive disturbance load of the cold stream C1 to the cooler, (b) path 2 is used to shift the negative disturbance load of the cold stream C1 to the heat, (c) path 3 is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

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

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

3.8 Design and Control of Heat Pathways for Heat Exchanger Networks

The 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 process 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 path for disturbance loads is co-current with all of the process streams.
- 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.

CHAPTER IV

PROCESS AND DESIGN

4.1 Introduction

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

4.2 The Synthesis Procedure

The synthesis of a resilient heat exchanger network proposed by Wongsri (1990) using (1) match pattern as operators in mapping one design state to the next and (2) heat load propagation technique can be carried in steps as follows:

1. Pop a match pattern operator from the ordered stack of match patterns.

2. Apply the match pattern to matched pair of streams. If the streams satisfy the pattern test and the resiliency requirement, go to the next step. Otherwise select a new pair of streams (go to the previous step).

   Match pattern test: Check the heat load, input temperature and heat capacity flow rate satisfy the match pattern operator, a pair of hot and cold streams.

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

3. If a match is found, exclude matched streams from a set of process stream. Change the condition of residual streams. Include the residual streams in to a set of process streams. Go to a new design state (the first step).

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

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

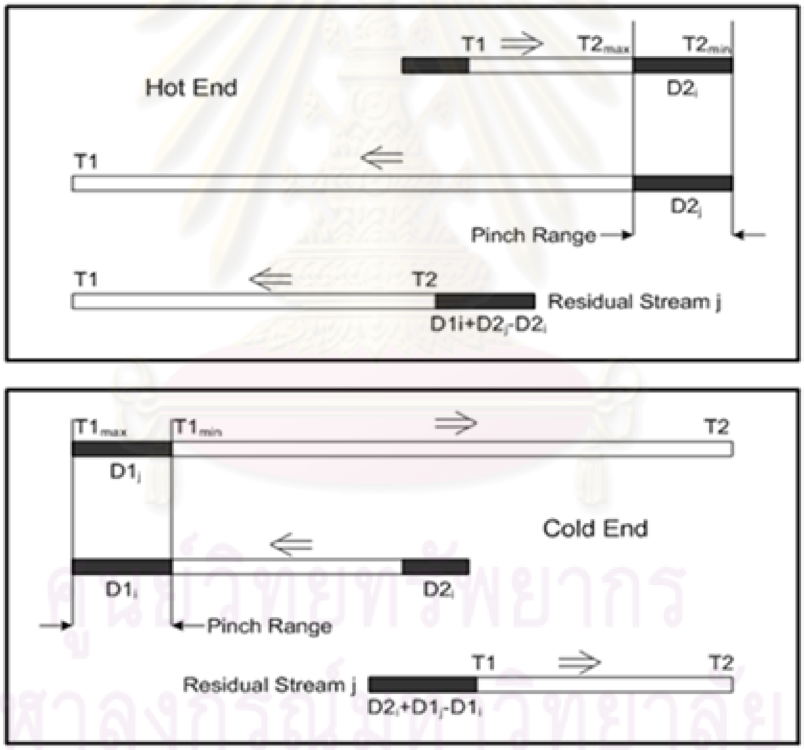


Figure 4.1 A Pinch Match on the Propagated Disturbance Concept

4. For a pinch match of stream i and j for which $W_j > W_i$ and $L_j > L_i$, the disturbance of a residual stream j:

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

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

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

- By the deductive effect described above. It should be denote here that by considering only match pattern Class A and Class B, only a larger heat load and heat capacity flow rate stream can be matched to such a stream. Therefore its downstream disturbance will be engulfed by a larger stream to which such a stream is matched. Only the remaining upstream disturbance of a larger stream (and don't forget the upstream disturbance of a small stream, if there is any) will be propagated to its own residual stream.

- No none-pinched stream can be matched to such stream because of the temperature constraint.

5. If there are only hot or cold streams left in the set of stream, match the streams with the utility.

6. If no match is found in a current design state, there might be other solutions available. Go to the second step.

4.3 The New Heuristic Design Procedure forHEN Control Configuration and Operation

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

1. The heat exchanger network for a particular processing plant should be designed as a resilient HEN following the match pattern proposed by Wongsri (1990)

(a) Design the match pattern in HEN as Class A or Class B so that they are considered to be potential resilient match pattern.

(b) If there is the match pattern in HEN as Class C or Class D, they are considered as non-resilient match pattern. For the remedy, any Class C or Class D in the match pattern should be redesigned so that its residual stream must be connected to either Class A or Class B. Hence the only two classes of interests are Class A and Class B.

2. Use Bypass stream for controlling. The bypass stream should be settled on the cold side because it would be safer to equip measure equipment and control valve on the hot side. On the other hand, it should settle bypass stream on the controlling side regardless whether it is hot or cold stream. However, the selection must bring about the best performance of control system.

3. 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.

4. From the economic point of view, we strongly suggest to:

   (a) shift D+ of cold stream or D-of the hot stream to the cooler utility, thus its duty will be decreased.

   (b) shift D- of cold stream or D+of the hot stream to the heater utility, thus its duty will be decreased.

5. A selective controller with low selector switch (LSS) should be employed to select an appropriate heat pathway through the network to carry the associated load to the utility unit.

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

   (a) Identify the heat pathway of disturbance.

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

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

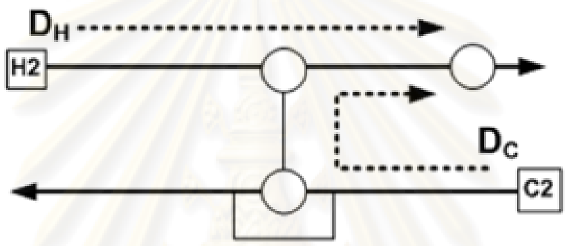


Figure 4.2 One heat pathway

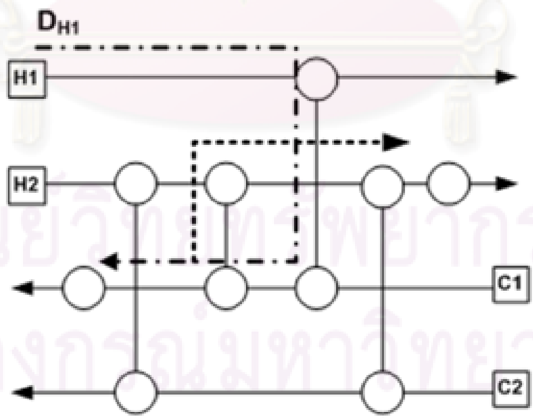


Figure 4.3 More than one heat pathway

4.4 The Hydrodealkylation Process, (HDA Process)

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

$$C_7H_8\text{(Toluene)}+H_2\text{(Hydrogen)} \rightarrow C_6H_6\text{(Benzene)}+\mathrm{C}H_4\text{(Methane)}$$
$$2C_6H_6\text{(Benzene)} \rightleftharpoons C_{12}H_{10}\text{(Benzene)}+H_2\text{(Hydrogen)}$$

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

$$r_1{=}3.6858 \times 10^6 \exp(\tfrac{-25616}{T})p_T p_H^{1/2}$$
$$r_2{=}5.987 \times 10^4 \exp(\tfrac{-25616}{T})p_B^2\text{-}2.553 \times 10^5 \exp(\tfrac{25616}{T})p_D p_H$$

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

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

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

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

Table 4.1 Process Stream Data, Part 1

	Fresh toluene	Fresh hydrogen	Purge gas	Stabilizer gas	Benzene product	Diphenyl product
Stream number	1	2	3	4	5	6
Flow(lb·mol/h)	290.86	490.38	480.88	21.05	272.5	6.759
Temperature(^oF)	86	86	115	113	211	559
Pressure(psia)	575	575	480	480	30	31
H_2, mole fraction	0	0.97	0.3992	0	0	0
CH_4	0	0.07	0.5937	0.9349	0	0
C_6H_6	0	0	0.0065	0.0651	0.9997	0
C_7H_8	1	0	0.0006	0	0.0003	0.00026
$C_{12}H_{10}$	0	0	0	0	0	0.99974

Table 4.2 Process Stream Data, Part 2

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

Table 4.3 Process Stream Data, Part 3

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

Table 4.4 Process Stream Data, Part 4

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

Table 4.5 Equipment Data and Specification

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

Table 4.6 Heat Transfer Rates

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

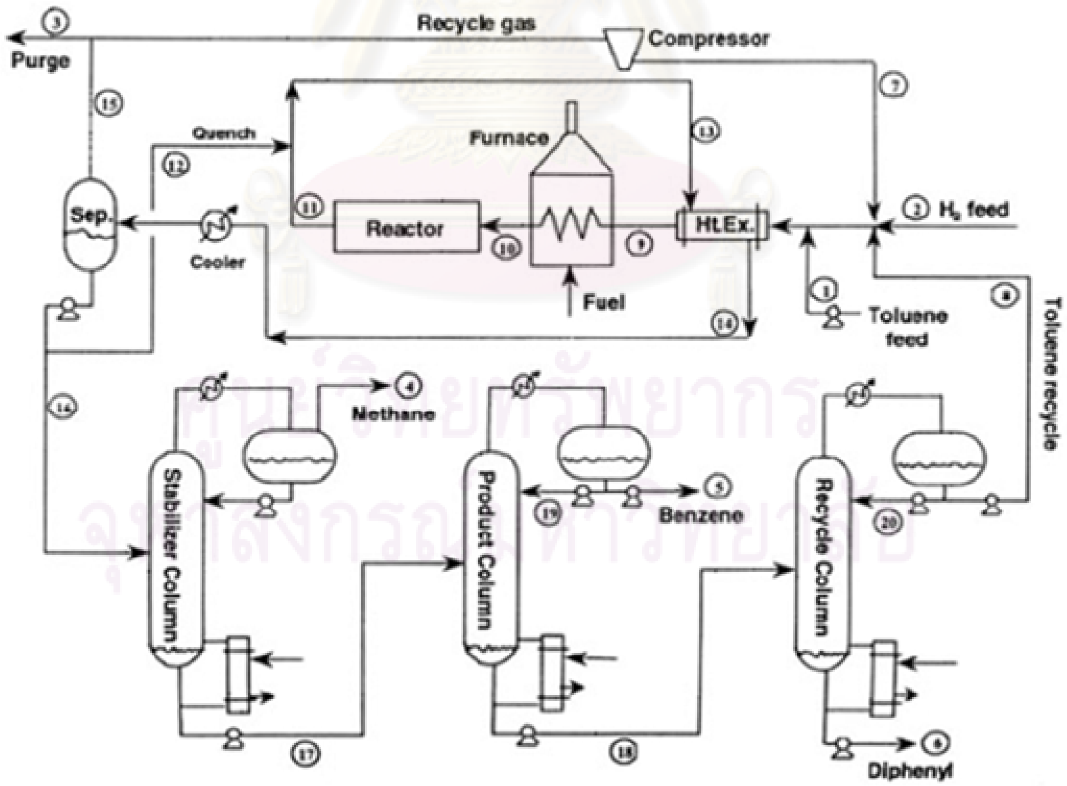


Figure 4.4 Hydrodealkylation HDA of toluene process

CHAPTER V

RESULT

5.1 Introduction

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

5.2 Example 1

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

5.2.1 Design Heat Exchanger network

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

A simple table called the synthesis table is constructed to facilitate the match pattern selection. The synthesis table is shown in Table 5.3. The displayed items are ordered for convenience in browsing. The heat load in the second column and the next displays values of heat capacity flow rate, whose relationship between

Table 5.1 Inlet and outlet condition of network in example 1

Stream No.	Stream Type	W (kW/^oC)			Start Temperature (^oC)			Target Temperature (^oC)
		Max	Nom	Min	Max	Nom	Min	Nom
1	Hot	1.65	1.5	1.35	145	140	135	110
2	Hot	4.95	4.5	4.05	165	160	155	20
1	Cold	9.68	8.8	7.92	-	90	-	120
2	Cold	3.85	3.5	3.15	25	20	15	140

Table 5.2 Problem table for Example 1

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

a hot and a cold stream tell us whether a selected pair belongs to the H or C category. Temperatures T1 and T2 tell us whether a selected pair belongs to Class A or B. T1 is a higher value of temperature of a stream, e.g. an inlet temperature of a hot stream, and T2 is a lower one, e.g. an inlet temperature of a cold stream. Temperature disturbance D1 and D2 are disturbance of high and low temperature end respectively, D_w is flow rate disturbance and D_T is total disturbance. The synthesis is carried out stepwise as follows:

1. The starting condition of the process streams in the hot end is shown in Table 5.3 (a)

2. The match pattern A[H] is selected first. A match is found between H1 and C2 since the following conditions satisfy the match pattern A[H].

$$L_{H1} \leq L_{C2}$$

$$W_{H1} \leq W_{C2}$$

$$T2_{C2}+\Delta T_{min} \leq T2_{H1}$$

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

$$D_{H1} \leq R_{C2,H1}$$

$$D_{H1} \leq L_{C2} - L_{H1}$$

This is the only requirement for the pattern A[H] (and also B[C]). In other words, the minimum heat load of the residual C2 (the value after the disturbance is shifted in) must be greater than zero.

The new process stream data in State 2 are shown in Table 5.3 (b). Notice that the new T2 temperature of C2 is the highest value of the range determined by using the propagation concept. So, the temperature variation range of the residual C2 is increased to $18.33^{o}C$. The new disturbance load of C2 is 13.5+10.5 = 24 kW.

3. The next operator is the match pattern B[C] and there are three active streams - H2, C1 and C2 to be considered. H2 and C2 satisfy the pattern and the resiliency tests.

4. C2 is match to H2 - State 2.

5. In State 3, C1 is matched to H2. Then there is only one pair of streams left - H2 and C1. They can be matched together by the pattern A[H]. See Table 5.3 (c). The disturbance load of C1 is less than the residual heat load of H2 or the minimum cooling load so the resiliency requirement is satisfied.

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

6. State 4. Table 5.3 (d). Match the residual C1 to a heating utility stream.

7. In the cold end, the starting condition of the process streams is shown in Table 5.4 (a)

8. There is only one pair of streams left so it is satisfied the match pattern B[C]. The new process stream data show in Table 5.4 (b) and match the residual H2 to cooling utility stream.

Table 5.3 Synthesis Table for Hot End of example 1

Hot end

Stream	Load	W	T1	T2	D1	D2	D_w	D_T	Action
(a)State 1									
H1	33.75	1.35	135	110	13.5	0	10.5	24	Selected
H2	222.75	4.05	155	100	40.5	0	58.5	99	
C1	237.6	7.92	120	90	0	0	52.8	52.8	
C2	157.5	3.15	140	90	0	0	35	35	Selected A[H]
(b)State 2									
H1									Matched to C2
H2	222.75	4.05	155	100	40.5	0	58.5	99	Selected B[C]
C1	237.6	7.92	120	90	0	0	52.8	52.8	
C2	99.75	3.15	140	108.33				59	Selected
(c)State 3									
H1									Matched to C2
H2	99	4.05	155	139.20				158	Selected A[H]
C1	237.6	7.92	120	90	0	0	52.8	52.8	Selected
C2									Matched to H2

Stream	Load	W	T1	T2	D1	D2	D_w	D_T	Action
(d)State 4									
H1									Matched to C2
H2									Matched to C1
C1	15.6	7.92	120	118.30				210.8	to heater
C2									Matched to H2

Table 5.4 Synthesis Table for Cold End of example 1

Cold end

Stream	Load	W	T1	T2	D1	D2	D_w	D_T	Action
(a)State 1									
H1									
H2	324	4.05	100	20	0	0	72	72	Selected
C1									
C2	204.75	3.15	90	25	0	31.5	52.5	84	Selected B[C]
(b)State 2									
H1									Matched to C2
H2	35.25	4.05	28.70	20				156	to cooler
C1									
C2									Match to H2

The test procedures for the match of

1. Match test. From the table we see that In Figure 5.1 the T2 temp of H1 and C1 different $10^oC = \Delta T_min$, so it is satisfied the requirement. Next, we must look at the Heat capacity flow rate constraint, since the match is class A[H], $L_{H1} \leq L_{C2}$ and $W_{H1} \leq W_{C2}$.

2. Resiliency test. The resiliency is required because both H1 and C2 are variable stream. The load of H1 will be use up. The residual load of C2 is 157.5 - 47.25 = 110.25 or $R_{C2,H1}$=110.25

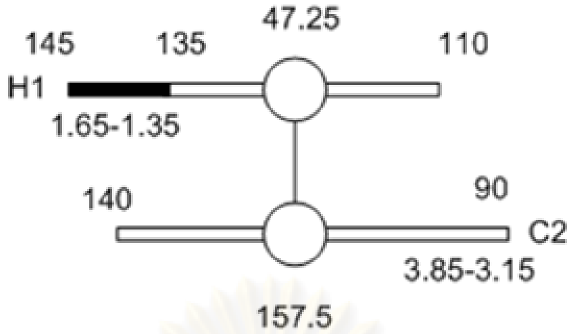


Figure 5.1 The stream H1 and C2 of example1

$$D^{\theta}_{H1} = 1.35(145\text{-}135) = 13.5$$

$$D^{\omega}_{H1} = (1.65\text{-}1.35)(145\text{-}110) = 10.5$$

$$D^{\theta}_{H1} + D^{\omega}_{H1} = 24 \leq R_{C2,H1}$$

The disturbance load is satisfied, the next test is feasibility of a match on the extra heat capacity flow rate. In this test we see whether the exchanger resilience parameter or the stream resiliency parameter can handle an extra load due to the heat capacity flow rate disturbance. Since the heat capacity flow rate of H1 is less than C2, the stream resiliency parameter is negated by definition.

$$E_{H1,C2} = 3.15(110\text{-}90\text{-}10) = 31.5$$

$$S_{H1,C2} = (3.15\text{-}1.35)(145\text{-}110) = 63$$

$$D^{\omega}_{H1} = 10.5 \leq E_{H1,C2} + S_{H1,C2}$$

The match of H1 and C2 passes the match and resiliency test.

The network solution is shown in Figure 5.2

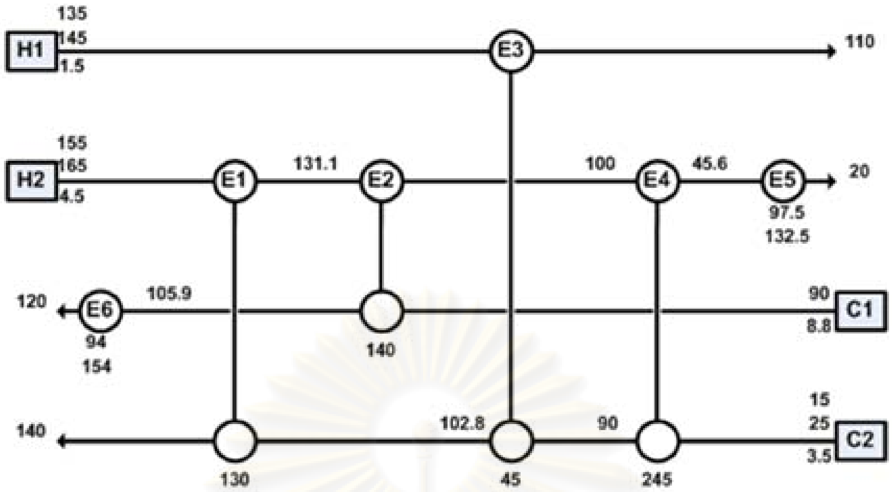


Figure 5.2 A network solution of example1

5.2.2 Design Control Structure

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

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

Network at hot end side (Figure 5.3)

Beginning with determination of set up control loop at utility of any stream in order to maintain target temperature. Then equip bypass at hot stream of E3 and at cold stream of E1 to control H1 and C2 outlet temperature because they are the end of the stream. H2 should be settled bypass and control loop for control the pinch temperature. Actually we have elected to install the bypass valves on the cold side to lower the investment cost but for facilitate maintenance we have chosen to install the bypass valves on the same side that we control.

Network at hot end side (Figure 5.4)

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

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

Considering Figure 5.5, dash lines show the pathway of disturbance, there are 2 ways at E2 and E4. Then, settle up cascade in order to calculate new set point temperature of hot stream and cold stream of E2 and E4 which provide no increase in cooler duty and heater duty (Figure 5.6).

In Figure 5.7 shows the heat pathway of disturbance in example 1 when settled the control structure and LSS, all disturbances will transfer to the utility. In Figure 5.8 shows the simulation in HYSYS flow sheet.

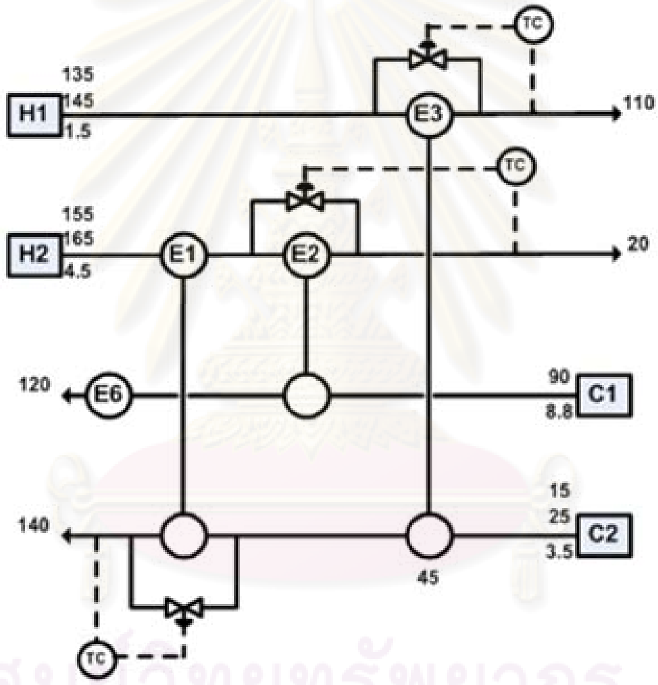


Figure 5.3 Control structure of hot end side for example 1

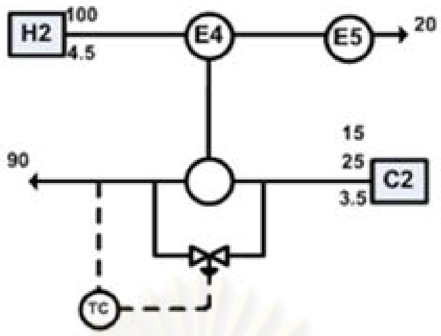


Figure 5.4 Control structure of cold end side for example 1

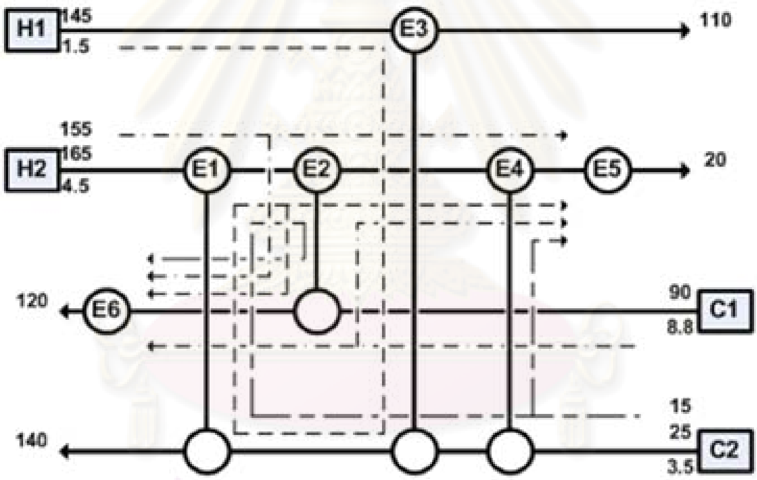


Figure 5.5 Heat pathways of disturbances in each stream for example 1

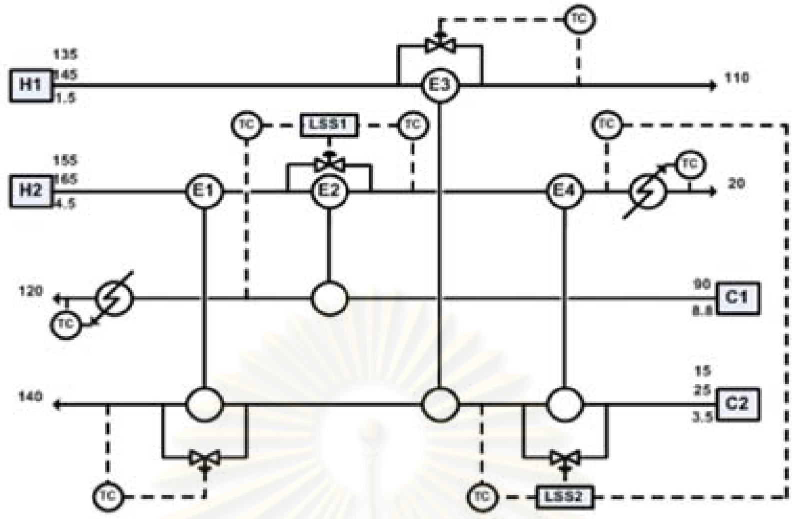


Figure 5.6 Control structure for Example 1 with LSS

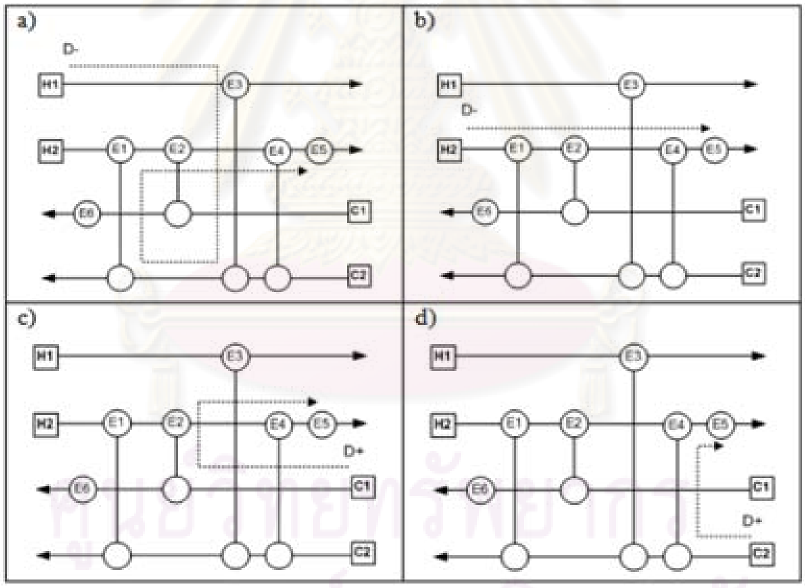


Figure 5.7 Heat pathway of control structure of network equipped with LSS when there is the disturbance at input temperature and inlet flow rate in Example 1
a) D- presented at H1, b) D- presented at H2
c) D+ presented at C1, d) D+ presented at C2

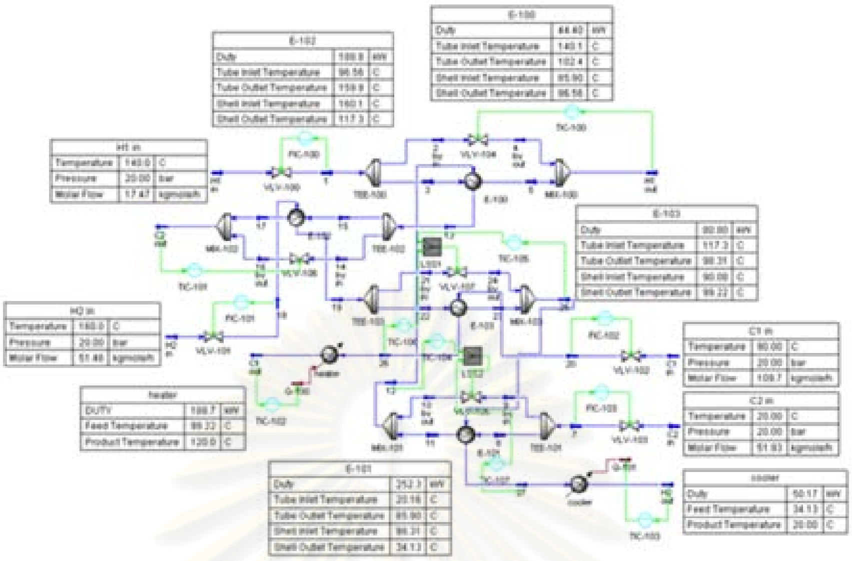


Figure 5.8 Heat exchanger network with LSS of example 1 from HYSYS flow sheet

5.2.3 Dynamic Simulation Result for HEN in example 1

In order to evaluate the dynamic behaviors of the HEN in Example 1, several disturbance loads were made, the dynamic responses of the control systems are shown in Figure 5.9-5.10. Left side shows dynamic behavior of system without LSS and the right side presents the dynamic behavior of the new control system using the LSS to select appropriate heat pathway through the network.

Change in Input Temperature and Flow Rate of All Streams for Example 1 (decrease input temperature of all streams, decrease flow rate of stream H1 H2 and increase flow rate of stream C1 C2)

Figure 5.9 and 5.10 show the disturbance load of all streams and dynamic responses of HEN respectively, without and with LSS in example 1. In order to make these disturbances, first the fresh feed H1 temperature decreases from 140^{o}C to 135^{o}C, H2 temperature decreases from 160^{o}C to 155^{o}C, C2 temperature decreases from 20^{o}C to 15^{o}C, H1 flow rate decreases from 17.47 to 15.72 kgmole/h, H2 flow rate decreases from 51.46 to 46.31 kgmole/h, C1 flow rate increases from 109.70 to 120.67 kgmole/h and C2 flow rate increases from 51.93 to 57.12 kgmole/h at time equals 10 minutes then temperature and flow rate of all streams return to nominal value at time equals 200 minutes.

- The hot stream input temperature (H1) decreases. That is called negative disturbance, (D-). Heat pathway is shown in Figure 5.7a. As a result, the cold outlet of HE3 temperature decreases below its minimum value. Then it makes the H2 temperature outlet from HE1 decreases. The LSS1 takes an action to control the cold outlet temperature of HE2.

- The hot stream input temperature (H2) decreases. That is called negative disturbance, (D-). Heat pathway is shown in Figure 5.7b. The LSS1 takes an action to control the cold outlet temperature of HE2 same as the hot stream input temperature (H1) decreases.

- The cold stream input temperature (C2) decreases. That is called positive disturbance, (D+). Heat pathway is shown in Figure 5.7d. As a result, the hot outlet of HE4 temperature decreases below its minimum value, the LSS2 takes an action to control the cold outlet temperature of HE4.

- The hot stream inlet flow rate (H1) decreases. That is called negative disturbance, (D-). As a result, the LSS1 takes an action to control the cold outlet temperature of HE2.

- The hot stream inlet flow rate (H2) decreases. That is called negative disturbance, (D-). The LSS1 takes an action to control the cold outlet temperature of HE2 same as the hot stream inlet flow rate (H1) decreases.

- The cold stream inlet flow rate (C1) increases. That is called positive disturbance, (D+). Heat pathway is shown in Figure 5.7c. As a result, the hot outlet of HE2 temperature decreases below its minimum value, the LSS1 takes an action to control the cold outlet temperature of HE2.

- The cold stream inlet flow rate (C2) increases. That is called positive disturbance, (D+). The LSS2 takes an action to control the cold outlet temperature of HE4.

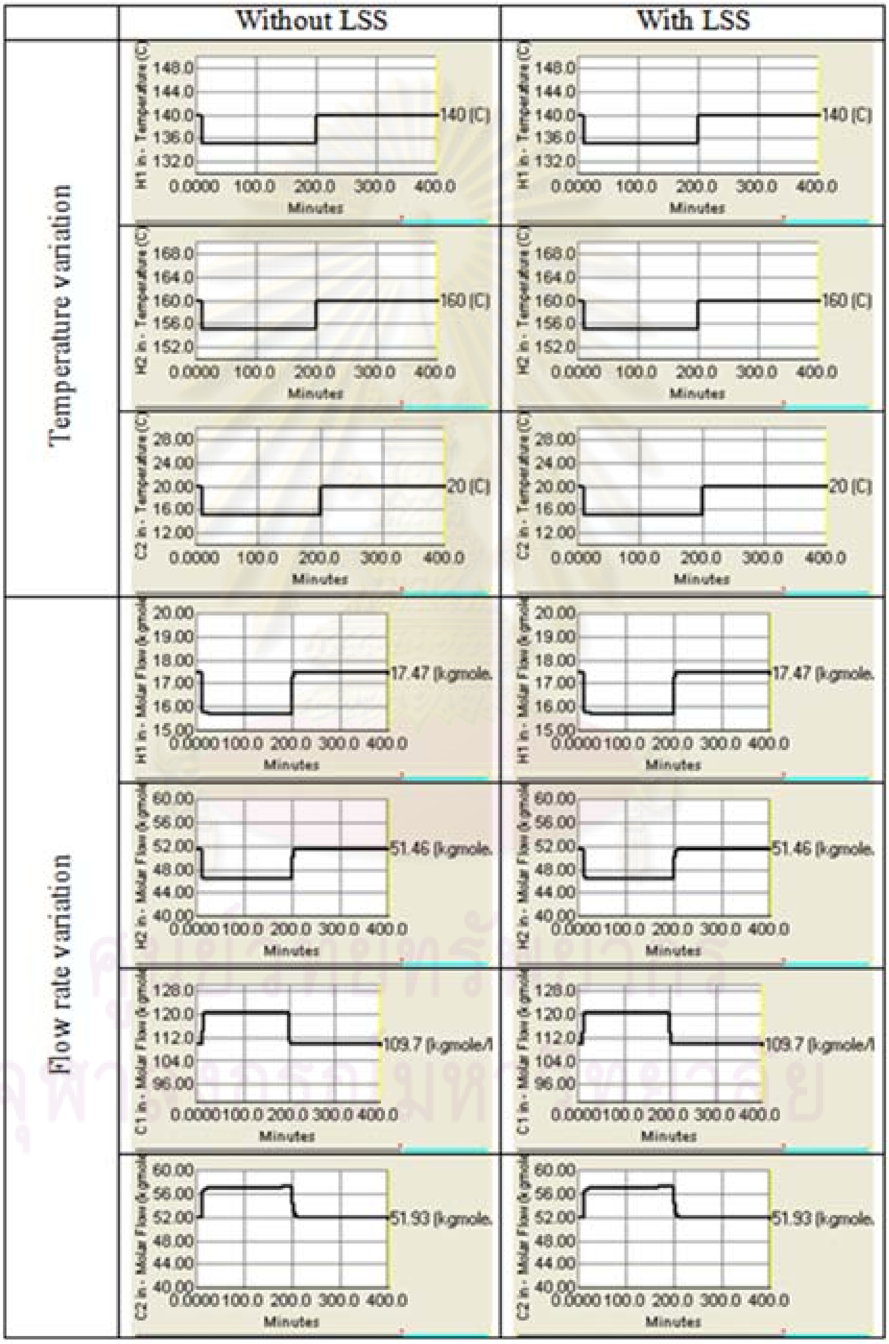


Figure 5.9 Disturbance load of all streams without and with LSS in example 1

Table 5.5 Comparison of the IAE of control structure without and with LSS in the case of example 1

Controller	IAE	
	Without LSS	With LSS
TIC-100	6.980	6.587
TIC-101	9.428	8.947
TIC-102	3.889	3.930
TIC-103	3.920	3.807
Average	6.054	5.818

Table 5.6 Comparison of the energy consumption of control structure with and without LSS in the case of Example 1

<table>
<tr><th rowspan="2">Stream Type</th><th rowspan="2">Variation</th><th rowspan="2">Disturbances</th><th colspan="2">Cooler Utility, kW</th><th colspan="2">Heater Utility, kW</th></tr>
<tr><th>Without LSS</th><th>With LSS</th><th>Without LSS</th><th>With LSS</th></tr>
<tr><td rowspan="2">H1</td><td>Input Temperature</td><td>Negative</td><td rowspan="7">7.07</td><td rowspan="7">6.44</td><td rowspan="7">328.56</td><td rowspan="7">327.99</td></tr>
<tr><td>Flow rate</td><td>Negative</td></tr>
<tr><td rowspan="2">H2</td><td>Input Temperature</td><td>Negative</td></tr>
<tr><td>Flow rate</td><td>Negative</td></tr>
<tr><td>C1</td><td>Flow rate</td><td>Positive</td></tr>
<tr><td rowspan="2">C2</td><td>Input Temperature</td><td>Positive</td></tr>
<tr><td>Flow rate</td><td>Positive</td></tr>
</table>

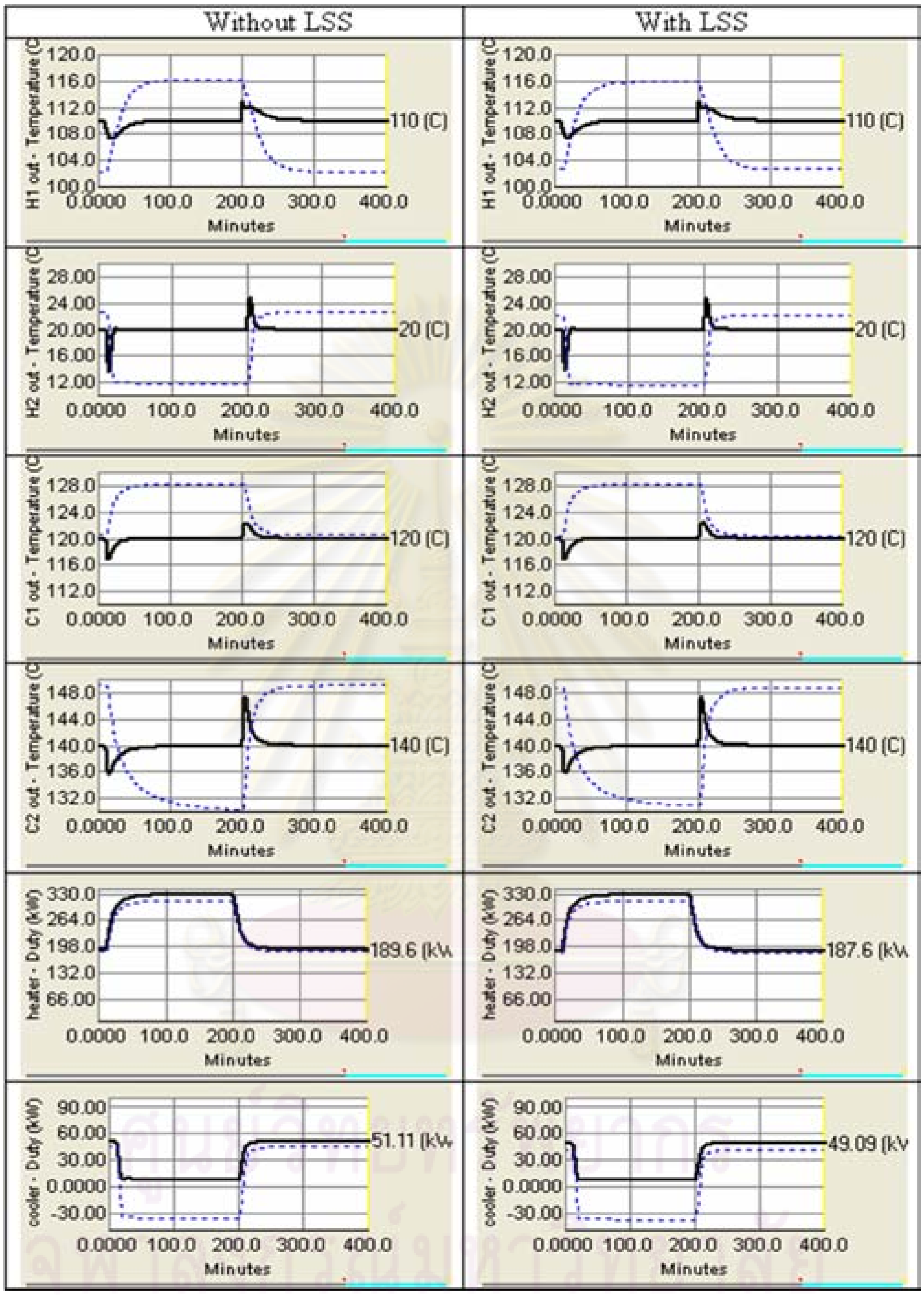


Figure 5.10 Dynamic responses of HEN with and without LSS in example 1

The cooler duty will be decreased from 49.09 kW to 6.44 kW while the duty of heater increases from 187.58 kW to 327.99 kW (Figure 5.10)

Table 5.5 and 5.6 show that the value of IAE of HEN with LSS is smaller than without LSS, and the LSS is likely an effective way to handle with disturbance come along with the variation of temperature that come from input temperature and flow rate. It brings about control structure of HEN that give dynamic maximum energy recovery.

5.3 Example 2

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

5.3.1 Design Heat Exchanger network

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

Table 5.7 Inlet and outlet condition of network in Example 2

Stream No.	Stream Type	W (kW/^oC)			Start Temperature (^oC)			Target Temperature (^oC)
		Max	Nom	Min	Max	Nom	Min	Nom
1	Hot	7.735	7.032	6.329	239	249	229	120
2	Hot	9.28	8.44	7.60	239	-	-	148
1	Cold	6.706	6.096	5.486	106	116	96	150
2	Cold	11	10	9	131	136	126	250

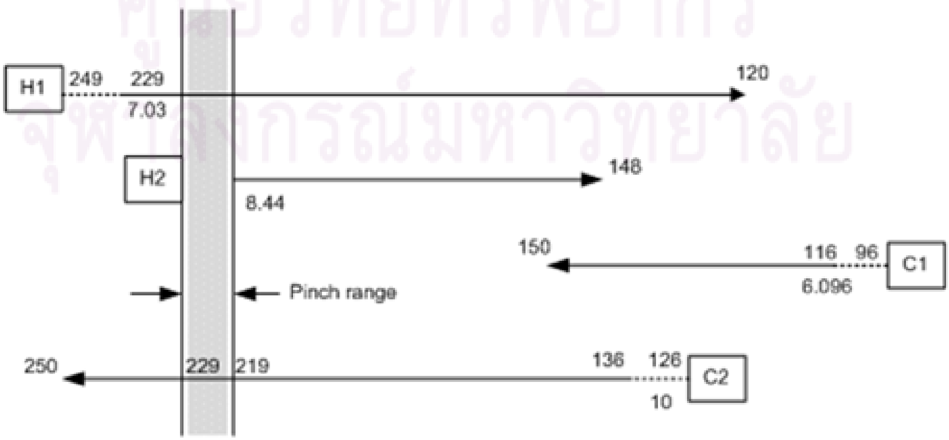


Figure 5.11 Process Streams Partitioning for Example 2

Table 5.8 Problem table for Example 2 for minimum heat load

W				T hot (^oC)	T cold (^oC)	ΣW (kW/^oC)	ΔT (^oC)	Required Heat (kW)	Interval (kW)	Cascade Heat (kW)	Sum Interval (kW)
H1	H2	C1	C2								
0	0	0	0	260	250	0		Qh			
0	0	0	10	239	229	-10	21	225.6	-210	15.6	-210
7.032	0	0	10	229	219	-1.56	10	15.6	-15.6	0	-225.6
7.032	8.44	0	10	160	150	5.472	69	0	377.568	377.568	151.968
7.032	8.44	6.096	10	148	138	-0.624	12	377.568	-7.488	370.08	144.48
7.032	0	6.096	10	146	136	-9.064	2	370.08	-18.128	351.952	126.352
7.032	0	6.096	0	126	116	0.936	20	351.952	18.72	370.672	145.072
0	0	6.096	0	120	110	7.032	6	370.672	42.192	412.864	187.264
										Qc	

The pinch region is between 239-229^{o}C on the hot side scale. The stream partitioning procedure:

- H1. The disturbance region of H1 in the hot end appears in the pinch zone (see Figure 5.11) and also exists outside the pinch zone, so it has not disappeared when the pinch moved up to the highest value. The disturbance in the pinch range diminished to zero only when the pinch is moved up to 239^{o}C. So H1 exists in both the hot end and cold end. The supply temperature (T1) in the hot end is subjected to a variation in the range of 249-239^{o}C and the outlet temperature (T2) in the hot end is fixed at 239^{o}C. The inlet temperature (T1) in the cold end is subjected to variation by the range of the pinch zone.

- H2. The inlet temperature is fixed even its entire part in the hot end is immersed in the pinch zone. Thus there exists a part of H2 in a hot end when the pinch is below its highest point. The inlet temperature of H2 in a hot end is fixed but its outlet temperature is varied according to the pinch temperature.

- C1. C1 is in the cold end.

- C2. C2 is a fixed stream and appear in both hot end and cold. The inlet temperature in the hot end (T2) and the outlet temperature (T1) in the cold end are varied.

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

Table 5.9 Hot End Process Stream Data for Example 2

Stream	W (kW/^{o}C)	Input Temperature (^{o}C)			Target Temperature (^{o}C)		
		Nom	Max	Min	Nom	Max	Min
H1	7.032	239	249	239	-	239	229
H2	8.44	239	-	-	-	239	229
C2	10	-	229	219	250	-	-

Table 5.10 Cold End Process Stream Data for Example 2

Stream	W (kW/^{o}C)	Input Temperature (^{o}C)			Target Temperature (^{o}C)		
		Nom	Max	Min	Nom	Max	Min
H1	7.032	-	239	229	120	-	-
H2	8.44	-	239	229	148	-	-
C2	6.096	106	116	96	150	-	-
C2	10	131	136	126	-	229	219

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

1. The starting condition for the hot end is shown in Table 5.11 (a). The first applicable pattern is A[H]. H2 is chosen to match to C2 since it has less heat load.

2. Next match the residual C2 to H1 with the pattern A[H]. The new stream condition is shown in Table 5.11 (b). Finally match C2 to a heating utility stream.

For the cold end synthesis, we see from Figure 5.11 that both H1 and H2 must be matched to C2 first since the target temperature of C2 is higher than of C1 and also the heat flow rate capacity of C2 is greater than both H1 and H2. So, in order to be matched to H1 and H2, C2 must be split.

Table 5.11 Synthesis table for Hot End of Example 2

Stream	Load	W	T1	T2	D1	D2	D_w	Action
(a)State 1								
H1	0	6.33	239	239	126.58	63.29	28.13	
H2	0	7.60	239	239	0	75.96	16.88	Selected
C1								
C2	199.5	9.5	250	229	0	90	31	Selected
(b)State 2								
H1	0	6.33	239	239	126.58	63.29	28.13	Selected
H2								Matched to C2
C1								
C2	182.62	9.5	250	231	0	61.92	0	Selected
(c)State 3								
H1								Matched to C2
H2								Matched to C2
C1								
C2	27.92	9.5	250	247	0	153.34	0	To heater

Table 5.12 Synthesis table for Cold End of Example 2

Stream	Load	W	T1	T2	D1	D2	D_w	Action
(a)State 1								
H1	689.84	6.33	229	120	63.29	0	153.30	Selected
H2	615.28	7.60	229	148	75.96	0	136.73	Selected
C1	186.54	5.49	150	116	0	109.73	65.84	
C2	747	9.5	219	136	95	95	93	Split
C21	266.84	3.21	219	136	32.15	32.15	31.47	Selected
C22	521.66	6.29	219	136	59.54	59.54	61.53	Selected
(b)State 2								
H1	359.38	6.33	177	120	94.76	0	0	Selected
H2	30.76	7.60	152	148	199.02	0	0	
C1	186.54	5.49	150	116	0	109.73	65.84	Selected
C21								Matched to H1
C22								Matched to H2
(c)State 3								
H1	63.11	6.33	130	120	336.16	0	0	to cooler
H2	30.76	7.60	152	148	199.02	0	0	to cooler
C1								Matched to H1
C21								Matched to H1
C22								Matched to H2

The synthesis is carried out stepwise as follows:

1. The starting condition for the cold end is shown in Table 5.12 (a). The first application pattern is B[C]. C2 is split and matched to H1 and H2. Calculate the minimum heat capacity flow rate which satisfy the resiliency Requirement for C22 to match to H2:

$$W_{C22}{=}L_{H2}/(T1_{C2min} - T2_{C2min})$$

$$=683.64/(219\text{-}126)=7.35$$

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

$$L_{C21} \leq L_{H1}$$

$$W_{C21} \leq W_{H1}$$

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

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

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

$$T1^{new}_{H1min} = T1_{H1min} - \frac{L_{C21}+D2_{C21}}{W_{H1}}$$

=229-(252.8+93.4)/6.33

=174

2. By satisfying the pattern B[C] and the resiliency, C2 is matched to H1 and H2. The condition of the new state is shown in Table 5.12(b). Since H2 has zero heat load, C1 must be matched to H1 and they satisfy the pattern B[C].

3. The next state shown in Table 5.12(c) has only hot streams left so they are matched to cooling utilities.

It should be noticed that H2, after being matched to C2, has zero heat load at the minimum heat load condition and requires 84.4 kW cooling duty at the maximum heating condition. The cooling duty of 84.4 kW can be supplied by C2. At the minimum heating condition this equivalent to 84.4/(219-136) = 1.01 kWC^{-1}. This amount of heat load can be supplied by C2 by increasing the ratio of C22. The ratio of heat capacity flow rate of C22 can be managed by a conventional controller by monitoring the inlet temperature of C2. Since C2 can supply all the cooling duty to H2 there is no need to install a cooler for H2. However, the change in flow rate of C2 will introduce a new disturbance in H1. The extra cooling duty (the consequence of increasing flow rate of C21) must be added to the cooler of H1. A resilient network structure solution to the Example 2 problem is show in Figure 5.12. The condition show in the figure is the nominal condition where the network has a pinch temperature at 239^{o}C on the hot scale. The heating requirement is 210 kW and the cooling requirement is 356.6 kW. The heat exchanger units 1 and 3, 2 and 4 can be merged together and a resilient network structure solution featuring minimum number of units is show in Figure 5.13.

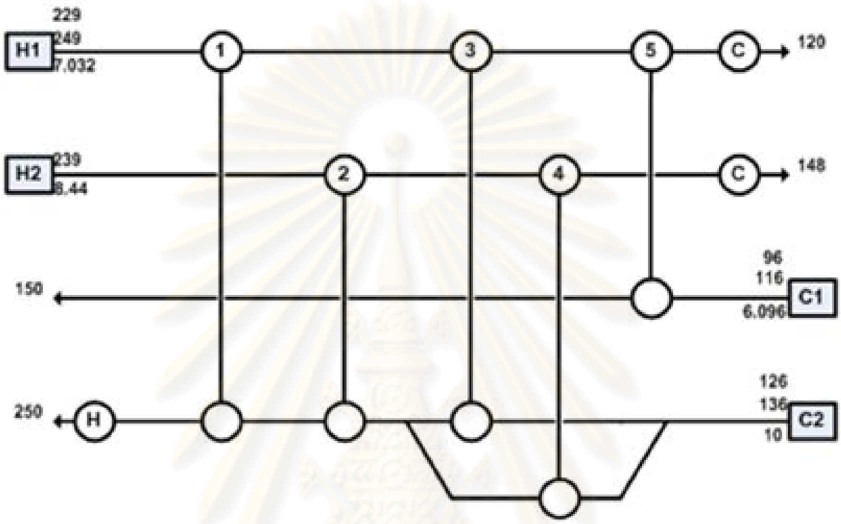


Figure 5.12 Heat Exchanger Network of Example 2

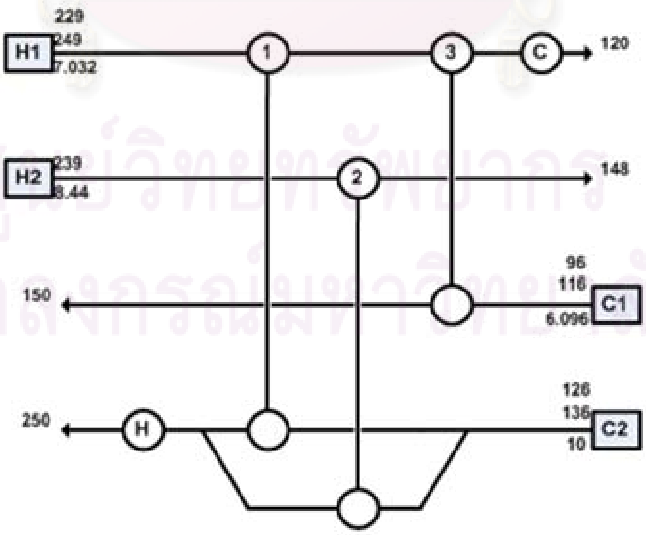


Figure 5.13 Heat Exchanger Network of Example 2 when merged the heat exchanger 1 and 3, 2 and 4

5.3.2 Design Control Structure

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

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

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

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

Considering the heat pathway in Figure 5.14, dash lines show the pathway of disturbance, there are 2 ways at HE1. Then, settle up cascade in order to calculate new setpoint temperature of cold stream of HE1 which provides no increase in cooler duty and heater duty. The control structures in Figure 5.15 to evaluate the performance.

In Figure 5.16 shows the heat pathway of positive and negative disturbance in Example 2 when settled the control structure and LSS. We see that all disturbances will transfer to the utility. In Figure 5.17 shows the simulation in HYSYS flow sheet.

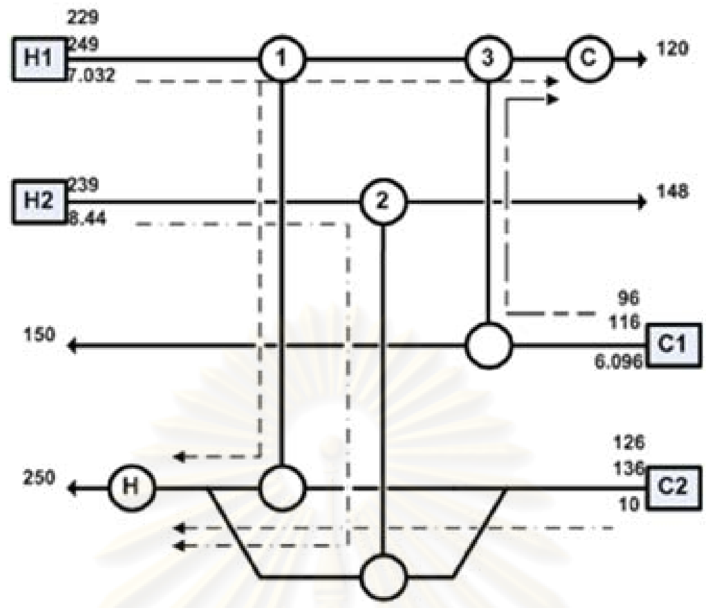


Figure 5.14 Heat pathway of disturbance in Example 2

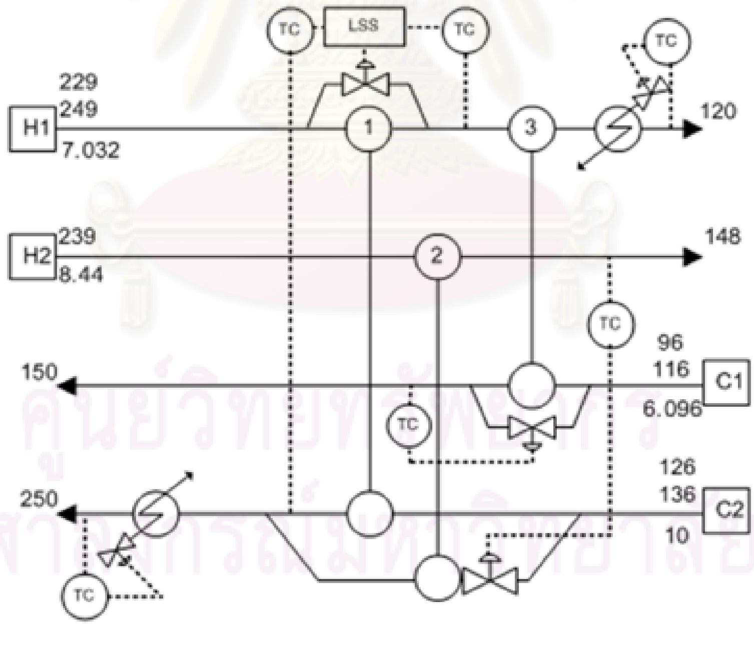


Figure 5.15 Control structure for example 2

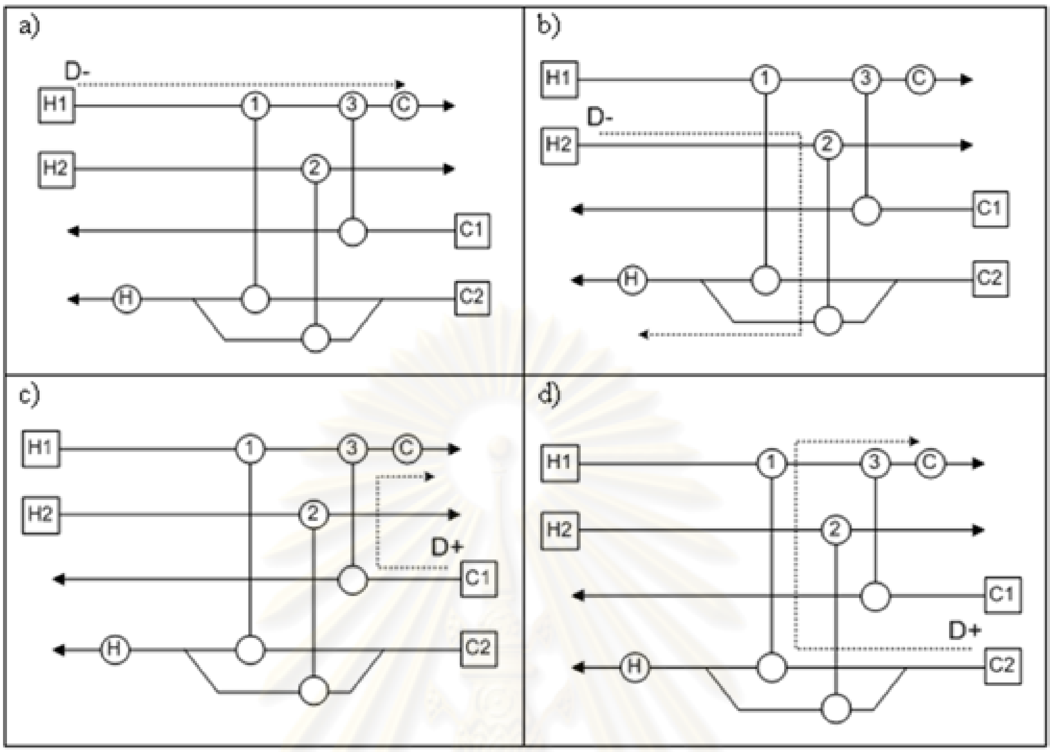


Figure 5.16 Heat pathway of control structure of network equipped with LSS when there is the disturbance at input temperature and inlet flow rate in Example 1
a) D- presented at H1
b) D- presented at H2
c) D+ presented at C1
d) D+ presented at C2

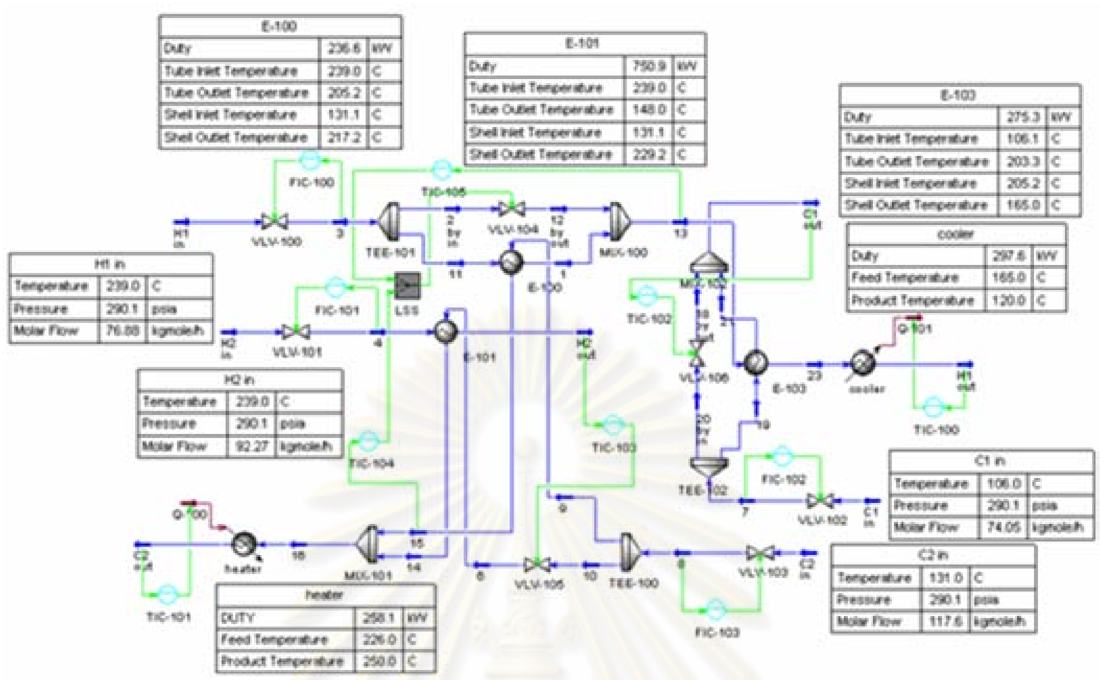


Figure 5.17 Heat exchanger network with LSS of example 2 from HYSYS flow sheet

5.3.3 Dynamic Simulation Result for HEN in example 2

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

Change in Input Temperature and Flow Rate of All Streams for Example 2 (decrease input temperature of all streams, decrease flow rate of stream H1 H2 and increase flow rate of stream C1 C2)

Figure 5.18 and 5.19 show the dynamic disturbance load of all streams and dynamic responses of HEN respectively, without and with LSS in example 2. In order to make these disturbances, first the fresh feed H1 temperature decreases from 244°C to 239°C, C1 temperature decreases from 106°C to 96°C, C2 temperature decreases from 131°C to 126°C, H1 flow rate decreases from 76.88 to 69.19

kgmole/h, H2 flow rate decreases from 92.27 to 83.04 kgmole/h, C1 flow rate increases from 74.05 to 81.45 kgmole/h and C2 flow rate increases from 117.60 to 123.48 kgmole/h at time equals 10 minutes then temperature and flow rate of all streams return to nominal value at time equals 200 minutes.

- The hot stream input temperature (H1) decreases. That is called negative disturbance, (D-). Heat pathway is shown in Figure 5.16 a). As a result, the hot outlet of HE1 temperature decreases below its minimum value. The LSS takes an action to control the cold outlet temperature of HE1.

- The cold stream input temperature (C1) decreases. That is called positive disturbance, (D+). Heat pathway is shown in Figure 5.16 c). As a result, to maintain target temperature of stream C1 the control loop is settled at the end of the stream. All disturbances occur on stream C1 are transferred to cooler.

- The cold stream input temperature (C2) decreases. That is called positive disturbance, (D+). Heat pathway is shown in Figure 5.16 d). As a result, the hot outlet of HE1 temperature decreases thus the LSS takes an action to control the cold outlet temperature of HE1 same as the hot stream input temperature (H1) decreases.

- The hot stream inlet flow rate (H1) decreases. That is called negative disturbance, (D-). As a result, the LSS takes an action to control the cold outlet temperature of HE1.

- The hot stream inlet flow rate (H2) decreases. That is called negative disturbance, (D-). Heat pathway is shown in Figure 5.16 b). Because no heat pathway transfers the disturbance to cooler therefore it is transferred to heater.

- The cold stream inlet flow rate (C1) increases. That is called positive disturbance, (D+). The result same as the cold stream input temperature (C1) decreases.

- The cold stream inlet flow rate (C2) increases. That is called positive disturbance, (D+). The LSS takes an action to control the cold outlet temperature of HE1.

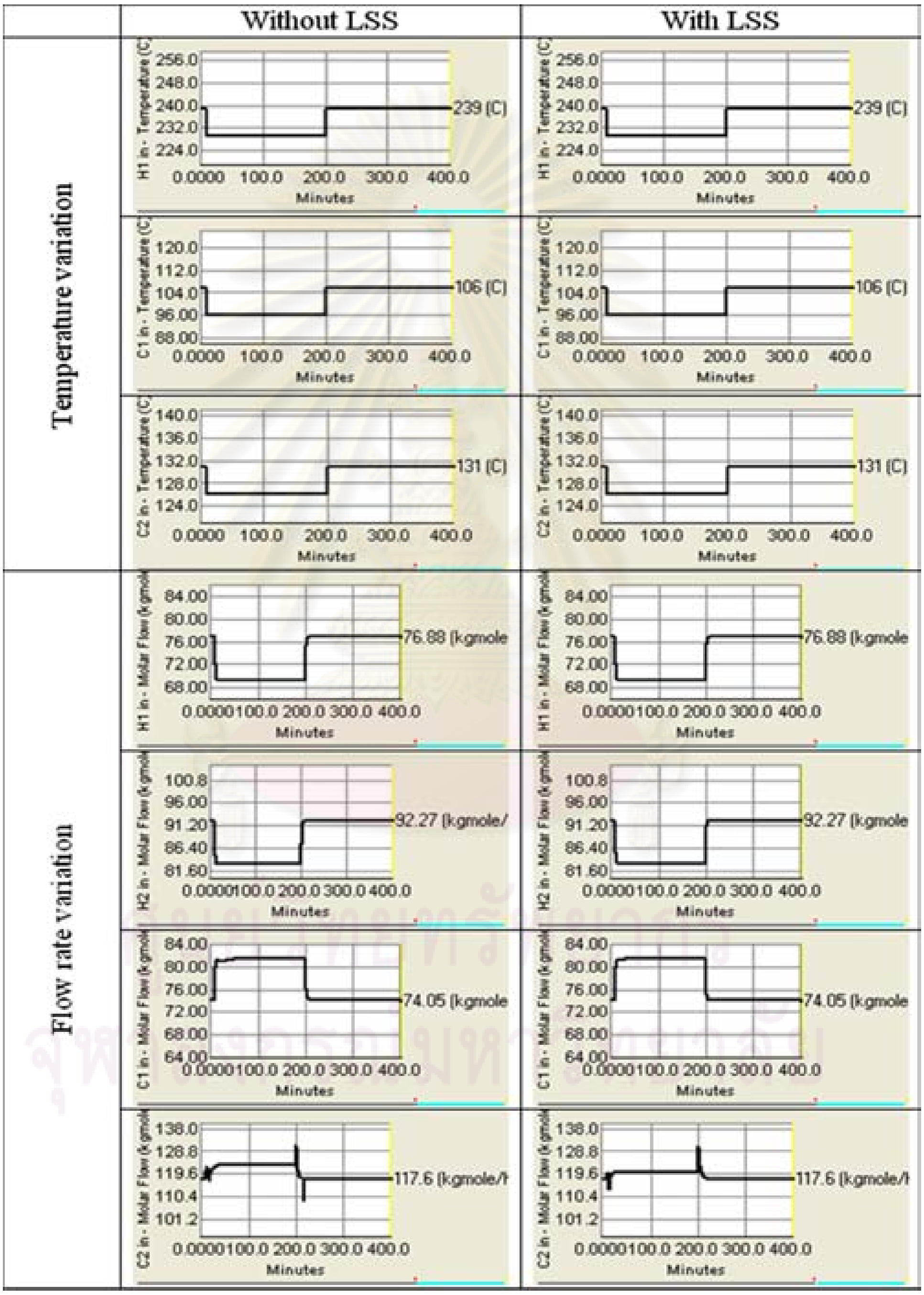


Figure 5.18 Disturbance load of all streams without and with LSS in example 2

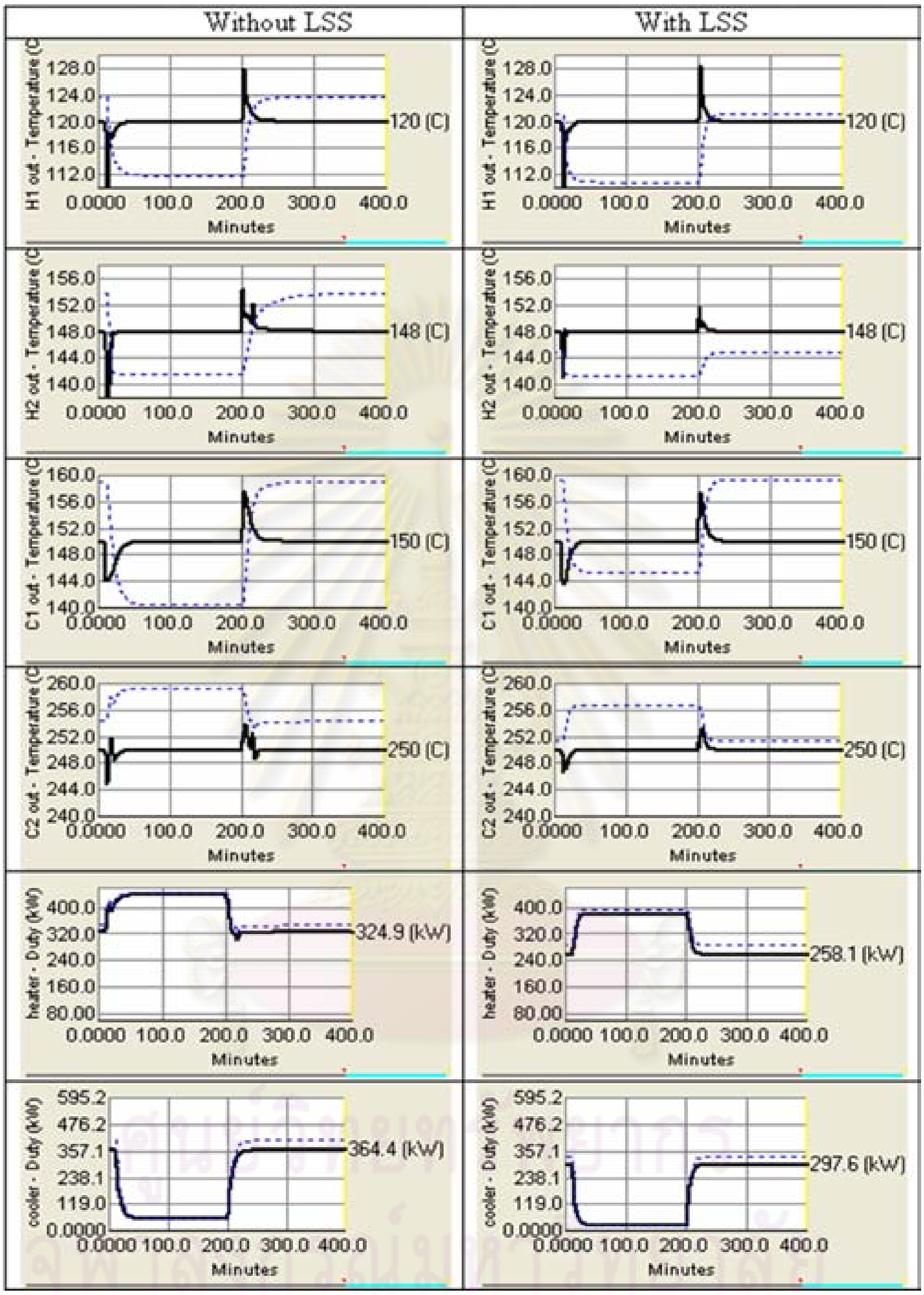


Figure 5.19 Dynamic responses of HEN without and with LSS in example 2

Table 5.13 Comparison of the IAE of control structure without and with LSS in the case of example 2

<table>
<tr><th rowspan="2">Controller</th><th colspan="2">IAE</th></tr>
<tr><th>Without LSS</th><th>With LSS</th></tr>
<tr><td>TIC-100</td><td>5.931</td><td>5.147</td></tr>
<tr><td>TIC-101</td><td>3.511</td><td>2.682</td></tr>
<tr><td>TIC-102</td><td>9.317</td><td>6.972</td></tr>
<tr><td>TIC-103</td><td>6.106</td><td>1.883</td></tr>
<tr><td>Average</td><td>6.216</td><td>4.171</td></tr>
</table>

Table 5.14 Comparison of the energy consumption of control structure with and without LSS in the case of Example 2

<table>
<tr><th rowspan="2">Stream Type</th><th rowspan="2">Variation</th><th rowspan="2">Disturbances</th><th colspan="2">Cooler Utility, kW</th><th colspan="2">Heater Utility, kW</th></tr>
<tr><th>Without LSS</th><th>With LSS</th><th>Without LSS</th><th>With LSS</th></tr>
<tr><td rowspan="2">H1</td><td>Input Temperature</td><td>Negative</td><td rowspan="7">49.50</td><td rowspan="7">24.34</td><td rowspan="7">437.86</td><td rowspan="7">379.33</td></tr>
<tr><td>Flow rate</td><td>Negative</td></tr>
<tr><td>H2</td><td>Flow rate</td><td>Negative</td></tr>
<tr><td rowspan="2">C1</td><td>Input Temperature</td><td>Positive</td></tr>
<tr><td>Flow rate</td><td>Positive</td></tr>
<tr><td rowspan="2">C2</td><td>Input Temperature</td><td>Positive</td></tr>
<tr><td>Flow rate</td><td>Positive</td></tr>
</table>

The cooler duty will be decreased from 50.17 kW to 7.31 kW while the duty of heater increases from 188.66 kW to 328.84 kW (Figure 5.19).

Table 5.13 and 5.14 show that the value of IAE of HEN with LSS is smaller than without LSS, and the LSS is likely an effective way to handle with disturbance come along with the variation of temperature that come from input temperature and flow rate. It brings about control structure of HEN that give dynamic maximum energy recovery.

5.4 Example 3 (HDA Process)

5.4.1 Design Heat Exchanger network

The Problem Table Method is applied to find pinch temperature and reach maximum energy recovery (MER). The information for design is shown in the following Table 5.15 (a) and (b).

Table 5.15(a) The information of HDA Process

Stream Name	Tin (^oC)	Tout (^oC)	W (kW/^oC)
H1: Reactor Product Stream (RPS)	621.1	45	33
H2: Recycle Column Condenser (RCC)	183	181	200
C1: Reactor Feed Stream (RFS)	65	621	32.24
C2: Product Column Reboiler (PCR)	145	193	91
C3: Stabilizer Column Reboiler (SCR)	190	215	59
C4: Recycle Column Reboiler (RCR)	349.5	350.7	456

Table 5.15(b) The information of HDA Process

Stream No.	W (kW/^oC)			Start Temperature (^oC)			Target Temperature (^oC)
	Max	Nom	Min	Nom	Max	Min	Nom
H1	-	34	-	620.85	626	616	45
H2	-	200	-	183.05	-	-	181
C1	32.44	32.24	32.04	69.63	75	65	621
C2	-	91	-	144.38	-	-	193
C3	-	59	-	189.92	-	-	215
C4	-	456	-	349.34	-	-	350.7

We can see that there are six streams in the network so we can find the Pinch temperature by using Problem Table Method as following: See Table 5.16

Table 5.16 Problem table for HDA process

W						T hot	T cold	ΣW	ΔT	Required Heat	Interval	Cascade Heat	Sum Interval
H1	H2	C1	C2	C3	C4								
0	0	0	0	0	0	631	621	0		Qh			
0	0	32.24	0	0	0	616	606	-32.24	15	6191.12	-483.60	5707.52	-483.60
33	0	32.24	0	0	0	360.7	350.7	0.76	255.3	5707.52	194.03	5901.55	-289.57
33	0	32.24	0	0	456	359.34	349.34	-455.24	1.36	5901.55	-619.13	5282.42	-908.70
33	0	32.24	0	0	0	225	215	0.76	134.34	5282.42	102.10	5384.52	-806.60
33	0	32.24	0	59	0	203	193	-58.24	22	5384.52	-1281.28	4103.24	-2087.88
33	0	32.24	91	59	0	199.92	189.92	-149.24	3.08	4103.24	-459.66	3643.58	-2547.54
33	0	32.24	91	0	0	183.05	173.05	-90.24	16.87	3643.58	-1522.35	2121.23	-4069.89
33	200	32.24	91	0	0	181	171	109.76	2.05	2121.23	225.01	2346.24	-3844.88
33	0	32.24	91	0	0	155	145	-90.24	26	2346.24	-2346.24	0	-6191.12
33	0	32.24	0	0	0	85	75	0.76	70	0	53.20	53.20	-6137.92
33	0	0	0	0	0	45	35	33	40	53.20	1320	1373.20	-4817.92
												Qc	

By using Synthesis procedure in Chapter III, we can receive 3 resilient networks. The network that has minimum IAE (Sapsawaipol, 2007) is chosen to simulate in HYSYS to check that it can achieve the maximum energy recovery and keep their target temperature at their desirable value when it is in the real process (see Table 5.17-5.18 and Figure 5.20-5.21).

Table 5.17 Synthesis Table for cold end

Stream	Load	W	T1	T2	D1	D2	D_w	Action
(a)State 1								
H1	3630	33	155	45	0	0	0	Selected
C1	2242.8	32.04	145	75	0	320.4	32	Selected
(b)State 2								
H1	1034.8	33	76.36	45	352.4	0	0	to cooler
C1								Matched to H1

Table 5.18 Synthesis Table for hot end

Stream	Load	W	T1	T2	D1	D2	D_w	Action
(a)State 1								
H1	15213	33	616	155	152130	0	0	Selected
H2	410	200	183.05	181	0	0	0	
C1	15251	32.04	621	145	0	0	190.4	
C2	4368	91	193	145	0	0	0	Selected
C3	1479.72	59	215	189.92	0	0	0	
C4	620.16	456	350.7	349.34	0	0	0	
(b)State 2								
H1	10845	33	616	287.36	330	0	0	Selected
H2	410	200	183.05	181	0	0	0	
C1	15251	32.04	621	145	0	0	190.4	
C2								Matched to H1
C3	1479.72	59	215	189.92	0	0	0	Selected
C4	620.16	456	350.7	349.34	0	0	0	
(c)State 3								
H1	9365.28	33	616	332.20	330	0	0	
H2	410	200	183.05	181	0	0	0	Selected
C1	15251	32.04	621	145	0	0	190.4	Selected
C2								Matched to H1
C3								Matched to H1
C4	620.16	456	350.7	349.34	0	0	0	

Stream	Load	W	T1	T2	D1	D2	D_w	Action
(d)State 4								
H1	9365.28	33	616	332.20	330	0	0	Selected
H2								Matched to C1
C1	14841	32.04	621	157.80	0	190.4	0	
C2								Matched to H1
C3								Matched to H1
C4	620.16	456	350.7	349.34	0	0	0	Selected
(e)State 5								
H1	8745.12	33	616	351.00	330	0	0	Selected
H2								Matched to C1
C1	14841	32.04	621	157.80	0	190.4	0	Selected
C2								Matched to H1
C3								Matched to H1
C4								Matched to H1
(f)State 6								
H1								Matched to C1
H2								Matched to C1
C1	5765.92	32.04	621	441.04	0	520.4	0	To heater
C2								Matched to H1
C3								Matched to H1
C4								Matched to H1

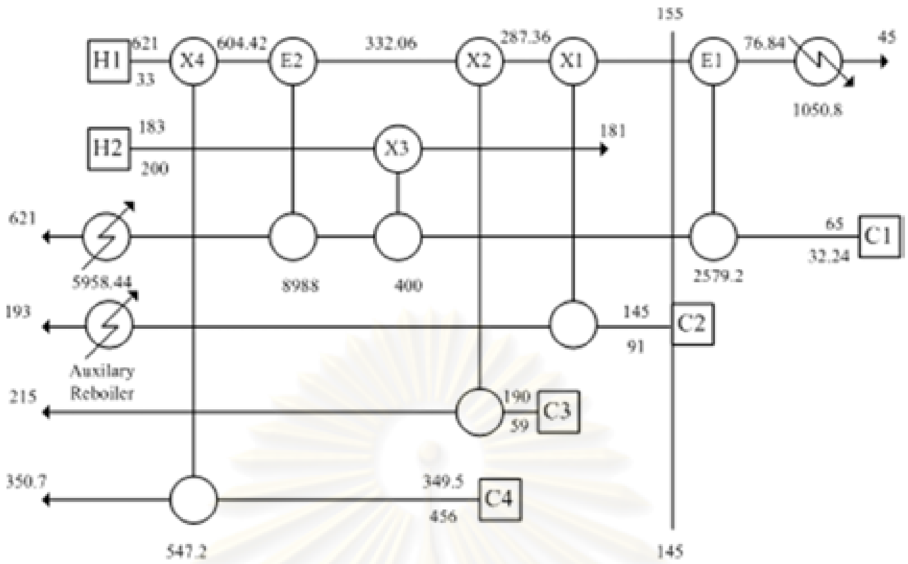


Figure 5.20 Resilient Heat Exchanger Network of Example 3

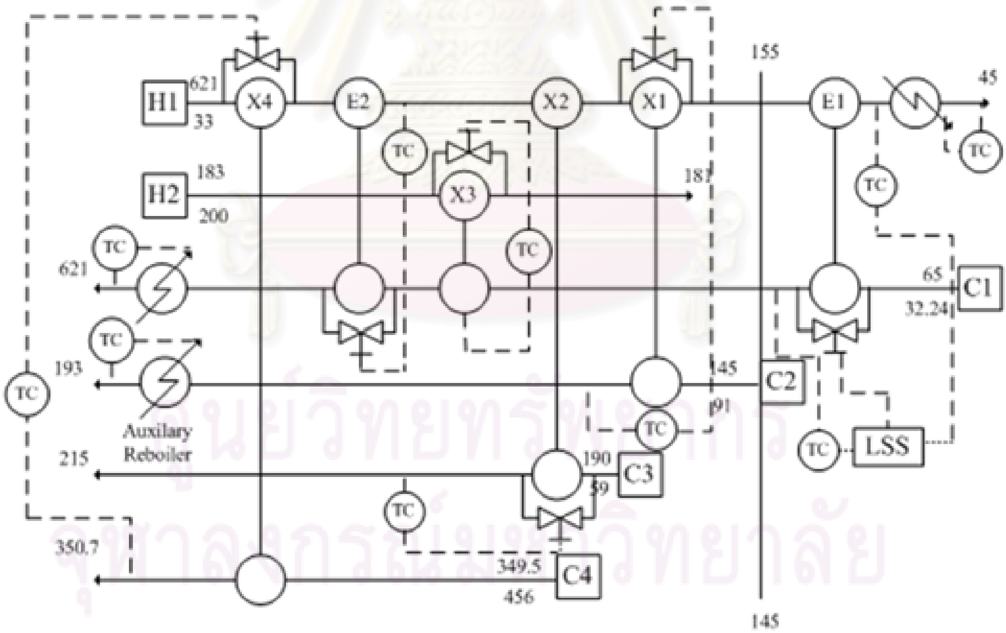


Figure 5.21 Control structure for example 3

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

In order to evaluate the dynamic behaviors of the HDA Process, several disturbance loads were made. This network that we chose to simulate in HYSYS because when disturbances present at input temperature of C3, we see that the heat link which go to the heater is shorter than the other. That means it can handle the disturbance faster.

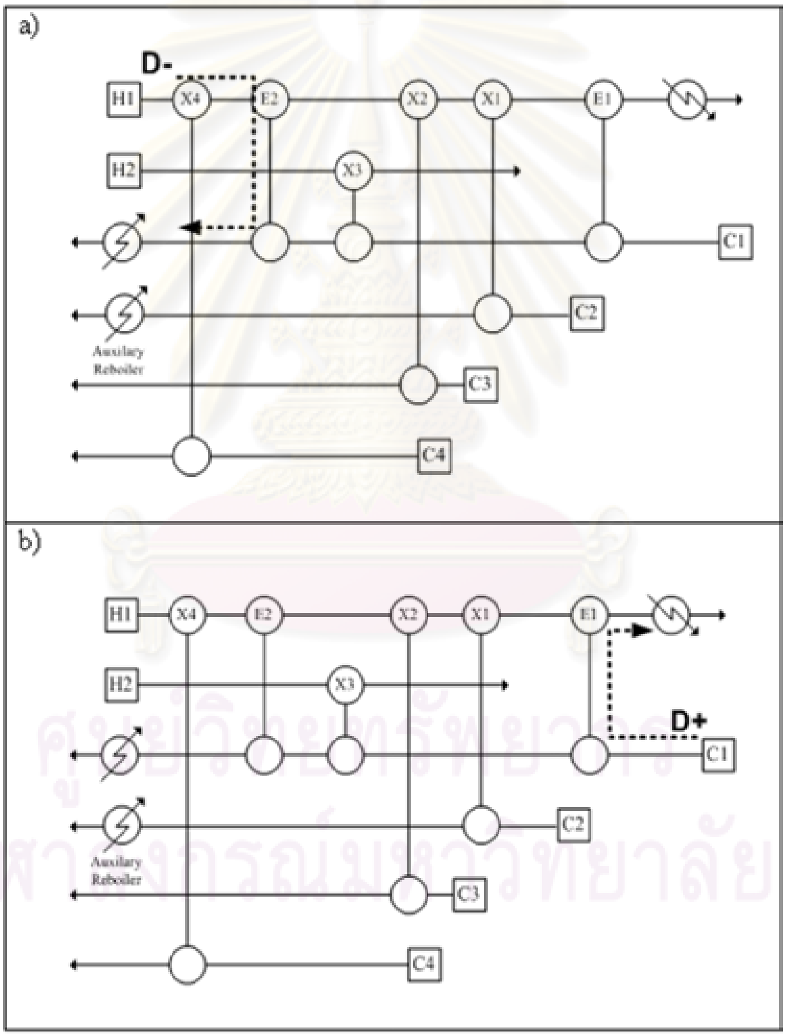


Figure 5.22 Heat pathway of control structure of network equipped with LSS when there is the disturbance at input temperature and inlet flow rate in Example 3
a) D- presented at H1
b) D+ presented at C1

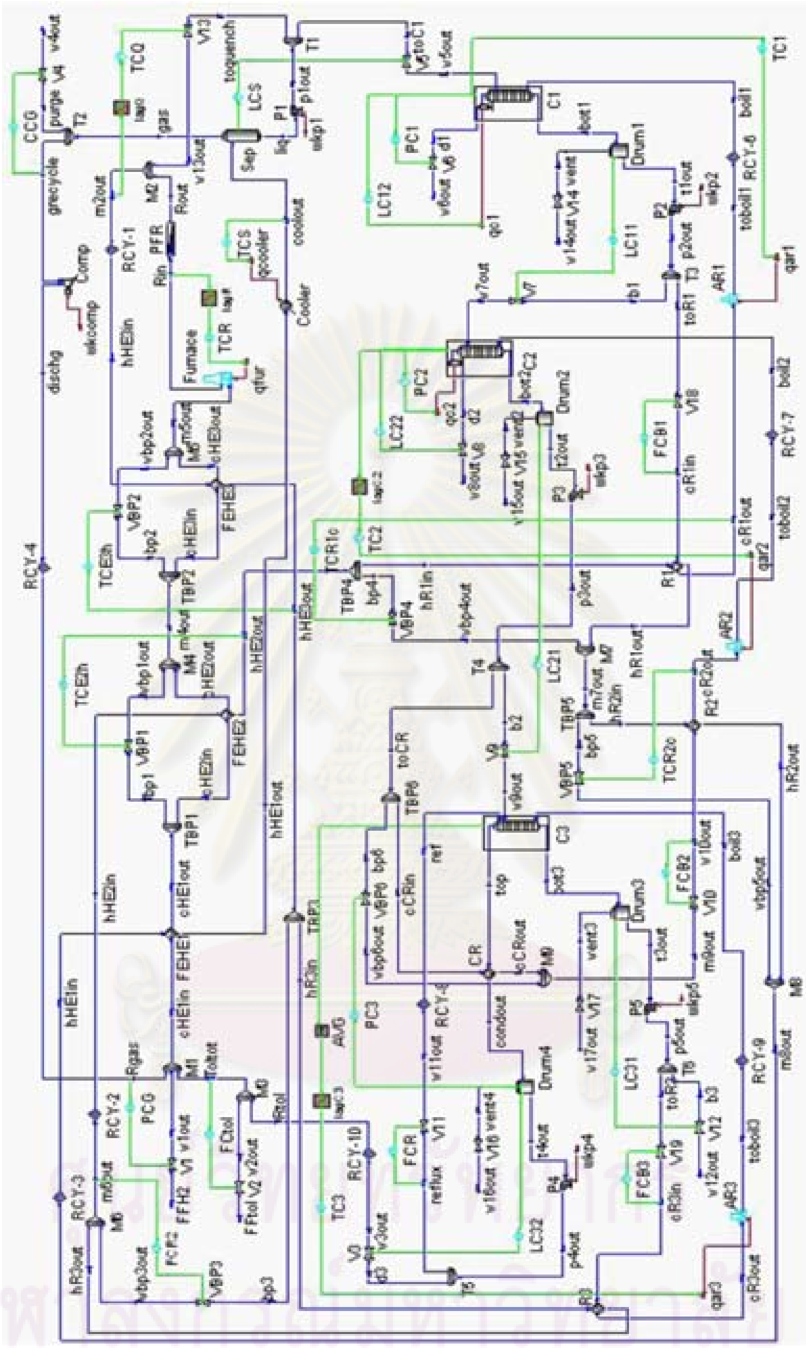


Figure 5.23 Control structure of example 3 (HDA Process) from HYSYS flow sheet

5.4.3 Dynamic Simulation Results for HDA Process

In order to illustrate the dynamic behavior of the control structure in HDA process, several disturbance loads are made. The dynamic responses of the control system are shown in Figures 5.24 to 5.25.

Change in the input temperature and Flow Rate of Streams for Example 3 (decrease input temperature of stream H1 C1, increase flow rate of stream C1)

Figure 5.24 and 5.25 shows the dynamic disturbance load of all streams and dynamic responses of HEN respectively, without and with LSS in HDA process. To a change in the disturbance load of hot stream from reactor, by changing its temperature from 620.85^{o}C to 616^{o}C, reactor feed stream temperature decreases from 69.63^{o}C to 65^{o}C and its flow rate increases from 1988.3 kgmole/h to 2087.7 kgmole/h at time equals 10 minutes then temperature and flow rate of these streams return to nominal value at time equals 200 minutes.

- The hot stream input temperature (H1) decreases. That is called negative disturbance, (D-). Heat pathway is shown in Figure 5.22 a). As a result, the control loop is settled at the hot outlet of HE2. All disturbances occur on stream H1 are transferred to heater because it can handle the disturbance faster.

- The cold stream input temperature (C1) decreases. That is called positive disturbance, (D+). Heat pathway is shown in Figure 5.22 b). As a result, the hot outlet of HE1 temperature decreases below its minimum value. The LSS takes an action to control the cold outlet temperature of HE1.

- The cold stream inlet flow rate (C1) increases. That is called positive disturbance, (D+). The result same as the cold stream input temperature (C1) decreases.

The cooler duty will be decreased from 1417.27 kW to 1142.18 kW while the duty of heater increases from 7751.08 kW to 8765.57 kW (Figure 5.25)

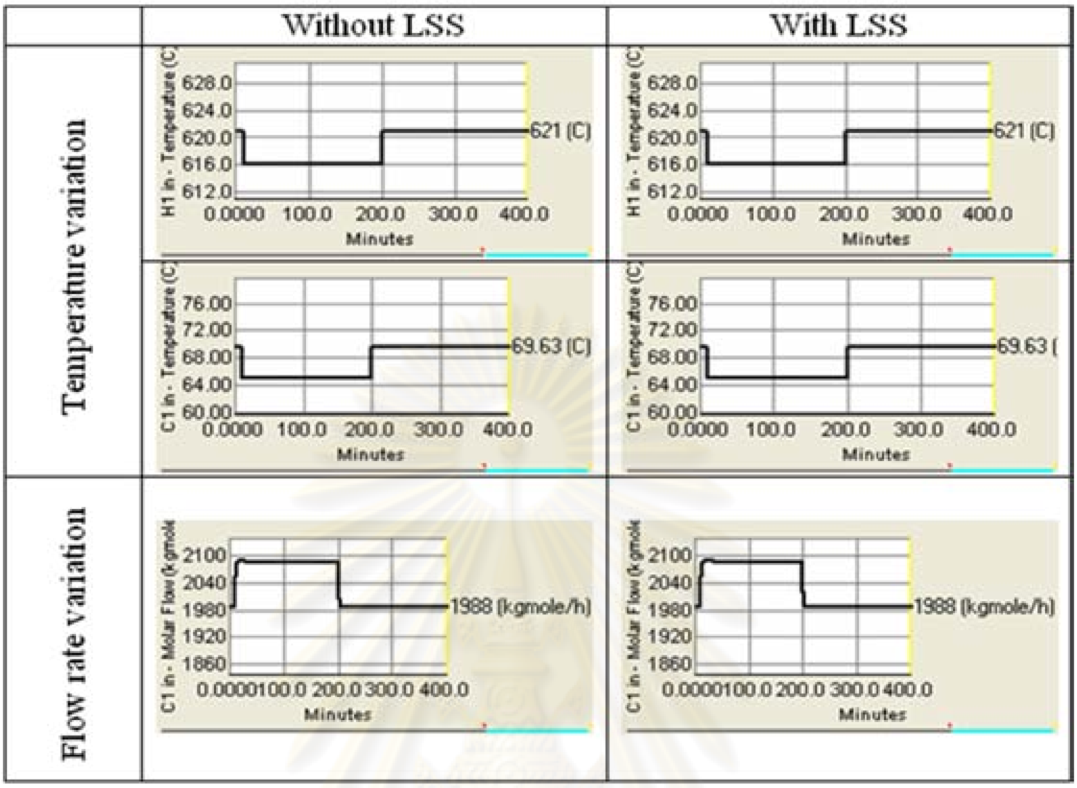


Figure 5.24 Disturbance load of all streams without and with LSS in example 3

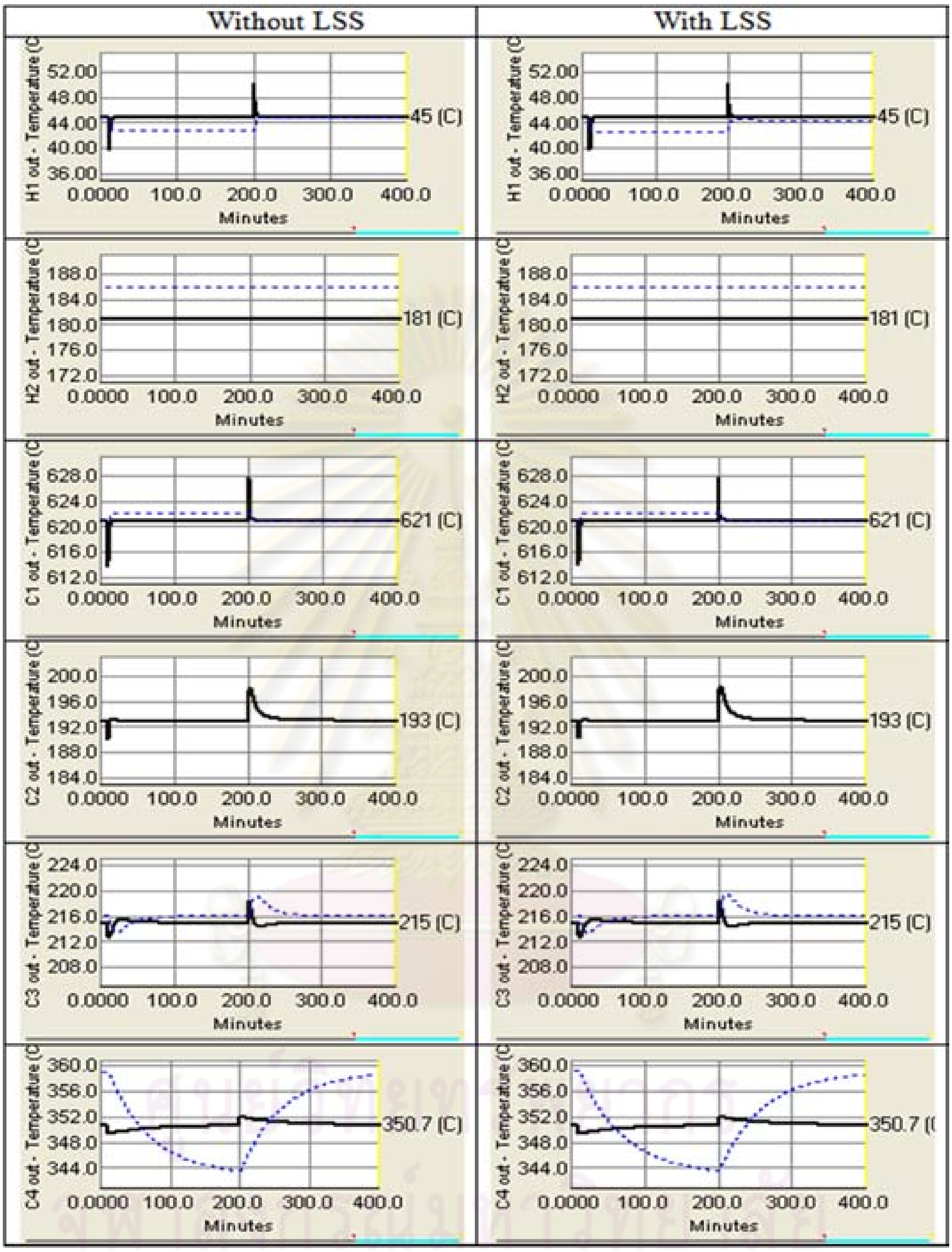


Figure 5.25 Dynamic responses of HEN without and with LSS in example 3

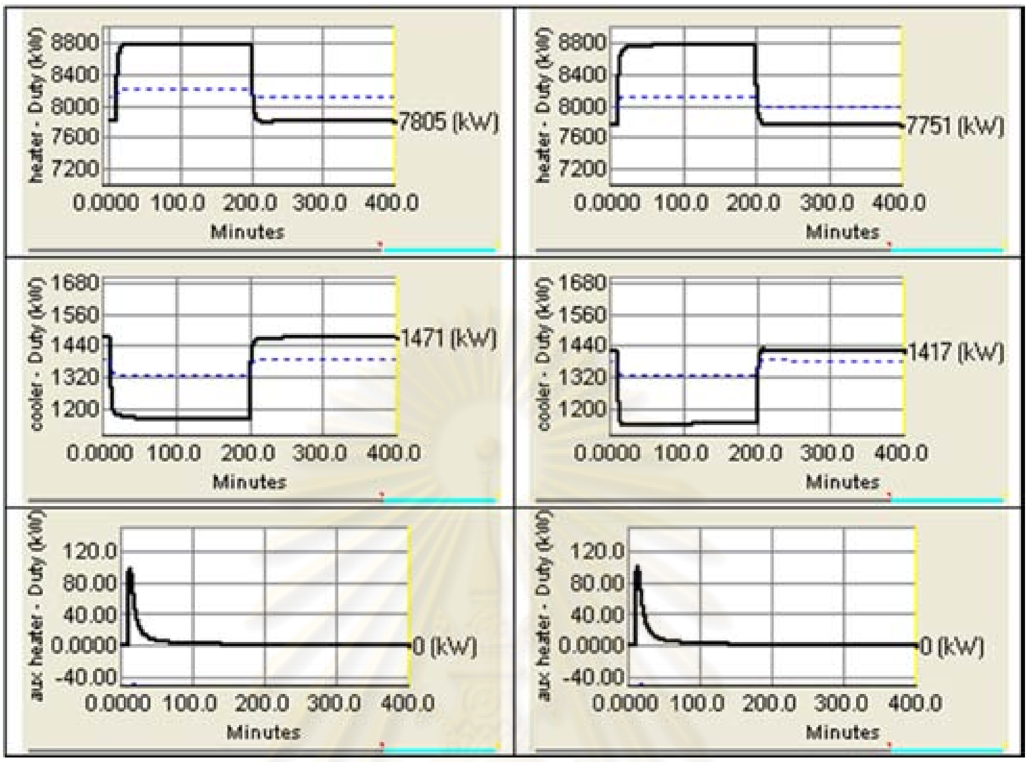


Figure 5.25(cont) Dynamic responses of HEN without and with LSS in example 3

Table 5.19 Comparison of the IAE of control structure without and with LSS in the case of example 3

Controller	IAE	
	Without LSS	With LSS
TIC-100	0.645	0.662
TIC-101	4.130	4.407
TIC-102	0.990	0.925
TIC-103	7.706	7.714
TIC-104	2.892	3.041
TIC-105	0.001	0.010
Average	2.728	2.793

Table 5.20 Comparison of the energy consumption of control structure with and without LSS in the case of Example 3

Stream Type	Variation	Disturbances	Cooler Utility, kW		Heater Utility, kW	
			Without LSS	With LSS	Without LSS	With LSS
H1	Input Temperature	Negative	1161.40	1142.18	8784.75	8765.57
C1	Input Temperature	Positive				
	Flow rate	Positive				

Table 5.19 and 5.20 show that the value of IAE of HEN with LSS closes to without LSS, and the LSS is likely an effective way to handle with disturbance come along with the variation of temperature that come from input temperature and flow rate. It brings about control structure of HEN that give dynamic maximum energy recovery.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

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

6.1.1 Procedures of Design Heat exchanger network

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

1. Pop a match pattern operator from the ordered stack of match patterns. If all the patterns are chosen, backtrack to the parent design state and repeat the procedure. If the current state is the starting state and all parents have been tried without success the problem cannot be solved with the current knowledge in the rule-based system. A trade-off between cost and resiliency may be needed.

2. Choose a pair of hot and cold streams from the set of unmatched process streams. If all streams have been chosen and none were satisfied, go back to the first step to try a new pattern.

3. Apply the match pattern to the selected pair of streams. If the streams satisfy the pattern test and the resiliency requirement (Table 4.1 and 4.2),

go to the next step. Otherwise go back to the previous step to select a new pair of streams.

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

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

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

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

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

6. If there are unmatched hot and cold streams, go to the second step. Otherwise go to the next step.

7. Match the only hot or cold streams with the utility streams.

8. If there are other unused match patterns go to the first step. This is equivalent to saying that there might be other solutions available, continue.

6.1.2 Procedures of Design Control Structure

1. Use Bypass stream for controlling. The bypass stream should be settled on the cold side because it would be safer to equip measure equipment and control valve on the hot side. On the other hand, it should settle bypass stream on the controlling side regardless whether it is hot or cold stream. However, the selection must bring about the best performance of control system.

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

3. From the economic point of view, we strongly suggest to:

   3.1 shift D^+ of cold stream or D^- of the hot stream to the cooler utility, thus its duty will be decreased.

   3.2 shift D^- of cold stream or D^+ of the hot stream to the heater utility, thus its duty will be decreased.

4. A selective controller with low selector switch (LSS) should be employed to select an appropriate heat pathway through the network to carry the associated load to the utility unit.

5. A selective controller with low selector switch (LSS) should be employed to select an appropriate heat pathway through the network to carry the associated load to the utility unit.

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

   6.1 Identify the heat pathway of disturbance

   6.2 If there is only one heat pathway, it do not need to be set the LSS.

   6.3 If there are more than one heat pathway, it need to be set the LSS between the outlet temperature of Heat exchanger.

The design procedure of heat exchanger network and control structure earned from this research can be applied to the usual network in the presence of variation from changing in flow rate, inlet temperature and outlet temperature because of this step considering the possible structure of overall network existed.

It can, moreover, be used to configure suitable control structure as a convenient and simply tool.

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

6.2 Recommendation

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

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APPENDICES

APPENDIX A

TUNING OF CONTROL STRUCTURES

A.1 Tuning Controllers

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

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

A.2 Tuning Flow, Level and Pressure Loops

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

Most level controllers should use proportional-only action with a gain of 1 to 2. This provides the maximum amount of flow smoothing. Proportional control means there will be steady state offset (the level will not be returned to its setpoint value). However, maintaining a liquid level at a certain value is often not necessary when the liquid capacity is simply being used as surge volume. So the recommended tuning of a level controller is $K_C = 2$. Most pressure controllers can be fairly easily tuned. The process time constant is estimated by dividing the gas volume of the system by the volumetric flowrate of gas flowing through the system. Setting the integral time equal to about 2 to 4 times the process time constant and using a reasonable controller gain usually gives satisfactory pressure control. Typical pressure controller tuning constants for columns and tanks are KC = 2 and = 10 minutes.

A.3 Relay- Feedback Testing

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

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

$$K_U = \frac{4h}{a\pi} \tag{1}$$

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

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

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

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

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

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

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

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

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

A.4 Inclusion of Lags

Any real physical system has many lags. Measurement and actuator lags always exist. In simulations, however, these lags are not part of the unit models. Much more aggressive tuning is often possible on the simulation than is possible in the real plant. Thus the predictions of dynamic performance can be overly optimistic. This is poor engineering. A conservative design is needed. Realistic dynamic simulations require that we explicitly include lags and/or dead times in all the important loops. Usually this means controllers that affect Product quality or process constraint. Table A.1 summarizes some recommended lags to include in several different types of control loops.

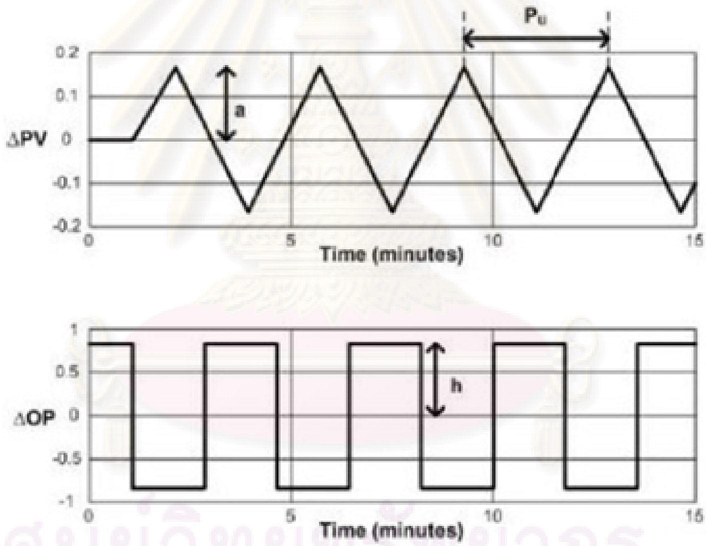

Figure A.1 Input and Output from Relay-Feedback Test

Table A.1 Typical measurement lags

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

Any real physical system has many lags. Measurement and actuator lags always exist. In simulations, however, these lags are not part of the unit models. Much more aggressive tuning is often possible on the simulation than is possible in the real plant. Thus the predictions of dynamic performance can be overly optimistic. This is poor engineering. A conservative design is needed.

VITA

Mr.Ekkarat Purimaporn was born in Bangkok, Thailand on September 6, 1984. He received the Bachelor Degree in Chemical Engineering from Kasetsart University in 2006. After that he entered the Graduate School of Chulalongkorn University to pursue the Master of Engineering in Chemical Engineering and completed in 2009.