Dynamics and Control of Heat Exchanger Networks

Dr. Duraid Fadhil Ahmed
Engineering College, University of Tikrit/ Salahaldin
Email: dr_duraid@yahoo.com
Cizan A. Ali
Engineering College, University of Tikrit/ Salahaldin
Email: engsezan@yahoo.com

Received on: 14/4/2013 & Accepted on 3/10/2013

ABSTRACT

In this paper dynamics of plate heat exchanger networks is given by combining dynamic models of plate heat exchangers in the network. A mathematical model for plate heat exchanger is developed based on energy balance. Dynamic simulation of plate heat exchanger networks to different step changes in flow rate of both process fluid and utility fluid is conducted using MATLAB simulink. Plate heat exchanger networks has been controlled using split range control method with two manipulated variables which are process fluid and utility fluid. The simulation results showed that split range controller is the best action and gives better response compared with conventional controller.

Keywords: Heat Exchanger Networks, Mathematical Modeling of Plate Heat Exchanger, MATLAB Simulink, Split Range Controller.

السلوك الديناميكي و السيطرة على شبكة المبادلات الحرارية

الخلاصة

تم في البحث الحصول على النموذج الديناميكي لشبكة المبادلات الحرارية الصفائحية من خلال الجمع بين النموذج الديناميكي لمبادلات الحرارية الصفائحية الموجودة في الشبكة. تم تطوير نموذج رياضي لمبادل الحراري الصفائحي بالاعتماد على موازنة الطاقة. أجريت محاكاة ديناميكية لشبكة المبادلات الحرارية الصفائحية باستخدام برنامج ماتلاب من خلال اجراء اضطراب درجي في معدل الجريان لمائعي العملية والخدمات. تمت السيطرة على شبكة المبادلات الحرارية الصفائحية باستخدام مسيطر المدى المنفصل ذو متغيرين للمعالجة و أظهرت نتائج المحاكاة بأن مسيطر المدى المنفصل هو أفضل أداء وأعطت استجابة جيدة مقارنة مع المسيطر التقليدي.

ABBREVIATIONS

Symbol	Definition
FSC	Flexible Structure Control
GAMS	General Algebraic Modeling System
HEN	Heat Exchanger Network
MV	Manipulated variable
NMPC	Nonlinear Model Predictive Control

https://doi.org/10.30684/etj.32.2A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

PHE	Plate Heat Exchanger

NOMENCLATURE

Symbol	Definition	Units
M_c	Mass of Cold water in Plate Heat Exchanger	Kg
m_{cs}	Mass flow rate of Cold water at Steady State	Kg/s
M_h	Mass of Hot water in Plate Heat Exchanger	Kg
m_{hs}	Mass flow rate of Hot water at Steady State	Kg/s
Th_{is}	Inlet Temperature of Hot water at Steady State	°C
Th_{os}	Outlet Temperature of Hot water at Steady State	°C
K	Gain	°C/Kg/s
m	Mass flow rate	Kg/s
M	Mass of water in Plate Heat Exchanger	Kg
t	Time	s
Tc	Temperature of cold water	°C
Tco1	Outlet temperature of cold utility fluid from cooler unit	°C
Tco2	Outlet temperature of cold process fluid from heater unit	°C
Th	Temperature of hot water	°C
Tho1	Outlet temperature of hot process fluid from cooler unit	°C
Tho2	Outlet temperature of hot utility fluid from heater unit	°C

GREEK LETTERS

Symbol	Definition	Units
τ	Time constant	s
τ_1	The time constant of cold water	s
τ_2	The time constant of hot water	s

INTRODUCTION

Large chemical processes usually require energy recovery systems to maintain a competitive operation. A heat-exchanger network (HEN) usually plays an important Lrole in these process systems, where the thermal outlet condition of several process streams must be controlled without reducing heat integration. In a HEN, the hot and cold streams are matched in order to reduce the amount of utility consumption and/or the total cost [1]. Control of heat exchanger networks has been a matter of research for many years. The control system must be capable of not only permitting the HEN system to reach the point of minimum utility consumption, but also of driving the final process-stream temperatures to their set points[2] . In the last years, the design of a proper control structure for the HEN system has become a subject to academic research, mainly after it was realized that hard constraints in the manipulated inputs plays an important part in the control problem [3]. Constraint problems on manipulated variables usually occur in chemical processes. Controlled ouputs can go away from the desired set point when some manipulated variables are saturated. Operability spaces are reduced because the adjustment of some additional inputs is required to keep outputs to their set points. Split- range control is a simple technique that can handle constraint problems on manipulated variables. In split range control, several manipulated variables are used to control one controlled variable [4]. Giovanini and Martchetti [5] proposed a low-Level flexible-structure control(FSC) for designing control systems capable of efficiently handling constraints on the manipulated variables of heat exchanger networks (HENs). They also studied dynamic simulation of flexible structure control and showed that FSC can deliver reasonable good control performance. Alejandro *et al*.[6] discussed the online optimization and control of a heat-exchanger network (HEN) through a two-level control structure. The low level is a constrained model predictive control (MPC) and the high level is a supervisory online optimiser. The proposed MPC algorithm uses an approximate linear model of the system to perform the output predictions and to account for the constraints. Akman and Uygun [7] studied nonlinear model predictive control (NMPC) of a heat-exchanger network (HEN) and they found that NMPC scheme, in which the nonlinear distributed-parameter HEN model is solved sequentially by referring to an algebraic steady state optimization model, satisfies the temporal and steady-state hard/soft constraints imposed on the target temperatures of the retrofit HEN. Alexandre [8] studied the operation of the heat exchanger network of a crude unit at Mongstad refinery (Statoil) by applying the concept of self-optimising control and two main control configurations are examined: a simple decentralised control configuration (PIDs Control) and an advanced multivariable control configuration (Model Predictive Control). The decentralised control configuration was found to present acceptable dynamic performances while the advanced multivariable configuration only enhances them a bit. Giovanini and Balderud [9] proposed an agent based decentralized predictive control approach, where the computational demand is distributed between several agents. They also explored the computational demand associated with the proposed approach and compared it against a traditional, centralized, predictive control approach. Marcelo and Jorge [10] presented and implemented the main approaches to solve the problem of heat exchanger network synthesis, sequential and simultaneous, using the general algebraic modeling System (GAMS). Initialization strategies for generating feasible starting points are proposed and the results showed the efficiency of the initialization strategies.

In this paper two main objectives are considered, the first is to create a dynamic model for simulation of a plate heat exchanger network to study the response of the process at different operating condition. Thus, theoretical studies on plate heat exchanger is carried out and the second one is to study the control of heat exchanger networks by using split range control with two manipulated variable to achieve target temperature with minimum utility cost.

Mathematical Modeling of Plate Heat Exchanger

Basic equations for present plate heat exchanger are obtained based upon energy balance. It is considered that each plate operates independently and the transfer function of one plate represents the overall transfer function of the whole plate heat exchanger. This plate can be considered as a lumped system where the theoretical analysis depends upon the inlet and outlet temperature, and variation of temperature along the length is neglected [11].

The mathematical description of the process can be carried out by simple energy balance based on enthalpy change of streams around the overall plate shown in Figure (1).

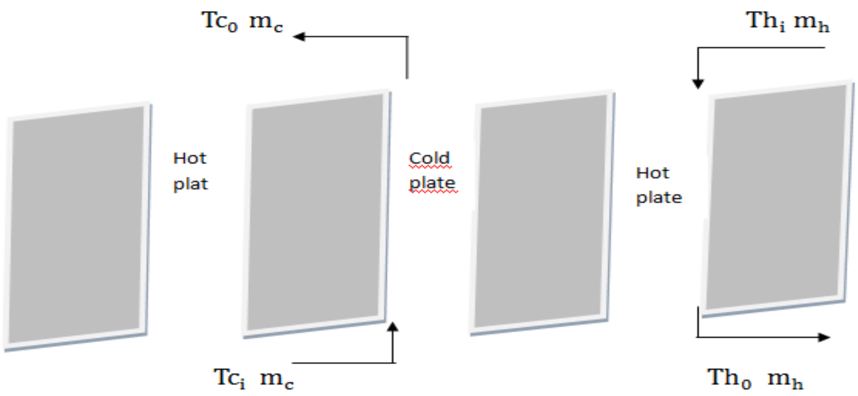

Figure (1) Arrangement of Cold and Hot streams for Plate Heat Exchanger.

Energy balance around cold water plates:

$$M_c\frac{dTc_o(t)}{dt}+m_{cs}Tc_o(t) = (Th_{is}-Th_{os})m_h(t)-m_{hs}Th_o(t) \qquad \ldots (1)$$

Taking Laplace transform of Eq. (1):

$$Tc_o(s)=\frac{K_1}{\tau_1 s+1}m_h(s)-\frac{K_2}{\tau_1 s+1}Th_o(s) \qquad \ldots (2)$$

The energy balance around hot water plate gives:-

$$M_h\frac{dTh_o(t)}{dt}+m_{hs}Th_o(t) = (Th_{is}-Th_{os})m_h(t)-m_{cs}Tc_o(t) \qquad \ldots (3)$$

Taking the Laplace transform of Eq. (3):

$$Th_o(s)=\frac{K_3}{\tau_2 s+1}m_h(s)-\frac{K_4}{\tau_2 s+1}Tc_o(s) \qquad \ldots (4)$$

Substituting equation(4) with equation (3) to eliminate $Th_o(s)$ gives:

$$G(s)=\frac{K}{\tau_P s+1}$$

Where: $K=\frac{K_1\tau_2}{(\tau_1+\tau_2)}$ and $\tau_p=\frac{\tau_1\tau_2}{\tau_1+\tau_2}$

Finally, it is observed that the transfer function of system can be represented by first order system with steady state gain and the time constant.

Synthesis of Heat Exchanger Networks

The synthesis of a HEN is usually a very complex task that implies a combinatory problem for matching hot and cold flow streams in order to permit a maximum energy recovery to be achieved. In general, the HEN synthesis process can be summarized as follows: A set of hot flow streams must be cooled to specific temperature values, while another set of cold flow streams must be heated up to determined values. Each flow stream is characterized by its own specific heat capacity and mass flow velocity. Thus, the problem to be solved consists in finding the optimal topology (i.e., heat exchanger structure) of a HEN having the most appropriate heat load distribution in such a way that the maximum thermal power can be transferred between the flow streams. It is obvious that the optimization process also must reduce the number of external utilities (i.e., heat sources and sinks). Therefore, the synthesis of the optimal HEN requires working in two different ‘‘solution spaces” [12]:

(**1**) a topological space where, according to the nature of the interaction between the flow streams different structures are possible.

(**2**) a thermal load space where different thermal power distributions between heat exchangers are possible.

Structure of Heat Exchanger Networks

The structure of heat exchanger networks is very important because it determines the relationships among input/output variable of heat exchangers in the network. Some input variables (i.e. inlet temperatures of heat exchangers) in a heat exchanger model are considered as state variables in a heat exchanger network model. Furthermore, only some outlet temperatures of heat exchangers can have targets (i.e. typically the temperatures concerning the outlet of process streams). To assess controllability of HENs, the dynamic model of heat exchangers is needed which is given by combining dynamic (structural) models of heat exchangers in the network [13]. The heat exchanger network studied in this work is composed by four recovery exchangers and two service unit (one cooler and one heater) as shown in Figure(2). There are two process streams that have to receive a proper thermal conditioning and two utility stream that help to reach the desired temperature. Thus, the complete system has four input or manipulated variables (two by passes and two utility flow rates) and two outputs to be controlled (process stream temperature). The objective is to reach a satisfactory control quality, which includes reasonable disturbance rejections, rapid tracking for set-point.

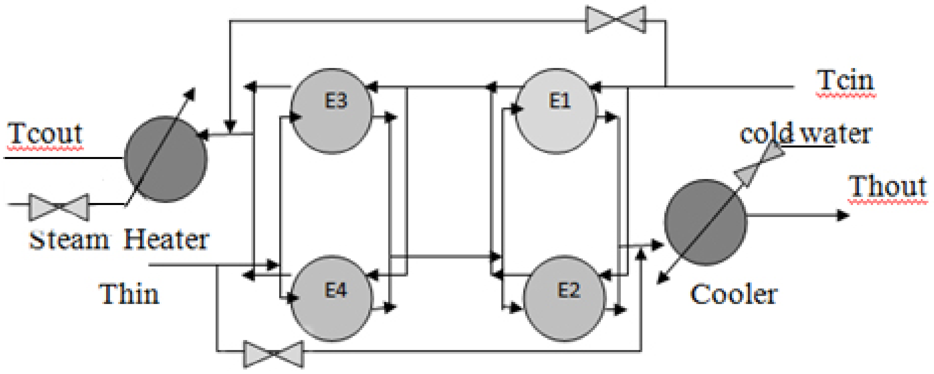

Figure (2) Structure of Studied Heat Exchanger Networks.

Control Strategies in Heat Exchanger Networks

The general optimal control of heat exchanger networks is to maximize heat integration with minimum utility usage. The most common strategies for the control of outlet temperatures in a HEN are via bypass flow of process-to process heat exchangers, duties of process-to-utility heat exchangers (utility streams flow rates) and flow rate division via process stream splitters. Each of these strategies was analyzed with the aim of proposing a set of heuristic rules for the synthesis of control structures for HENs [14].

(a)Process-to-utility heat exchangers

A hot process stream may be cooled down using a cold utility such as cold water. In the same way, a cold process stream may be heated up using a hot utility such as low-pressure steam. Several different control schemes can be used to control the outlet temperature of the process stream, such as throttling the utility fluid, throttling the process fluid, and bypassing the process fluid [14, 15].

(b)Process-to-process heat exchangers

A bypass stream is usually employed to control the outlet temperature of one process stream in a process-to-process heat exchanger. in a process-to-process heat exchanger only one outlet temperature can be controlled. The action of the bypass stream can be explained as follows: if for any reason, the outlet temperature of the hot stream is greater than its setpoint, the flowrate through the bypass stream must be decreased, because this action will cause an increase in the heat exchanger’s duty (direct acting controller). In order to deal with positive and negative disturbances, the heat exchanger has to be designed with a steady-state flow rate for the by-pass stream different than zero. Figure (3) shows the studied heat exchanger network with two controller, where MV is manipulated variable.

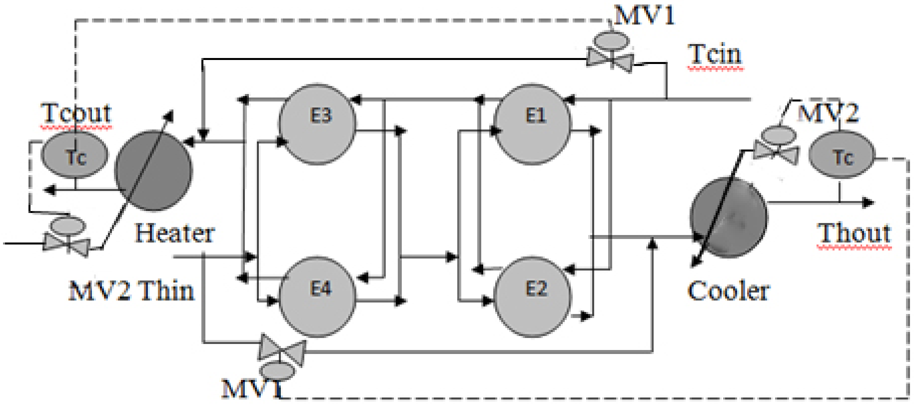

Figure (3) Heat Exchanger Networks with Two Controllers.

Split Range Control

Split- range control is a simple technique that can handle constraint problems on manipulated variables. In split range control, several manipulated variables are used to control one controlled variable, in such a way that when one manipulated variable saturates, the next manipulated variable takes over. In this work, two manipulated variables are used for each controller. When two manipulated variables are used in a split-range controller, one of them is referred as primary manipulated variable and the other as a secondary manipulated variable. The primary manipulated variable can be thought of as the manipulated variable that is used to control a target under the nominal condition. However, the final choice of primary and secondary manipulated variables can be based on other considerations also [13]. In order to obtain smooth control, there is often overlap between the operating ranges of the different manipulated variables [4]. There are three possible control structures to protect the manipulated variable from saturation. These control structures are:

1. Only primary manipulated variable is active.
2. Only secondary manipulated variable is active (reactive protection).
3. Both primary and secondary manipulated variables are active (preventive protection).

A simple illustration will be provided for the above example. Assume that one split-range controller contains only two manipulated variables and region 1 is the “primary” region. Then MV2 and MV3 are the “primary” manipulated variables used for control of the target temperatures. For optimality, the active constraint should be switched to MV3 when the operation moves into region 2, and to MV2 in region 3. In terms of control, when moving into region 2, MV1 needs to take over the task of saturated MV3 (“MV1 is used as a secondary manipulated variable for MV3”), and when moving into region 3, MV1 needs to take over the task of saturated MV2 (“MV1 is used as a secondary manipulated variable for MV2”). Hence, we should combine MV2 & MV1 and MV3 & MV1 as split-range pairs and assign MV1 as the secondary manipulated variable.

Simulation Study Using Matlab

Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies for the operation of the system. Simulink and Matlab provide an ideal integrated environment for developing models, performing dynamic system simulations, and designing and testing new ideas. Simulation results of open loop response for outlet temperature of both hot process fluid (Tho1) and cold utility fluid(Tco1) from cooler unit and also both cold process fluid(Tco2) and hot utility fluid (Tho2) from heater unit to different step change in flow rate of hot process fluid, cold process fluid**,** cold utility fluid and hot utility fluid are obtained from our simulation program for plate heat exchanger networks by using MATLAB simulink which is shown in Figure (4), and control the outlet temperature of both hot process and cold process fluid from heat exchanger networks with manipulated variables which are flow rate of hot process fluid, cold process fluid**,** cold utility fluid and hot utility fluid to show control response of temperature to negative and positive step changes in the mentioned variables as shown in Figure (5). Figure(6) shows simulink model for the inside of heat exchanger subsystem which is created with MATLAB by using equations (1) and (3).

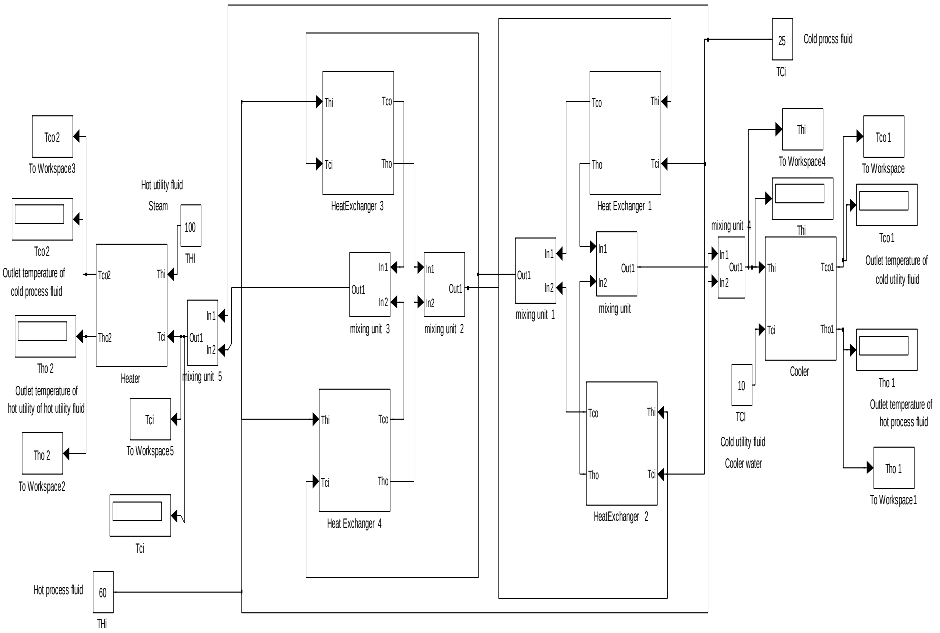

Figure (4) Simulink Model for Dynamic of Heat Exchanger Networks.

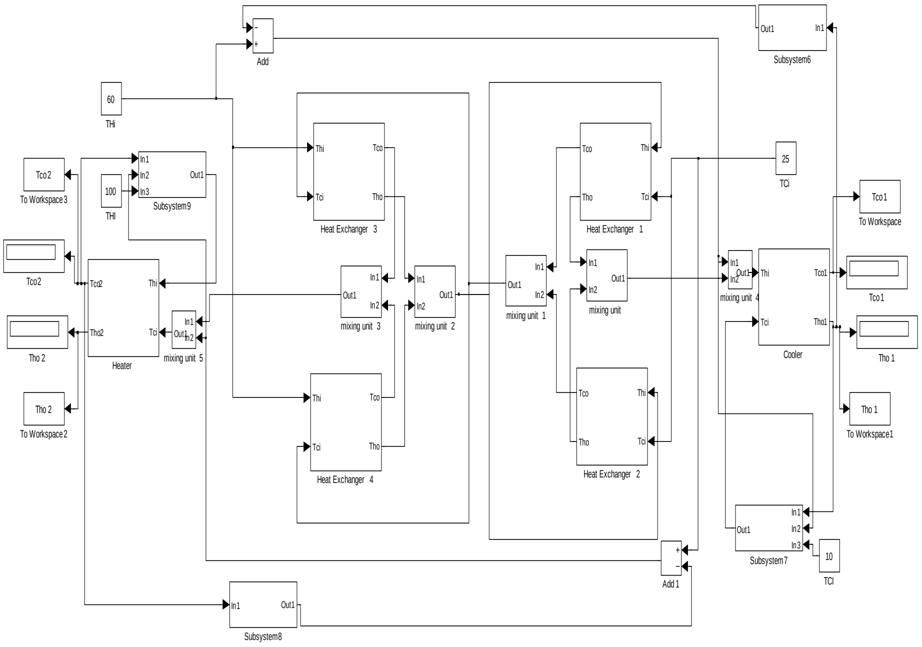

Figure (5) Simulink Model for control of Heat Exchanger Networks.

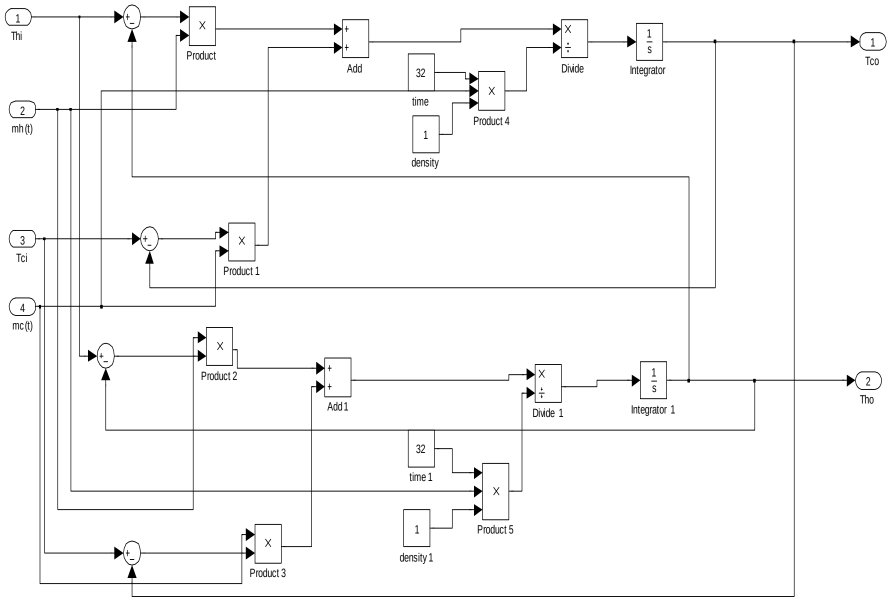

Figure (6) Simulink Model for Inside of Heat Exchanger Subsystem.

RESULTS AND DISCUSSION

Open-loop of Heat Exchanger Networks

The open-loop experiments were carried out to determine process characteristics for the implementation of the best controller. Simulation results of open loop response of plate heat exchanger networks using MATLAB simulink for outlet temperature of both hot process fluid (Tho1) and cold utility fluid (Tco1) from cooler unit and also both cold process fluid (Tco2) and hot utility fluid (Tho2) from heater unit for different step change in manipulated variables which are flow rate of cold process, hot process, cold utility, and hot utility fluid are shown in Figures (7 to 14). The Figures (7 to 10) show the effect of negative step change in flow rate of cold process fluid and positive step change in flow rate of hot utility fluid to increase outlet temperatures in two cases. First the cold process fluid is decreased from 3 to 2 lit./min and hot utility fluid is increased from 1 to 2 lit./min. and second the cold process fluid is decreased from 2 to 1 lit./min. and hot utility fluid is decreased from 2 to 3 lit./min.. In this work, our goal is to increase the outlet temperature of cold process fluid(Tco2) with step change in flow rate of both cold process and hot utility fluid. From the figures 8 and 10 it can be seen that Tco2 in first case is 65°C but in case2 it increased to 110.63°C. Therefore, high outlet temperature in cold process fluid can be achieved easily with heat exchanger networks. While, Figures (11 to 14) show effect of negative step change in flow rate of hot process fluid and positive step change in flow rate of cold utility fluid to decrease outlet temperatures in two cases. First the hot process is decreased from 4 to 3 lit./min. and hot utility is increased from 2 to 3 and the second the cold process is decreased from 3 to 2 lit./min and the hot utility is increased from 3 to 4 lit./min. In this work, our goal is to decrease the outlet temperature of hot process fluid (Tho1) with step change in flow rate of both hot process and cold utility fluid. From this figures, it can be seen that Tho1 in first case is 34.44°C but in second case it decreased to 30.97°C. Therefore, this lower outlet temperature of hot process can be achieved easily with heat exchanger networks. From the responses, it can be observed that order of the system is first and The positive increase in flow rate of cold stream has negative effect on all temperatures and a positive increase in flow rate of hot stream has a positive effect on all temperatures and vice versa.

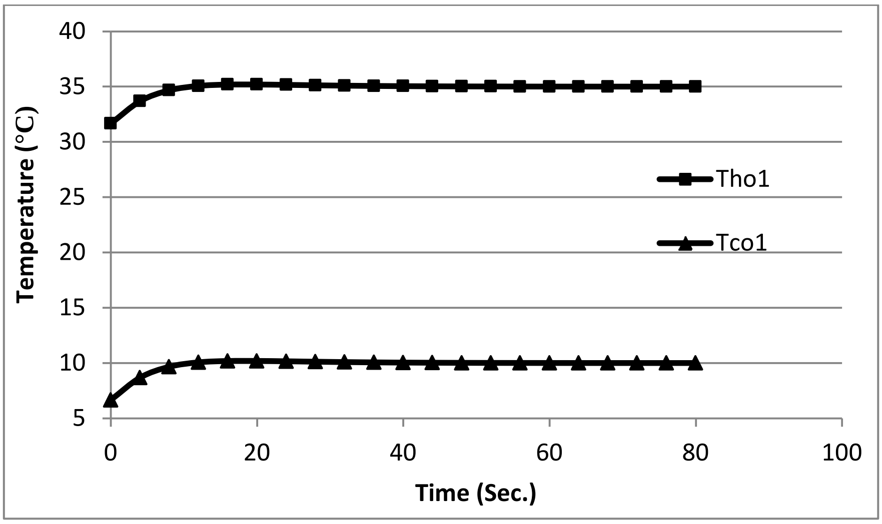

Figure (7) Temperature response of both hot process fluid(Tho1) and cold utility fluid(Tco1) from cooler unit for heat exchanger networks to a step change in flow rate of both cold process from 3 to 2 lit./min. and hot utility from 1 to 2 lit./min.

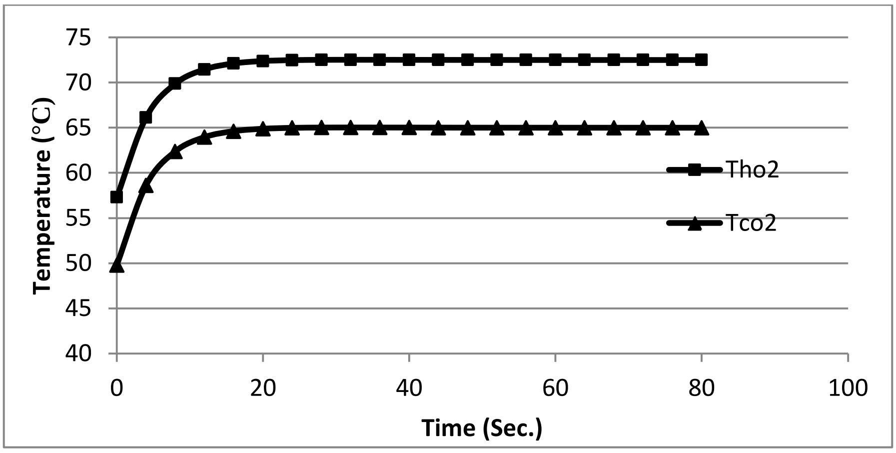

Figure (8) Temperature response of both cold process fluid(Tco2) and hot utility fluid (Tho2) from heater unit for heat exchanger networks to a step change in flow rate of both cold process from 3 to 2 lit./min. and hot utility fluid from 1 to 2 lit./min .

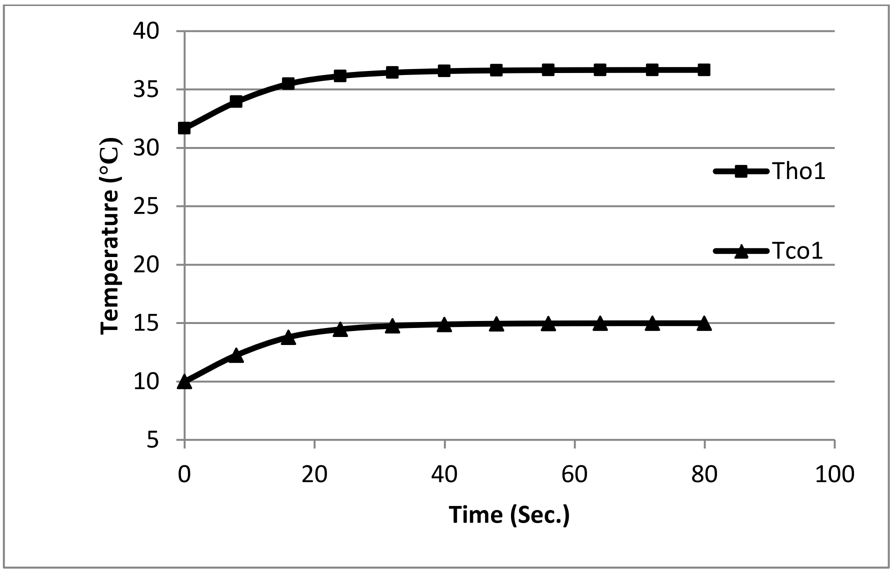

Figure (9) Temperature response of both hot process fluid(Tho1) and cold utility fluid(Tco1) from cooler unit for heat exchanger networks to a step change in flow rate of both cold process from 2 to 1 lit./min. and hot utility fluid from 2 to 3 lit./min.

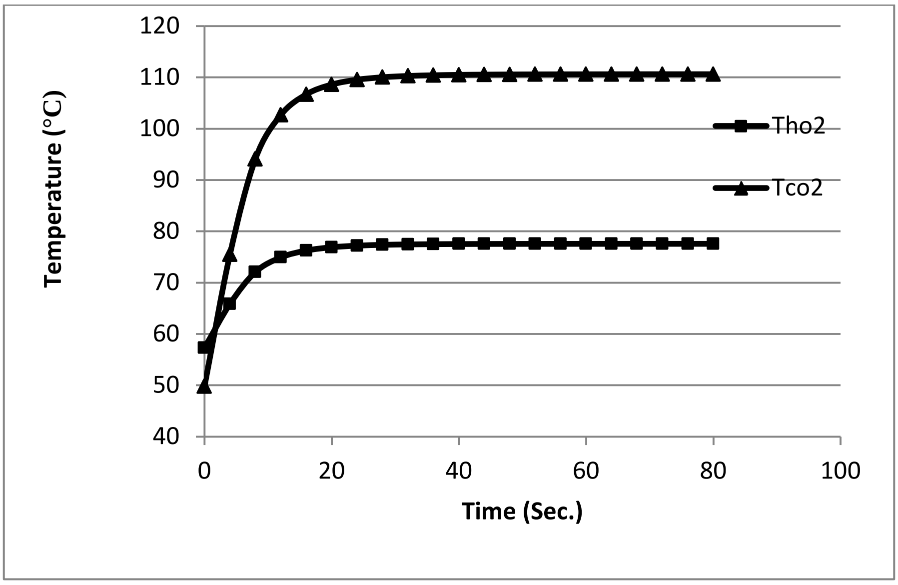

Figure (10) Temperature response of both cold process fluid(Tco2) and hot utility fluid (Tho2) from heater unit for heat exchanger networks to a step change in flow rate of both cold process from 2 to 1 lit./min. and hot utility fluid from 2 to 3 lit./min.

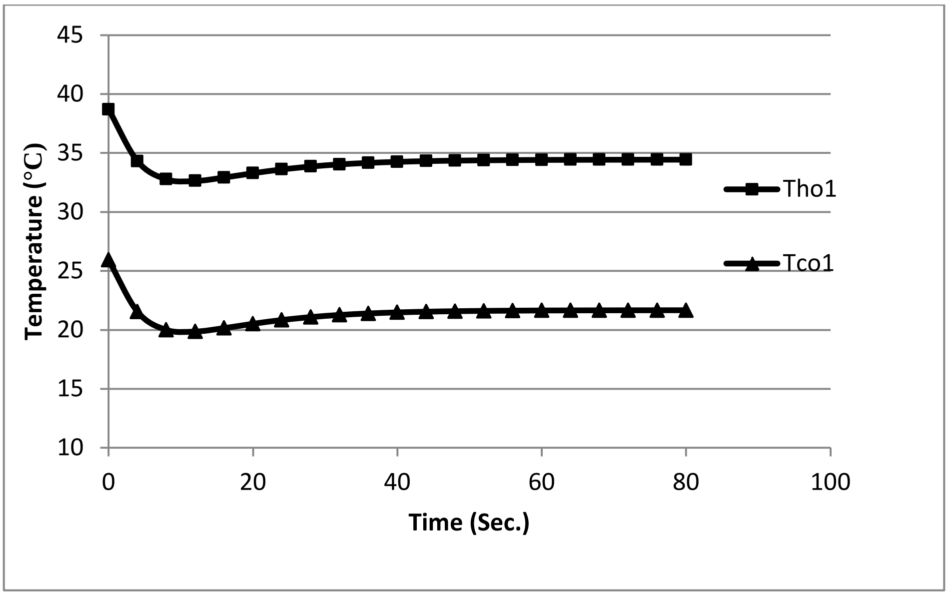

Figure (11) Temperature response of both hot process fluid(Tho1) and cold utility fluid(Tco1) from cooler unit for heat exchanger networks to a step change in flow rate of both hot process from 4 to 3 lit./min. and cold utility from 2 to 3 lit./min.

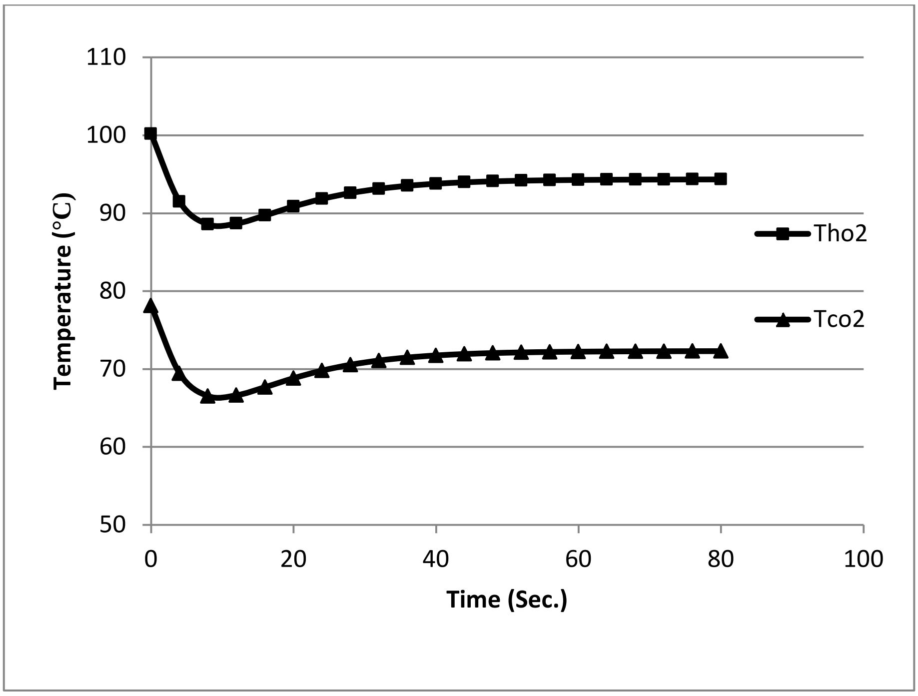

Figure (12) Temperature response of both cold process fluid(Tco2) and hot utility fluid (Tho2) from heater unit for heat exchanger networks to a step change in flow rate of both hot process from 4 to 3 lit./min. and cold utility fluid from 2 to 3 lit./min.

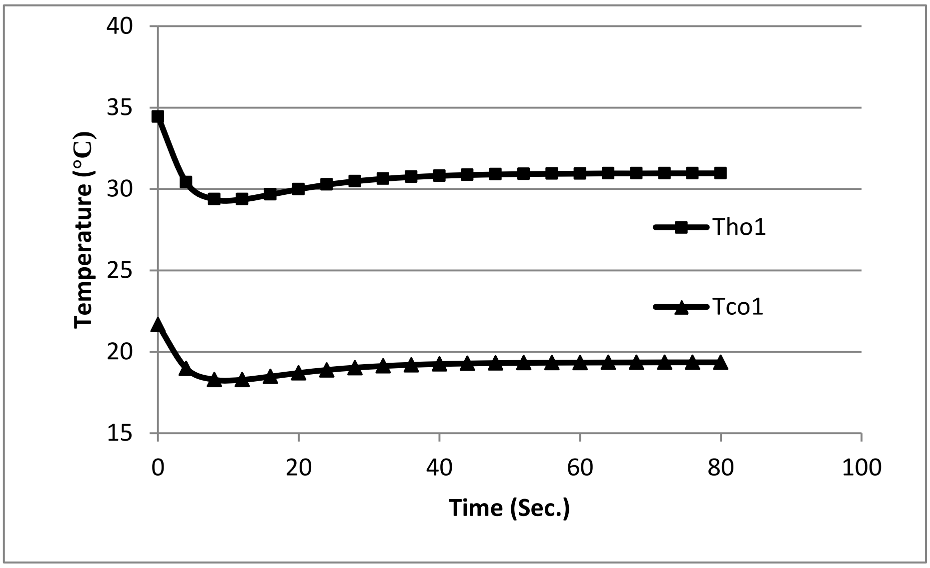

Figure (13) Temperature response of both hot process fluid(Tho1) and cold utility fluid(Tco1) from cooler unit for heat exchanger networks to a step change in flow rate of both hot process from 3 to 2 lit./min and cold utility from 3 to 4 lit./min.

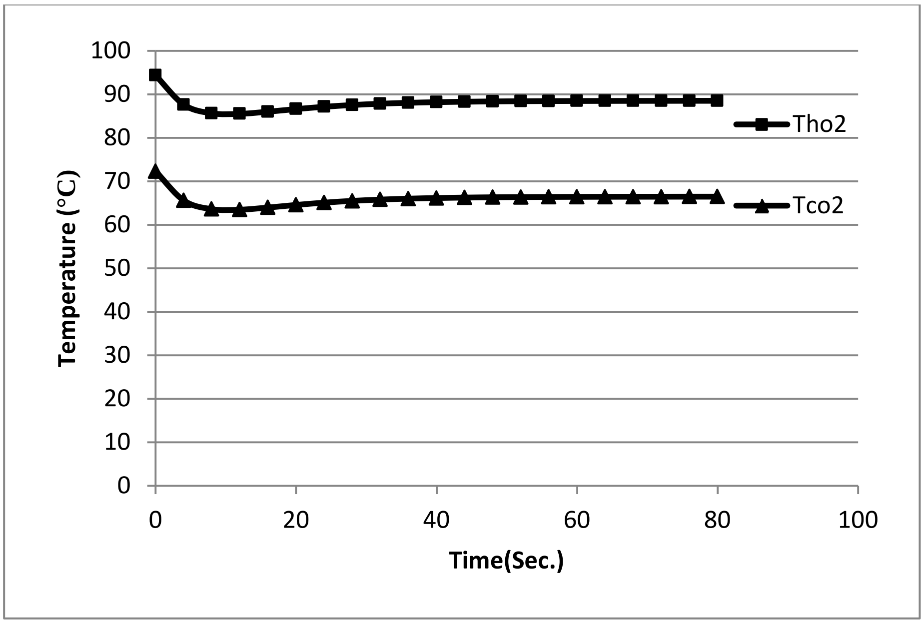

Figure (14) Temperature response of both cold process fluid(Tco2) and hot utility fluid (Tho2) from heater unit for heat exchanger networks to a step change in flow rate of both hot process from 3 to 2 lit./min. and cold utility fluid from 3 to 4 lit./min.

Control of Heat Exchanger Networks

Testing of a controller should be performed to ensure some desired performance criteria, such as it is robust, closed-loop system must be stable, rapid, smooth response is obtained, offset and overshoot are eliminated, excessive control action is avoided. To examine and evaluate the control performance of the split range controller over all regions, the control the outlet temperature of both hot process (Tho1) and cold process fluid (Tco2) from heat exchanger networks using split range controller with two manipulated variables which are flow rate of hot process, cold process, cold utility and hot utility fluid to negative and positive step changes in the manipulated variables. The performance conventional controller with one manipulating variable (case one) is compared with the performance of the spilt range controller with two manipulating variables (case two) are shown in Figures (15 and 16). It is indicate that the two variables controller give smooth and faster response control signal is also smaller in magnitude at the instant of temperature increase and settles down in shorter time in comparison with the case one. They indicate that the controller with two variables give smoother and better control performance than the conventional controller with smaller offset values when disturbances are introduced into the system. The two variables controller responds as quickly as one variable controller. The Figures illustrate that the controller with two variables strategy brought the temperature to the set points is faster than conventional controller and give smooth control response. The conventional controller give overshoot in the process response with a long response time. They indicate that two variables controller gives less error and gives better control performances than the conventional controller, similar to the disturbance case study. These results also show the robustness of the two variables in dealing with disturbances.

From these two Figures, it can be seen that the temperature response with step change in two manipulated variables is the best and give better results with less offset and lower over shoot than with step change in conventional controller.

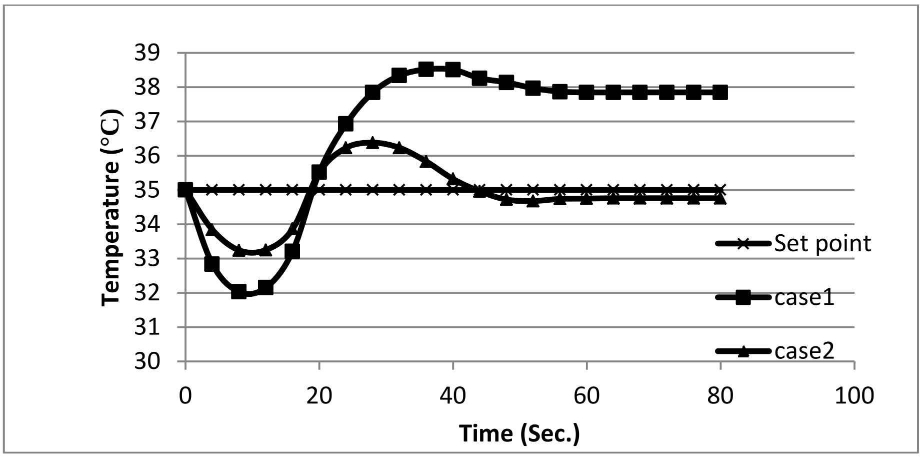

Figure (15) Comparison between conventional controller (case one) and split range with two manipulating variables controller (case two) to step change in flowrate at set point 35 °C.

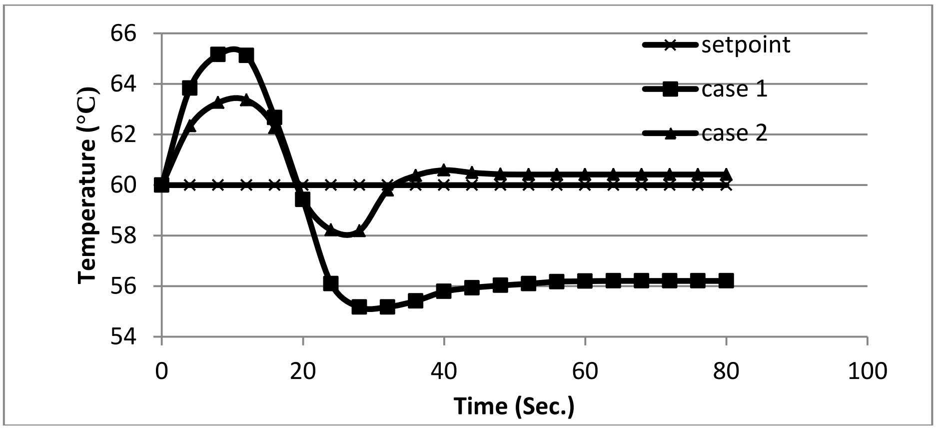

Figure (16) Comparison between conventional controller (case one) and split range with two manipulating variables controller (case two) to step change in flowrate at at set point 60 °C.

CONCLUSIONS

From open loop of heat exchanger networks, the order of this system is first. The positive increase in flow rate of cold stream has negative effect on all temperatures and a positive increase in flow rate of hot stream has a positive effect on all temperatures and vice versa. In control of heat exchanger networks, outlet temperature of both hot and cold process fluid reached to desired value in less time and lower over shoot by using split range control with two manipulated variables, primary manipulated variable which is process fluid and secondary manipulated variable which is utility fluid. The comparison of performance between split range controller with two manipulated variables and conventional controller indicated that two variables controller was more robust than the conventional controller and gave better results in cases involving disturbances.

REFERENCES

[1]. Alp E. S. K., Ugur A. and Mehmet C. C., "Optimal Design of Controllable Heat-Exchanger Network Under Multi-Directional Resilency - Target Constraints", Computers Chem. Engng Vol. 19, Suppl., PP. Sl49-S154, (1995).

[2]. Zhihong L., "Method for Incorporation of Controllability in Heat Exchanger Network Synthesis by Integration Mathematical Programming and Knowledge Engineering", Chinese J. Chem. Eng., Vol. 10, No. 6, PP. 711-716, (2002).

[3]. Gonzalez A. H., Odloak D., Marchetti J. L. and Sotomayor Z. O. A., "Infinite Horizon MPC of A Heat Exchanger Network", Trans Institution of Chemical Engineers, Chemical Engineering Research and Design, Vol. 84, No. 11, PP. 1041–1050, (2006).

[4]. Marlin T. E., "Process control: Designing Processes and Control System for Dynamic Performance. 2nd ed." McGraw Hill, (2000).

[5]. Giovanini L. L. and Martchetti J. L., "Low Level Flexible- Structure Control Applied to Heat Exchanger Networks", Computers and Chemical Engneering, Vol. 27, PP.1129-1142, (2003).

[6]. Alejandro H. G., Darci O. and Jacinto L. M., "Predictive Control Applied to Heat-Exchanger Networks", Chemical Engineering and Processing, Vol.45, PP.661–671, (2006).

[7]. Akman U. and Uygun K., "Nonlinear Model Predictive Control of Retrofit Heat-Exchanger Networks", Computers and Chemical Engineering Supplement, PP. S231-S234, (1999).

[8]. Alexandre L., "Heat Exchanger Network Self-Optimising Control". Thesis, MSC. in Chemical Engineering, (2012).

[9]. Giovanini L. and Balderud J., "Control and Operation of Heat Exchanger Networks using Model Predictive Control", Proceedings of the 2nd International Workshop on Networked Control Systems Rende, Italy, PP.51-56, (2006).

[10]. Marcelo E. and Jorge O. T., "Optimal Heat Exchanger Network Synthesis: A Case Study Comparison", Applied Thermal Engineering, Vol. 51, Issues 1–2, PP. 801–826, (2013).

[11]. Cizan A. A., "Dynamic Model and Control of Heat Exchanger Networks", M.SC. Thesis, University of Tikrit, (2013).

[12]. Jean D., Alberto T. and Mikhail S., "Synthesis of Heat Exchanger Networks Using Genetic Algorithms" , Applied Thermal Engineering, Vol. 28, PP. 1763–1773, (2008).

[13]. Veerayut L.," Development of Control Structure Design and Structural Controllability for Heat Exchanger Networks", Ph.D. Thesis, Kasetsart University, (2008).

[14]. Westphalen D. L., Young B. R. and Svrcek W. Y., "Strategies for the Operation and Control of Heat Exchanger Network", Proceedings Foundations of Computer-Aided Process Operations, PP. 425-428, (2003).

[15]. Svrcek W. Y., Mahoney D. P., Young B. R., "A Real- Time Approach to Process Control", John Wiley & Sons Ltd., Chichester, (2000).

[16]. Driedger W., "Controlling Shell and Tube Exchangers". Hydrocarbon Processing, Vol.77, No.3, (1998).