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Application of Passivity Concept for Split Range Control of Heat Exchanger Networks

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Abstract

Split range control design provides a stable and optimal operation for targeted temperatures, while the utility cost is minimized for all possible disturbance variations. An effective controller design named passivity concept is presented to regulate the stability of split range control of heat exchanger networks, in this work. The dynamic models of the proposed system are formulated in state space domain. These state space models of heat exchanger networks can represent both the process and the disturbance transfer functions. These transfer functions can determine whether the heat exchanger networks is passive or not by analyzing the passivity index. As a result, the split range control of heat exchanger networks is non-passive system. Therefore, the introduction of the weighting function is proposed to adapt the heat exchanger networks into strictly passive system. The passive controllers are then designed in order to keep the heat exchanger networks at the robust operation. The proposed method is tested and compared with PI controllers and illustrates that the passivity approach can give a better performance over conventional PI controllers. In addition, the dynamic responses of target temperature with passive controllers have a lower oscillation.

Keywords: Split range control; Heat exchanger networks; State space model; Passivity concept

Introduction

Heat exchanger networks (HEN) are the networks, which facilitate the heat transfer between hot side and cold side streams that have significant different temperature. Glemmestad [1] proposed the optimal operation of heat exchanger networks, when the following three requirements are satisfied; the target temperature, the minimized utility cost, and the dynamic behavior. In order to control the target temperature of heat exchanger networks, the bypassed heat exchanger is required by suitable split fractions. In some case studies, these split fractions may be saturated and cannot maintain the target temperatures. Thus, these problems are proved by the attempt to find a simple operation policy; the split range control, as presented by Lersbamrungsuk et al. [2]. The second requirement is minimized utility cost as studied by Aguilera et al. and Glemmestad et al. [3,4]. Not only the satisfied target temperature and the minimized utility cost are interesting but also the stability of heat exchanger networks is very important. Therefore, the stability analysis of this system should be considered. Recently, a technique to analyze the stability of general processes is the passivity concept as presented by Bao [5]. The objective of this research is to apply passivity concept to the split range control of heat exchanger networks.

Mathematical Modeling and Methodology

A mathematic approach of the split range control of heat exchanger networks and passivity will be proposed in following sections.

Heat exchanger networks

The dynamic model of heat exchanger networks was developed by Glemmestad [1]. The general heat exchanger model uses energy balance equation in terms of ordinary differential equations (ODE) with the following assumptions; incompressible fluid, constant specific heat capacities, constant thermal efficiency, constant flow, independent heat transfer coefficient, lumped model, the water with no phase change. A countercurrent heat exchanger networks can be modeled from the assumptions that each side is shown in Figure 1.

The dynamic models of heat exchanger can be illustrated as following:

$$\text{Hot side: } \frac{\partial T_{h,i}}{\partial t} = \frac{F_h}{V_{h,i}}\left(T_{h,i-1} - T_{h,i}\right) - \frac{UA_i}{\rho_h V_{h,i} C_{V,h}}\left(T_{h,i} - T_{c,i}\right) \tag{1}$$

$$\text{Cold side: } \frac{\partial T_{c,i}}{\partial t} = \frac{F_c}{V_{c,i}}\left(T_{c,i+1} - T_{c,i}\right) + \frac{UA_i}{\rho_c V_{c,i} C_{V,c}}\left(T_{h,i} - T_{c,i}\right) \tag{2}$$

The dynamic models of utility exchanger can be illustrated as following:

$$\text{Cooler: } \frac{\partial T_{h,i}}{\partial t} = \frac{F_h}{V_{h,i}}\left(T_{h,i-1} - T_{h,i}\right) + \frac{Q_c}{\rho_h V_{h,i} C_{V,h}} \tag{3}$$

$$\text{Heater: } \frac{\partial T_{c,i}}{\partial t} = \frac{F_c}{V_{c,i}}\left(T_{c,i-1} - T_{c,i}\right) - \frac{Q_h}{\rho_c V_{c,i} C_{V,c}} \tag{4}$$

Where A_i is the heat exchanger area at stage i. V_{hi} and $V_{c,i}$ are

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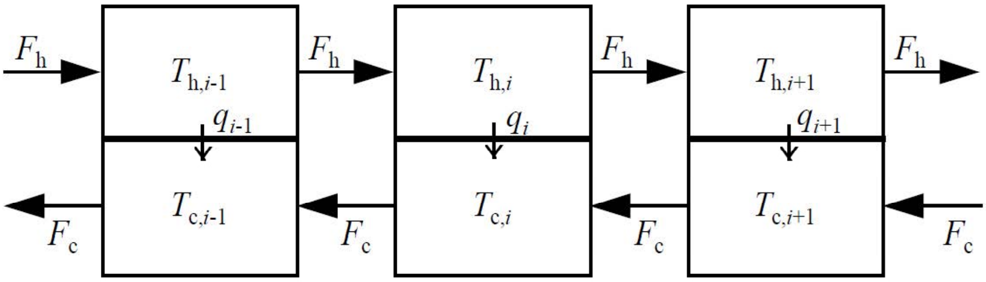

Figure 1: The countercurrent heat exchanger networks model, Glemmestad [1].

the volumes of each compartment at hot side and cold side stream; respectively. Because of the stage number starting from 1 to *i*, the heat exchanger model consists of 2*i* ordinary differential equations.

Split range control of heat exchanger networks

The split range control uses the structural information to formulate am optimal control structure for optimal operation of heat exchanger networks, - proposed by Glemmestad et al. and Lersbumrungsuk et al. [2,6] developed the split range control of heat exchanger networks that control the target temperature when the manipulated variables is active constraint. The active constraints of heat exchanger networks are lower-bounded utility duties or upper/lower-bounded split fraction of bypassed heat exchanger. The split range control describes possible methods to implement optimal policy by disturbance tracking. For example of split range control, system has 3 manipulated variables (MV_1, MV_2, and MV_3) and 2 controlled variables (CV_1 and CV_2). In general, 2 manipulated variables are needed for control 2 controlled variables as SISO control loop. Therefore, one of these manipulated variables must be the active constraints or saturated. For operating window, the active constraint regions can be found by parametric programming. The manipulated variable one (MV_1) is saturated as an active constraint in region 1. Thus, the manipulated variable two and three (MV_2 and MV_3) are used in order to control the controlled variable one and two (CV_1 and CV_2) as SISO control loop. Moreover, the system will be switching from R_1 to a different region R_2 or change active constraint, when the system was disturbed.

Passivity concept

Passivity concept is presented to analyze the stability of general processes as proposed by Bao [5]. The algorithm of passivity concept is shown in Figure 2.

The dynamic models derived from physical principles typically consist of one or more ordinary differential equations. The linear models referred to as state space models as follow:

$$\dot{X} = Ax + Bu + Ex_0 \tag{5}$$

$$y = Cx + Du \tag{6}$$

Where $x \in X \subset R^n$ = State vector ($T_{h,I}$ and $T_{c,i}$)

$x_0 \in X_0 \subset R^k$ = Manipulated vector (Q_c, Q_h, and *f*)

$x_0 \in X_0 \subset R^k$ = Disturbance vector ($T_{H, in}$ and $T_{c, in}$)

$y \in Y \subset R^j$ = Controlled vector ($T_{H, out}$ and $T_{c, out}$)

A, B, C, D and E = Constant matrix

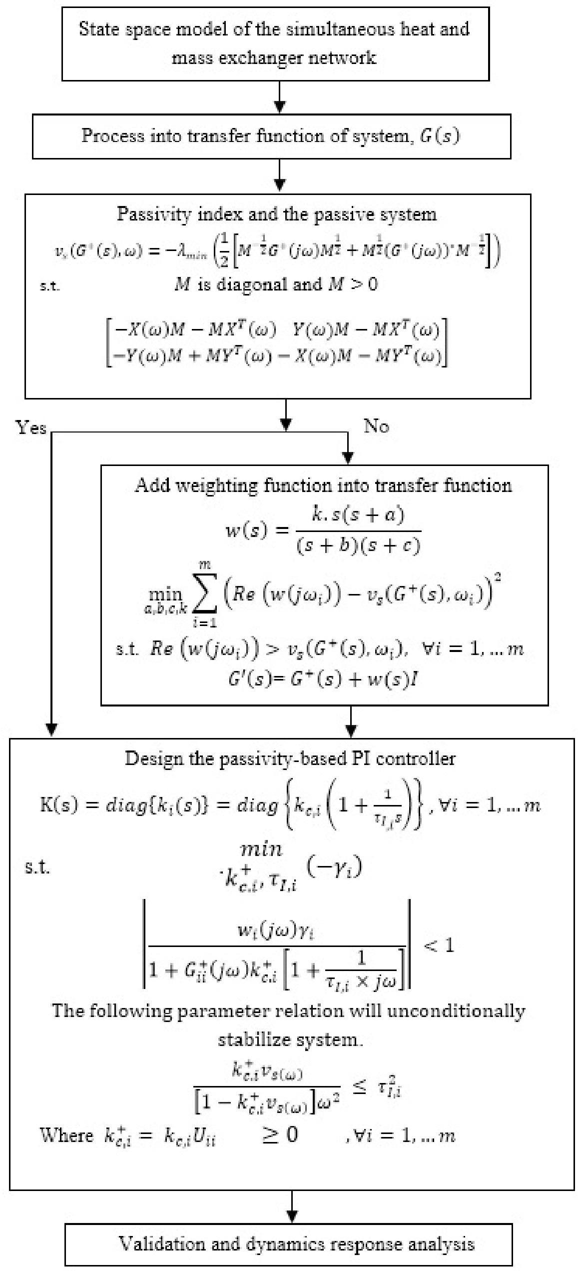

Figure 2: The algorithm of passivity concept.

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The representation $x(t)= f(t,t_0,x_0,u)$ is used to denote the state at time t.

The state space models are used to formulate the related *Process transfer function matrix*, $G_p(s)$ is defined as

$$G_p(s) = C(sI - A)^{-1}B + D \tag{7}$$

Application of Passivity Concept

The heat exchanger networks from Glemmestad [1] as shown in Figure 3 are studied. This network has two heat exchangers and two utility exchangers. In addition, four manipulated variables are the split fraction of bypassed heat exchangers 1 and 2 (u_{b1} and u_{b2}) and utility duties of cooler and heater (Q_c and Q_h). These are available for control of target temperatures including outlet temperature of stream H1, outlet temperatures of stream C1 and C2. The disturbance is varied ± 10°C in the inlet temperature of stream H1.

In case study, the heat exchanger networks generate two active constraint regions that proposed by Lersbumrungsuk et al. [2] as shown in Table 1.

After that, the integer linear programming will be used to suggest an optimal split range control structure. There are three control loops as following:

- First loop: Outlet hot temperature of stream H1 is controlled by utility duties of cooler.
- Second loop: Outlet cold temperature of stream C1 is controlled by utility duties of heater.
- Third loop: Outlet cold temperature of stream C2 is controlled by switching between split fraction of bypassed 1 and 2.

Next, the dynamic models of heat exchanger network are developed in order to find the state space models. The dynamic models of heat exchanger are considered as referring to equations 1-2. The dynamic model of cooler and heater can be illustrated by equations 3-4, respectively. The state space models are proved by rearranging linear dynamic models and substituting the numerical values at steady state into A, B, C, D and E constant matrixes of the state space form, which can be illustrated in Appendix A.

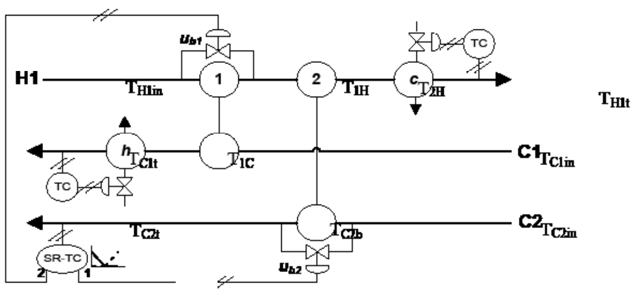

Figure 3: The split range control structure of heat exchanger networks.

Region	Manipulated variables			
	Q_c	Q_h	u_{b1}	u_{b2}
1	U	U	S_L	U
2	U	U	U	S_L

U: Unsaturated manipulated variable (inactive constraint); S_L: Saturated manipulated variable (active constraint) at the lower bound

Table 1: Set of active constraints.

Therefore, the state space models of the heat exchanger networks are:

$$\begin{bmatrix} \dot{T}_{1H} \\ \dot{T}_{2H} \\ \dot{T}_{1C} \\ \dot{T}_{C2b} \end{bmatrix} = \begin{bmatrix} -0.003626 & 0.001245 & 0 & 0 \\ 0.001245 & -0.004817 & 0 & 0 \\ 0.002381 & 0 & -0.005529 & 0.003148 \\ 0 & 0 & 0.003148 & -0.004338 \end{bmatrix} \begin{bmatrix} T_{1H} \\ T_{2H} \\ T_{1C} \\ T_{C2b} \end{bmatrix}$$

$$+ \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.1320 \end{bmatrix} \begin{bmatrix} f_{C2} \end{bmatrix} + \begin{bmatrix} 0.0024 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} T_{H1in} \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} T_{C2t} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0.9999 \end{bmatrix} \begin{bmatrix} T_{1H} \\ T_{2H} \\ T_{1C} \\ T_{C2b} \end{bmatrix} + \begin{bmatrix} -110.9 \end{bmatrix} \begin{bmatrix} f_{C2} \end{bmatrix} \tag{9}$$

The state space models of cooler are:

$$\begin{bmatrix} \dot{T}_{H1t} \end{bmatrix} = \begin{bmatrix} -0.002381 \end{bmatrix}\begin{bmatrix} T_{H1t} \end{bmatrix} + \begin{bmatrix} -0.002381 \end{bmatrix}\begin{bmatrix} Q_c \end{bmatrix} + \begin{bmatrix} 0.0024 \end{bmatrix}\begin{bmatrix} T_{2H} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} T_{H1t} \end{bmatrix} = \begin{bmatrix} 1 \end{bmatrix}\begin{bmatrix} T_{H1t} \end{bmatrix} \tag{11}$$

The state space models of heater are:

$$\begin{bmatrix} \dot{T}_{C1t} \end{bmatrix} = \begin{bmatrix} -0.003571 \end{bmatrix}\begin{bmatrix} T_{C1t} \end{bmatrix} + \begin{bmatrix} 0.002381 \end{bmatrix}\begin{bmatrix} Q_h \end{bmatrix} + \begin{bmatrix} 0.0036 \end{bmatrix}\begin{bmatrix} T_{1C} \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} T_{C1t} \end{bmatrix} = \begin{bmatrix} 1 \end{bmatrix}\begin{bmatrix} T_{C1t} \end{bmatrix} \tag{13}$$

The characteristics of heat exchanger networks are analyzed. The transfer functions including the process transfer function and the disturbance transfer function are solved by using equations 7**.**

The matrix transfer function can be determined as following:

- The process transfer function matrix of inner heat exchanger networks

$$\begin{bmatrix} T_{C2t} \end{bmatrix} = \left[\frac{-110.9s^2 - 0.9621s - 0.0008311}{s^2 + 0.009867s + 1.408e^{-005}} \right] \begin{bmatrix} f_{C2} \end{bmatrix} \tag{14}$$

- The process transfer functi.on matrix of cooler

$$\begin{bmatrix} T_{H1t} \end{bmatrix} = \left[\frac{-0.002381}{s + 0.002381} \right] \begin{bmatrix} Q_c \end{bmatrix} \tag{15}$$

- The process transfer function matrix of heater

$$\begin{bmatrix} T_{C1t} \end{bmatrix} = \left[\frac{0.002381}{s + 0.003571} \right] \begin{bmatrix} Q_h \end{bmatrix} \tag{16}$$

There are three conditions for the passivity as proposed by Bao[7].

1. *G(s)* is analytical in Re > 0
2. G (jω) + G*(jω) ≥ 0 for all frequency ω that ω is not a pole of G(S)

If there are poles $p_1, p_2, \ldots p_m$ of G(S) on the imaginary axis, they are non-repeated and the residue matrices at the poles $\lim_{s \to p_i} (s \to p_i)G(s)$ are Hermitian and positive semi definite.

In addition, the *process transfer function matrix* is said to be strictly passive or strictly positive real (*SPR*) when the above two conditions are changed to:

1.*G(s)* is analytical in Re > 0

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2.G (jω) + G*(jω) ≥ 0 for ω ϵ (-∞,+∞)

To analyze whatever the system is passive or not, the system can be verified by using passivity index (V_F) propose by Bao [5]. The passivity index v_F (G, ω) indicates the magnitude of the system G(S) from the system passive. The system is the passive system when passivity index v_F (G, ω) is negative. The passivity index can be defined as following:

$$\nu_F(G,\omega) = -\lambda_{\min}\left(\frac{1}{2}\left[G(j\omega)+G^*(j\omega)\right]\right) \quad (17)$$

Where $G^*(j\omega)$ is the complex conjugate transpose of transfer function $G(j\omega)$

After the process transfer functions are obtained, the passivity index is employed to analyze the passive of the process. The passivity index of heater is a negative value that means the system is the passive system. On the other hand, inner heat exchanger networks and cooler are non-passive due to positive values of passivity index. According to the passivity concept, the non-passive processes can be shifted to the passive processes by suitable weighting function w_p (s).

In case of the system is non-passive with positive value of passivity index, the weighting function w(s) or minimum phase transfer function is needed and embedded into the system in order to move non passive system to strictly passive system. The equations 18-19 shows the strictly passive system H(s) after the system is added by weighting function.

$$\nu(w(s),\omega) < -\nu(G(s),\omega) \quad (18)$$

$$H(s) = G(s) + w_p(s)I \quad (19)$$

Then w_p (S) can be chosen to have the following:

$$w_p(s) = \frac{ks(s+a)}{(s+b)(s+c)} \quad (20)$$

Where *a, b, c* and *k* are positive real parameters

Therefore, the weighting functions can be obtained as follow;

- The weighting function of inner heat exchanger networks

$$w_p(s) = \frac{111.4442\cdot s\cdot(s+0.6338)}{(s+0.000093)\cdot(s+0.6373)} \quad (21)$$

- The weighting function of cooler

$$w_p(s) = \frac{0.1309\cdot s\cdot(s+0.2539)}{(s+1.2\times10^{-7})\cdot(s+0.0333)} \quad (22)$$

The weighting functions from equations 21-22 are introduced into the transfer function of inner heat exchanger networks and cooler; respectively. Then the non-passive parts of heat exchanger networks are shifted to the passive system with the passivity index illustrated in Figure 4a.

In order to be determined by the following optimization obtained from the passivity concept. Objective function

$$\min_{a,b,c,k} \sum_{i=1}^{m}(\mathrm{Re}(w_p(j\omega_i)) - \nu_s(G^+(s),\omega_i))^2 \quad (23)$$

Subject to

$$\mathrm{Re}(w_p(j\omega_i)) > \nu_s(G^+(s),\omega_i)\ \forall i = 1,\ldots,m \quad (24)$$

For the passive system, the controller achieving the following conditions will be the passive controller with decentralized unconditional stability.

$$\text{- Re}\left\{\frac{k_i(j\omega)}{1-\nu_s(G(s),\omega)k_i(j\omega)}\right\} \geq 0 \quad \forall \omega \in R, i = 1,\ldots,n \quad (25)$$

- K(s) is analytic in Re(s) > 0 (26)

The decentralized unconditional stability condition given in equations 23-24 implies:

- k_i (S) is passive and

$$\text{- }\left|k_i(j\omega) - \frac{1}{2\nu_s(G(s),\omega)}\right| \leq \left|\frac{1}{2\nu_s(G(s),\omega)}\right| \quad \forall \omega \in R, i = 1,\ldots,n \quad (27)$$

For multiloop control system, the multiloop controllers can be designed based on the proposed stability condition. To achieve decentralized unconditional stability of the close loop system as well as good performance, a controller tuning method is proposed to minimize the sensitivity function of each loop, subject to equations 21-22. For multi loop PI controller synthesis, this tuning problem is converted into the following optimizations:

Objective function

$$\min_{k_{c,i}^+,\tau_{I,i}} (-\gamma_i) \quad (28)$$

Such that

$$\left|\frac{1}{1+G_{ii}^+(j\omega)k_{c,i}^+[1+1/\tau_{I,i}\times j\omega)]}\frac{\gamma_i}{j\omega}\right| < 1 \quad (29)$$

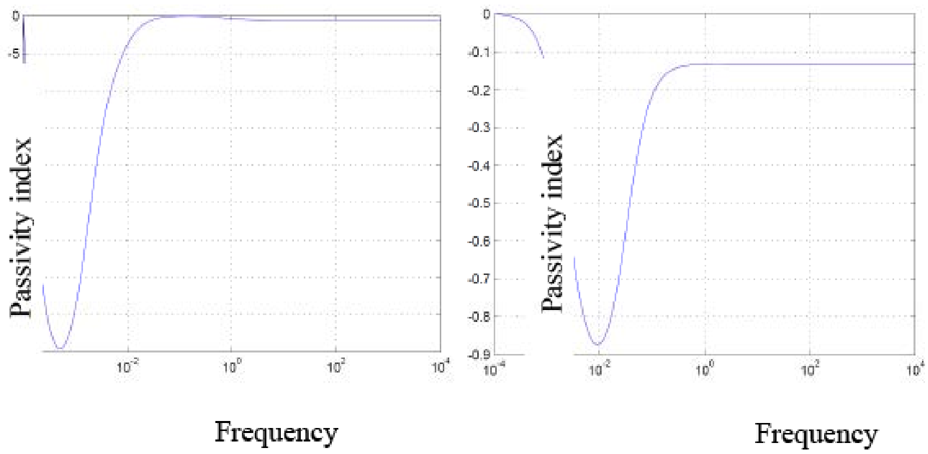

Figure 4: The new passivity index **(a)** Inner heat exchanger networks and **(b)** cooler.

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$$\tau_{I,i}^2 \geq \frac{k_{c,i}^+ v_s(\omega)}{[1 - k_{c,i}^+ v_s(\omega)]\omega^2} \quad \forall \omega \in R, i = 1,\ldots,n \tag{30}$$

For the multi loop control system comprising a stable subsystem G(s)and a multi loop controller K(S) = diag{k_i (s)}, i = 1,..., n, if a stable and minimum phase transfer function w(s) is chosen such as equation 20, then the closed loop system will be stable. For any loop i = 1,..., n, the passive controllers are designed as follow:

$$k_i^{'}(s) = k_i\ (s)[1 - w(s)k_i\ (s)]^{-1} \tag{31}$$

However, the weighting function cannot be added into the system directly because the system cannot be changed. Therefore, the weighting function will be absorbed into the controller to design the passive controller. The passive controllers with PI controller are designed from the optimization. The results of the $k_{c,i}$ and $\tau_{I,i}$ for each loop control are shown in Table 2.

The result for k_i of each loop control is shown in the following:

$$k_{u_{b1}-T_{c2t}} = 0.0080\left(1 + \frac{1}{49.9826s}\right);\ k_{u_{b1}-T_{c2t}} = 0.0080\left(1 + \frac{1}{49.9826s}\right);$$

$$k_{u_{b1}-T_{c2t}} = 0.0080\left(1 + \frac{1}{49.9826s}\right);\ k_{u_{b2}-T_{c2t}} = 0.0080\left(1 + \frac{1}{49.9826s}\right) \tag{32}$$

According to the passivity method, the close loop system of inner heat exchanger networks and outer heat exchanger networks at cooler are stable when the weighting function is absorbed into the controller.

These three passive controllers are used in the system.

$$k_{Q_c-T_{h1t}}^{'}(s) = \frac{6s + 0.7998}{9.2144s + 0.055};\ k_{u_{b1}-T_{c2t}}^{'}(s) = \frac{0.3999s + 0.2629}{5.4204s + 2.7221};$$

$$k_{u_{b2}-T_{c2t}}^{'}(s) = \frac{0.3999s + 0.2629}{5.4204s + 2.7221} \tag{33}$$

Results and Discussion

The heat exchanger networks model verification included closed loop control of heat exchanger networks with noise and time delays. There are 4 available manipulated variables for controlling all of target outlet temperatures, the bypasses of heat exchangers 1 and 2 (u_{b1} and u_{b2}) and utility duties of cooler and heater (Q_c and Q_h). For this study, the disturbances are changing of inlet hot temperature of stream H1 form 190 to 200°C at the time of 1,500 seconds and changing from 200°C to 180°C at the time of 3,000 seconds.

The result from passive controller process will be compared with PI auto tuning; the heat exchanger networks are controlled by using the PI controller instead of the passive controller in every control loop. After the disturbance is applied to process, the transient responses are presented and the results of control and manipulated variables are compared between passive controllers and PI controllers.

Figure 4b shows the results of controlled variable responses after changing the inlet hot temperature of stream H1 at the time of 1,500 seconds and of 3,000 seconds, respectively. Both controllers can adjust the target temperatures. When system is a disturbance at the time of 1,500 seconds, the system will be changing from steady state operation to active constraint region 1 as shown in Figure 6. Therefore, the split fraction of bypassed 1 will be operating from saturated or active constraint in order to control the outlet cold temperature of stream C2. Likewise, after system operates at the time of 3,000 seconds. The system will be switched from active constraint region 1 to the active constraint region 2. Figure 5 shows the split fraction of bypassed 1 becomes saturated or active constraint. On the other hand, the split fraction of bypassed 2 is operated in order to control the outlet cold temperature of stream C2. The responses of outlet hot temperature of stream H1, outlet cold temperature of stream C1, and outlet cold temperature of stream C2 with PI controller are more oscillate than passive controller. Moreover, the rising time of system with PI controller is more than passive controller. As a result, the split range control of heat exchanger networks with noise and time delays that are designed by the passivity method can be adjusted the target temperature and guarantee the stability.

Loop	$k_{c,i}$	$\tau_{I,i}$ (second)
1. Q_c-T_{H1t}	0.6000	10.0000
2. Q_h-T_{C1t}	9.6098	2.9793
3. u_{b2}-T_{C2t}	0.0080	49.9826
4. u_{b1}-T_{C2t}	0.0080	49.9826

Since the controllers used in multi control system are PI controller, the values of $k_{c,i}$ and $\tau_{I,i}$ from Table 2 are plugged in the simple form of PI controller.

Table 2: The results of the $k_{c,i}$ and $\tau_{I,i}$ for each loop control.

Conclusion

This research considers about the control system of split range control in heat exchanger networks. The split range control of heat exchanger networks should be stable and the optimal operation which can regulate the temperature at their certain level, while the utility cost is minimized for all possible disturbance variations. The controlled variables of heat exchanger networks using split range are the target temperature controlled by the split fraction of bypassed, utility duties of cooler and heater.

The dynamic models, which are split range control of heat exchanger networks, generated for the controlled, manipulated and

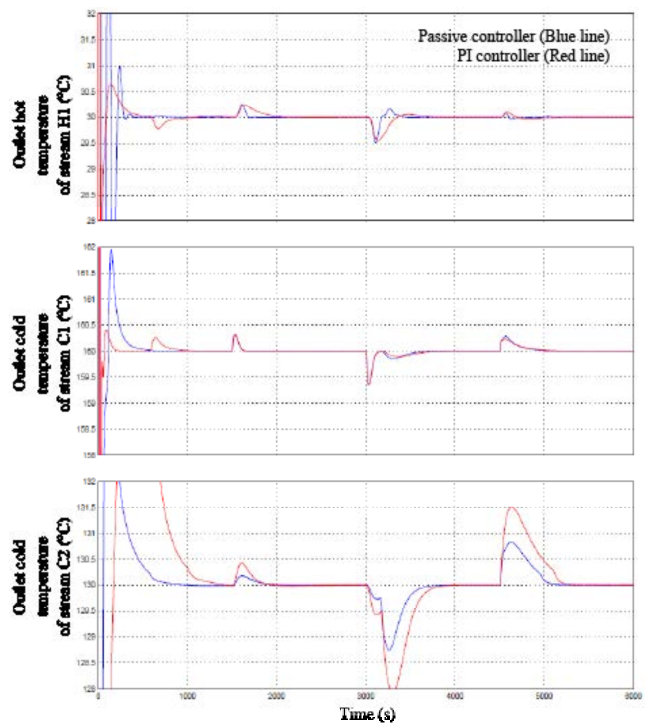

Figure 5: The comparison of controlled variable responses between passive controllers and PI controllers with load disturbance.

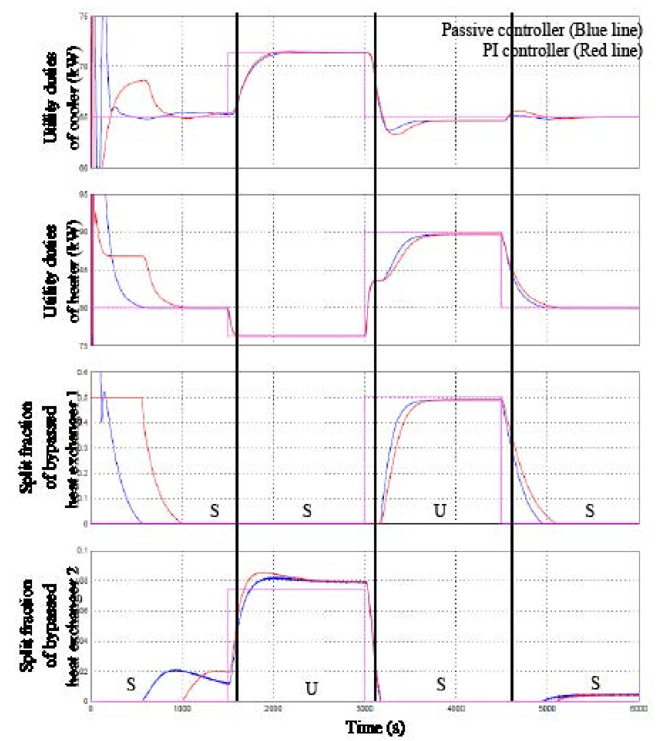

Figure 6: The comparison of manipulated variable between passive controllers and PI controllers with load disturbance.

disturbance variables of the unit. Since the dynamic models of heat exchanger networks are the nonlinear model, linearization by using Taylor's series expansion is necessary before generate the state space models. After that the state space models of heat exchanger networks are analyzed in term of process transfer function and disturbance transfer function. Next, the transfer function was formulated to indicate that the heat exchanger networks were passive or not by considering the passivity index. As a result, the split range control of heat exchanger networks are non-passive system. Therefore, the weighting function is added to make heat exchanger networks become strictly passive system. Consequently, the passive controller was designed that make the heat exchanger networks are stable.

The passivity method can practically be applied to split range control of heat exchanger networks. The passive controllers can adjust the target temperature. In addition, the dynamic responses of target temperature with passive controllers are less oscillates than PI controller. And the rising time of system with passive controller is higher than PI controller. Moreover, the passivity concept can practically be used in more complex split range control of heat exchanger networks, which include more amount of heat exchanger, number of stream, and number of operating region. The split range control design of heat exchanger networks by passivity method can adjust the design temperature and guarantee stable at all region.

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