Modeling and Simulation of Control System Response to Temperature Disturbances in a Coupled Heat Exchangers-AHTR system.

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Abstract

An effective control strategy is essential for maintaining optimum operational efficiency of the advanced high Temperature Reactor (AHTR)-intermediate heat exchanger (IHX)-secondary heat exchanger (SHX) system for power conversion or process heat applications. A control system design is presented in this paper for the control of the coupled intermediate and secondary heat exchangers. The cold side outlet temperature of the SHX (T_{co}) and the hot side outlet temperature of the IHX (T_{ho2}) were identified as the controlled variables that were maintained at their set points by manipulating the flow rates of heat exchange media. Transfer functions describing the relationships between the controlled variables and the manipulated and load variables were developed and the system response to various temperature disturbances was simulated using a custom-developed MATLAB program. It was found that a step disturbance of $\pm 10^\circ\text{C}$ in the process loop changed the thermal duty by $\pm 650\text{ kW}$, equal to 6.5% of the initial duty. Similar disturbances in the primary loop had a higher impact on the system. The control system design included a provision for the switching of manipulated variables to limit the adjustment in the magnitudes of the primary manipulated variables. Simulation results indicate that the controlled variables are maintained successfully at their desired points by the control system.

Keywords: Advanced Nuclear Reactors, Transfer Functions, Control System Response, Heat Exchangers, Temperature Disturbances

1. Introduction

As Gen-II and Gen-III reactors approach the end of their lifecycles, Gen-IV reactors are beginning to be researched and designed (Sabharwall et al., 2009, 2010). A number of different Gen-IV reactor designs have been proposed based on using different coolants and techniques in order to achieve high temperatures and efficiencies including the fluoride salt-cooled Advanced High Temperature Reactor (AHTR) described in more detail in literature (Skavdahl et al., 2015, Chen et al., 2015). The intermediate heat exchanger (IHX) transfers heat between the reactor and the secondary heat exchanger (SHX). The primary function of the SHX is to transport thermal energy, in the form of heat, from the reactor to the downstream applications while isolating the upstream and downstream coolants from each other and providing a pressure boundary for the system (Sabharwall et al., 2012). Development of high-efficiency heat exchangers for salt-to-salt and salt-to-gas heat transfer is one of key research and development challenges for this reactor system (Ingersoll et al., 2004). Successful deployment of AHTR systems requires increasing the technology readiness levels of the reactor as well as heat exchange system for stable operation and reliable process heat delivery (Sabharwall et al., 2015). Heat exchangers are designed to not only transfer the heat but also to contain radiation within the primary loop to minimize hazards. Controlling the operation of these heat exchangers is critically important for maintaining system stability and operating efficiency. For example, for the system shown in Fig. 1, the temperature entering the reactor (T_{ci3}/T_{ho2}) needs to be controlled in order to minimize temperature effects on the power of the reactor. Additionally, the temperature entering the process (T_{co}) may need to be controlled

based on the constraints faced for operating the process within specified design parameters. A potential control scheme for the intermediate heat exchanger (IHX) and the secondary heat exchanger (SHX) which accomplishes the control of both these temperatures can be seen in Fig. 1.

Fig. 1. Process flow diagram of AHTR process with control of heat exchangers.
IHX: Intermediate heat exchanger, SHX: Secondary heat exchanger, TT: Temperature transmitter, TC: Temperature controller, FC: Flow controller, T: Temperature, F: Flow rate

Precise control of the heat exchangers is an important aspect in the design of the reactor system. Controlling the operation of a single heat exchanger has been reported by a few investigators. Dynamic models were created and a fuzzy logic controller developed for plate type heat exchanger (Al-Dawery et al., 2012). Other investigators employed a model based approach that used the total energy stored in the heat exchanger by the two coolants as the variable of interest rather than the outlet temperatures. These controls were then tested by simulating the models for a single heat exchanger (Michel and Kugi, 2014). **It should be noted that the total thermal energy stored in the heat exchanger is a derived quantity which requires the knowledge of inlet and outlet temperatures. No integral action is performed by their control system, as would be when using a PI (Proportional-Integral) or PID (Proportional-Integral-Derivative) controller. Integral action is important for mitigating oscillations and offset in control.** Due to the multiple loops existing in the design for the AHTR, changes in one exchanger will be propagated to the other and vice-versa. **Elimination of offset would be important in such systems to avoid potential instabilities.**

Reports on the control of a system that includes two coupled heat exchangers are lacking in literature. The present paper describes the control strategy for the coupled operation of the IHX and SHX in the above system in response to potential temperature disturbances. The control system architecture is presented, followed by the selection of controller tuning

parameters. Temperature disturbances were introduced into the system from either the process side (T_{ci}) or the primary side (T_{hi2}), and the system response simulated using a MATLAB program. It was found that the control system was able to maintain the controlled variables at their desired set points, allowing the reactor and process to operate at design conditions.

2. Materials and Methods

2.1 System Description

As mentioned above, the system consists of a fluoride-salt cooled AHTR supplying heat to a process through IHX and SHX. Such a system with a nominal 10 MW-thermal capacity has been described previously by Chen et al. (2015). The reported steady state design parameters of the system for the IHX and SHX are reproduced below in Table 1 with the controlled temperature shown as boldfaced numbers. The cold side outlet temperature of the SHX (T_{co}) is to be maintained at 651.2 °C and the hot side outlet temperature of the IHX (T_{ho2}) is to be maintained at 600 °C.

Table 1
Steady-State Design Parameters

Variable	Units	IHX		SHX	
		cold	hot	cold	Hot
Q	kW	10000		10000	
<i>Coolant</i>		FLiNaK	FLiBe	Helium	FLiNaK
T_{in}	°C	545	704	498.9	690
T_{out}	°C	690	600	651.2	545
$\dot{m}$	kg/s	36.6	40.3	12.6	36.6

Two PID controllers are added into the system making it possible to control the two temperatures as described below.

2.2 Control System Architecture and Methodology

The first step in the design of a control system is the identification and selection of the controlled variables (**variables maintained at desired set-point values**) and manipulated variables (**variables changed in order to maintain the controlled variables at their set points**). For the SHX, the controlled variable is chosen to be the cold side outlet temperature (T_{co}) of the process coolant. The process coolant travels through the process loop and is used either to generate electricity or provide thermal energy to drive a chemical process. Processes are designed to operate at specified temperatures, and the temperature difference between the process coolant and design temperature provides the necessary driving force for its operation. Controlling the process coolant temperature (T_{co}) will maintain the necessary driving force at the desired value, enabling the process to operate at the optimum efficiency. This control is accomplished by using the hot side flow rate (F_{hi}) as the manipulated variable. Other variables, called load variables, represent disturbances that will have an effect on the controlled variable.

For the SHX, the load variables include the hot and cold inlet temperatures (T_{hi} , T_{ci}) and the cold side flow rate (F_{ci}).

The controlled variable for IHX is the hot side outlet temperature (T_{ho2}). This is the temperature of the primary coolant entering the nuclear reactor. Fluctuations in this temperature will have an effect on the reactivity and thus the power of the reactor, which is undesirable. The hot side flow rate (F_{hi2}) is used as the manipulated variable. The load variables include the hot and cold inlet temperatures (T_{hi2} , T_{ci2}) and the cold side flow rate (F_{ci2}), which is the same as the hot side flow rate of the SHX (F_h). The summary of variables is shown in Table 2.

Table 2

Summary of controlled, manipulated and load variables

Process Unit	Controlled Variable	Manipulated Variable	Load Variables
SHX	T_{co}	F_{hi}	F_{ci} , T_{ci} , T_{hi}
IHX	T_{ho2}	F_{hi2}	F_{ci2} , T_{ci2} , T_{hi2}

2.3. Block Diagrams

Control block diagrams are created to represent the control strategy shown in Fig. 1. Fig. 2 and 3 show the block diagrams for the SHX and IHX, respectively. Each block in these figures represents a transfer function which relates the variables entering and leaving the block. Each variable within the block is expressed as the deviation from the steady-state values of that particular parameter. For example, the topmost block in Fig. 2 relates the deviation in the cold stream outlet temperature (ΔT_{co}) from its steady state value to the deviation in the temperature of the hot inlet stream (ΔT_{hi}) from its steady state value. These two deviations are related by the transfer function G_{S4} . The asterisk on a variable (for example, ΔT_{co}^*) indicates a set-point value which is 0. Both the block diagrams are structured identically, differing only in the controlled and manipulated variables, and the transfer functions. For each diagram G_c is the controller transfer function, G_v is the valve or pump transfer function and G_S/G_I are the process transfer functions for the SHX and IHX, respectively.

The process transfer functions (G_S/G_I) represent the mathematical relationships between the controlled variables and the manipulated variable or load variables. Referring to Fig. 2, the transfer functions G_{S2} , G_{S3} and G_{S4} represent the transfer functions which effectively convert the deviations (or disturbances) in the load variables F_{ci} , T_{ci} and T_{hi} , respectively, to the deviation in the controlled variable T_{co} . G_{S1} is the transfer function between the controlled (T_{co}) and the manipulated variable (F_{hi}). All the deviations are summed up at the summation point at the right end of the figure, and total deviation is compared to the set-point at the summation junction at the left end of the figure. The error signal (E1) generated is sent to the controller

(G_{cS}). Depending on the error and the controller algorithm, the controller sends an output signal (P1) to the valve transfer function block. The manipulated variable F_{hi} is changed based on the valve transfer function (G_{vS}), to keep the controlled variable at its desired value.

Fig. 2. Block diagram for SHX control.

Fig. 3. Block diagram for IHX control.

The transfer function for the controller is shown in Eq. 3. It is the characteristic equation for a PID controller, with a proportional, integral, and derivative gain value to control precisely the system based on a given error value.

$$G_c = K_P + K_I \frac{1}{s} + K_D s \quad (3)$$

The transfer function for the valve or pump is shown in Eq. 4. This function has a gain value (K_v), which is just set to 1, and a time constant (τ_v) which determines the time it takes the pump to adjust. This is taken to be 0.05 seconds, which is a near instantaneous response.

$$G_v = \frac{F(s)}{P(s)} = \frac{K_v}{\tau_v s + 1} \quad (4)$$

Eq. 3-6 show transfer functions for the SHX relating to changes in the cold outlet temperatures based on changes of the other variables. The gain value (K) relates how outlet temperature, in this case the cold side, changes from the initial steady-state value with changes in either the manipulated variable or load variables. For example, K_{cFh} is ~ 1.5 °C/(kg/s) meaning that if the hot side flow rate changes by 1 kg/s the cold side outlet temperature will change by 1.5 °C. The time constant (T) determines the time it takes for the heat transfer. In Eq. 7 there is an extra variable, τ_c , which is a time delay term for the cold side of the SHX. This exists because changes in the cold inlet temperature will not immediately effect the cold outlet temperature. There is a certain amount of time it takes for the coolant to travel through the heat exchanger. Until this occurs effects from changes in the cold inlet temperature will not be seen. The other 4 transfer functions for the SHX and the equations used to calculate the gain and times constant values can be found in Appendix A. Equations for the IHX are identical to those for SHX. The only difference are different gain values and time constants.

$$G_{s1} = \frac{\Delta T_{co}}{\Delta F_{hi}} = \frac{K_{cFh}}{T_c s + 1} \quad (5)$$

$$G_{s2} = \frac{\Delta T_{co}}{\Delta F_{ci}} = \frac{K_{cFc}}{T_c s + 1} \quad (6)$$

$$G_{s3} = \frac{\Delta T_{co}}{\Delta T_{ci}} = \frac{K_{ctc} e^{-\tau_c s}}{T_c s + 1} \quad (7)$$

$$G_{s4} = \frac{\Delta T_{co}}{\Delta T_{hi}} = \frac{K_{cth}}{T_c s + 1} \quad (8)$$

2.4. Controller Tuning

The gain, time constant and time delay values in the transfer functions described above are determined by coolant properties and the system geometry. Designing the controller requires specifying the gain and time constants in the characteristic equation for the controller. A built-in MATLAB function was used called **pidTuner** in order to do this. **This function opens a PID Tuner GUI and chooses proportional, integral, and derivative gain values for your system.** The equation used for tuning must first be determined. In this case for each exchanger this will be the valve transfer function (G_v) multiplied by the transfer function that relates how the controlled variable changes with variation of the manipulated variable (G_{s1}/G_{l1}). Eq. 9 and 10 shows the transfer functions used to tune the controllers for the SHX and IHX, respectively. Table 3 and 4 show the tuned controller for P, PI, and PID options. These are tuned parameters when both hot side flow rates are being used as the manipulated variables. If the cold side flow rates are used as manipulated variables, two different controller settings must be used. Eq. 11

and 12 are used for tuning in that case and the resulting controller parameters are shown in Table 5.

$$G_{vS}G_{S1} = \frac{1}{0.05s+1} * \frac{K_{cFh}}{T_{cS}+1} \quad (9)$$

$$G_{vI}G_{I1} = \frac{1}{0.05s+1} * \frac{K_{hFh2}}{T_{h2S}+1} \quad (10)$$

Table 3

SHX controller tuned parameters (Hot side flow rate)

Controller	K _P (°C*s/kg)	K _I (°C*s/kg)	K _D (°C*s/kg)
P	10.712		
PI	0.7994	0.7680	
PID	0.7976	0.9683	0.1643

Table 4

IHX controller tuned parameters (Hot side flow rate)

Controller	K _P (°C*s/kg)	K _I (°C*s/kg)	K _D (°C*s/kg)
P	14.236		
PI	0.4296	0.2054	
PID	0.6163	0.3821	0.2353

$$G_{vS}G_{S2} = \frac{1}{0.05s+1} * \frac{K_{cFc}}{T_{cS}+1} \quad (11)$$

$$G_{vI}G_{I2} = \frac{1}{0.05s+1} * \frac{K_{hFc2}}{T_{h2S}+1} \quad (12)$$

Table 5

PID controller parameters for IHX and SHX (Cold side flow rates)

	K _P (°C*s/kg)	K _I (°C*s/kg)	K _D (°C*s/kg)
HX			
SHX	-0.1695	-0.2057	-0.0349
IHX	-0.6985	-0.4331	-0.2666

Stability of the system with the tuned control parameters can be seen by examining the step response and Nyquist plots for each of the heat exchangers. Fig. 4 shows step responses and Nyquist plots for the SHX and IHX using the PID controller tunings stated in Tables 3 and 4. Fig. 4a shows the step response for the SHX with the PID controller. The rise time is 1.75 seconds with a settling time of 2.44 seconds. The slight overshoot of 1.53% is seen in the response. Fig. 4b shows the Nyquist plot for the SHX indicating the closed-loop stability of the system. The point (-1, 0) can be seen on the left as a red cross. The system is considered closed-loop stable because the loop does not circle around this point. Fig. 4c shows the step response for the IHX with the PID controller previously tuned. A slightly slower response is seen due to

the larger size of the IHX. The rise time is 3.23 seconds with a settling time of 4.79 seconds. In this case a lower (as compared to the SHX) overshoot of 0.66% is observed. Fig. 4d shows the Nyquist plot for the IHX. The loop does not encircle the point $(-1,0)$ and thus the system is considered closed-loop stable.

Fig. 4. Step response and Nyquist plots for SHX and IHX. a: step response for SHX, b: Nyquist plot for SHX, c: step response for IHX, d: Nyquist plot for IHX.

2.5. MATLAB Code

Initially a Simulink model was created to simulate the control of the heat exchangers. Though the Simulink model worked well and was able to simulate the control of the system, it does not offer the capability to change the gain values (K), time constants (T), and time delay values (τ) with changing system conditions. In a real system, any system disturbance will result in variations in these parameters. Hence, a MATLAB code was created using the Simulink model as the foundation, making the system dynamically responsive. The program accounts for changing gain values, time constants and time delays arising out of changes in flow rates which in turn affect the velocity of the fluids and the heat transfer coefficients. For the IHX the heat transfer coefficients are based off of models developed for a fluted tube heat exchanger (Garimella, 1990) and for the SHX heat transfer coefficients are based off models developed for an offset strip-fin heat exchanger (Manglik and Bergles, 1995). These heat exchangers are chosen for their compactness and heat transfer capabilities.

3. Results and Discussion

A number of temperature disturbances were introduced into the system and system response simulated. The cause of these disturbance could be heat removal problems in the process, or a problem with the reactor.

3.1. Process Loop Disturbances

Fig. 5 shows the controller system response after a +10 °C step change in the temperature of the stream entering the cold side of the SHX (T_{ci}). Fig. 5a and 5d show the time profiles for the controlled variables for the SHX (T_{co}) and IHX (T_{ho2}), respectively. As can be seen these two temperatures are successfully controlled around their set-point values. Fig. 5e shows the change in the manipulated variables (F_h/F_{h2}) as a function of time. An increase in the inlet temperature of the cold stream implies a lower heat duty requirement in the heat exchanger when the outlet temperature of that stream is controlled. This lower heat duty is achieved by decreasing the flow rate of the stream on the hot side of the heat exchanger. The hot side flow rates for the IHX (F_{h2}) and SHX (F_h) shown in Fig. 5e decrease by -6.5% and -5.0%, respectively. Fig. 5b and 5c show the increases in the uncontrolled variables for the SHX (T_{ho}) and the IHX (T_{co2}), respectively. The hot side outlet temperature of the SHX (T_{ho}) increases by 3.5 °C and the cold side outlet temperature of the IHX (T_{co2}) increases by a little more than 1 °C. After the disturbance occurs, it takes the system about 400 seconds to come to a controlled equilibrium at a new steady state. Due to the drop in the flow rates the duty of the heat exchangers drop to about 9350 kW, which is ~6.5% less than the initial duty of 10 MW as shown in Fig. 5f.

Fig. 5. Control of IHX and SHX after +10 °C step increase entering the cold side of the SHX.
a: SHX cold outlet temperature, b: SHX hot outlet temperature, c: IHX cold outlet temperature, d: IHX hot side outlet temperature, e: hot side flow rates of SHX and IHX, f: Duties of the hot and cold side of SHX and IHX

Fig. 6 shows the system response for the control of the IHX and SHX after a -10 °C step change in the temperature of the stream entering the cold side of the SHX (T_{ci}). Fig. 6a and 6d show the response as a function of time for the controlled variables for the SHX (T_{co}) and IHX (T_{ho2}), respectively. As before, these variables are controlled successfully around their set-point values by manipulating the hot side flow rates. In this case, the increased heat duty requires increasing the flow rates of the streams on the hot side of the heat exchangers. The change in the hot side flow rates for the IHX (F_{h2}) and SHX (F_h) are 6.7% and 6.8%, respectively as seen in Fig. 6e. Fig. 6b and 6c show the uncontrolled variables for the SHX (T_{ho}) and IHX (T_{co2}) and they are seen to decrease. The hot side outlet temperature of the SHX (T_{ho}) decreases by ~ 1.4 °C and the cold side outlet temperature of the IHX (T_{co2}) decreases by ~ 1.7 °C. After the disturbance occurs, it takes the system about 700 seconds to come to a controlled equilibrium. Due to the increase in the flow rates, the duty of the heat exchangers rise to about 10650 kW, which is about 6.5% higher than the initial duty as shown in Fig. 6f.

Fig. 6. Control of IHX and SHX after -10°C step increase entering the cold side of the SHX.
a: SHX cold outlet temperature, b: SHX hot outlet temperature, c: IHX cold outlet temperature, d: IHX hot side outlet temperature, e: hot side flow rates of SHX and IHX, f: Duties of the hot and cold side of SHX and IHX

3.2. Primary Loop Disturbances

Fig. 7 shows the system control after a -10°C step change in the temperature of the stream entering the hot side of the IHX (T_{hi2}). In this scenario, the cold side flow rates are used as the manipulated variables rather than the hot side flow rates. The controlled variables for the SHX (T_{co}) and IHX (T_{ho2}) are unchanged, as shown in Fig. 7a and 7d. The decrease in the temperature of the hot stream entering the heat exchanger implies lowering the amount of

heat transferred to the cold stream. In order to maintain a constant outlet temperature of the hot stream, the cold side flow rates are decreased. The cold side flow rates of the IHX (F_{c2}) and SHX (F_c) decrease by 6.3% and 9.5% respectively. Fig. 7b and 7c show the uncontrolled variables for the SHX (T_{ho}) and IHX (T_{co2}), respectively. Both of these temperatures decrease, with the decrease being more severe for the temperature of the cold outlet stream (T_{co2}) of the IHX. It decreases by $\sim 7^\circ\text{C}$ and the temperature of the hot outlet stream of the SHX (T_{ho}) decreases by $\sim 1^\circ\text{C}$. The system exhibits oscillatory behavior, stabilizing at a new equilibrium in ~ 1000 seconds. The thermal duty decreases to about 9000 kW, 10% lower than the initial duty as seen in Fig. 7f.

Fig. 7. Control of IHX and SHX after -10°C step decrease entering the hot side of the IHX.
a: SHX cold outlet temperature, b: SHX hot outlet temperature, c: IHX cold outlet temperature, d: IHX hot side outlet temperature, e: cold side flow rates of SHX and IHX, f: Duties of the hot and cold side of SHX and IHX

Fig. 8 shows the system control after a $+10^{\circ}\text{C}$ step change in the temperature of the stream entering the hot side of the IHX (T_{hi2}). Again, the cold side flow rates are used as the manipulated variables rather than the hot side flow rates. Fig. 8a and 8d show the time profiles of the controlled variables for the SHX (T_{co}) and IHX (T_{ho2}), respectively. After the disturbance, the temperatures are controlled at their desired values by changing the cold side flow rates (F_c/F_{c2}). The system exhibits oscillatory behavior. The initial drop in the cold outlet temperature is compensated by increasing the flow rate as seen in Fig. 8e. This causes the temperature rise across the SHX to decrease and thus keeps the temperature at its desired value. The hot outlet temperature of the IHX (T_{ho2}) also rises initially. The cold side flow rate increases in order to make the heat transfer greater and increase the temperature drop across the hot side. The cold side flow rates of the IHX (F_{c2}) and SHX (F_c) rise by 8.5% and 10.3% respectively. Fig. 8b and 8c show the uncontrolled variables for the SHX (T_{ho}) and IHX (T_{co2}), respectively. Both temperatures increase, with the increase being slightly greater for the cold outlet stream of the IHX. The cold outlet of the IHX (T_{co2}) rises by about 4.5°C and the hot outlet of the SHX (T_{ho}) rises by about 3.2°C . A new equilibrium is established in ~ 800 seconds and the duty rises to about 11000 kW, 10% higher than the initial value as seen in Fig. 8f.

Fig. 8. Control of IHX and SHX after +10 °C step decrease entering the hot side of the IHX.
a: SHX cold outlet temperature, b: SHX hot outlet temperature, c: IHX cold outlet temperature, d: IHX hot side outlet temperature, e: cold side flow rates of SHX and IHX, f: Duties of the hot and cold side of SHX and IHX

3.3. Switching Manipulated Variables

Larger disturbances in load variables require progressively larger adjustments in the manipulated variables for system control. However, the range of a manipulated variable may be subject to other constraints arising from limitations in other components of the system. For example, the pump capacity may limit the maximum flow rate of a manipulated variable. The flow rate may also be constrained by a limit on the acceptable pressure drop. Conversely, a minimum limit may be specified on the flow rate, arising from the equipment constraints. In such cases where the system disturbances result in reaching limiting condition of a manipulated variable, the control system design must provide for switching to using another combination of manipulated variables for further control. In the present work, the limits of manipulated variables are specified at $\pm 20\%$ of its initial flow rates. Once a manipulated variable reaches its limit, further control requires manipulation of another variable. Fig. 9 shows the controller system response after a $-22\text{ }^{\circ}\text{C}$ step decrease in the temperature of the stream entering the cold side of the SHX (T_{ci}). Fig. 9a and 9d show the controlled variables for the SHX (T_{co}) and IHX (T_{ho2}), respectively. Both the controlled temperatures show an immediate decrease after the disturbance is introduced. Both the manipulated variables – the SHX the hot side flow rate (F_h) and the hot side flow rate of the IHX (F_{h2}) – increase in response, causing the controlled temperatures to increase to their set points. Fig. 9b and 9c show the uncontrolled variables for the SHX (T_{ho}) and IHX (T_{co2}). The hot side outlet temperature of the SHX (T_{ho}) decreases by about $15\text{ }^{\circ}\text{C}$ initially before rising to a temperature of $547\text{ }^{\circ}\text{C}$, which is $2\text{ }^{\circ}\text{C}$ higher than the initial value. The cold outlet temperature of the IHX (T_{co2}) drops by about $6\text{ }^{\circ}\text{C}$. At about 650 seconds the hot side flow rate of the SHX reaches the limit (120% of initial flow) as seen in Fig. 9f. At this point the system switches to using the cold side flow rate of the SHX (F_c) as the manipulated variable, as seen in Fig. 9g. The hot side flow rate of the IHX seen in Fig. 9e never reaches the limit and is used as the manipulated variable for the IHX for the entirety of the control. This flow rate increases by about 13%. The hot and cold side flow rates of the SHX change by $+20\%$

and -1%, respectively. The system takes around 1100 seconds to come to equilibrium and the duty increases by around 13% to ~11300 kW as shown in Fig. 9h.

Fig.9. Control of IHX and SHX with changing manipulated variables after -22 °C step decrease entering the cold side of the SHX. a: SHX cold outlet temperature, b: SHX hot outlet temperature, c: IHX cold outlet temperature, d: IHX hot side outlet temperature, e: hot side flow rate IHX, f: hot side flow rate of SHX, g: cold side flow rate of SHX, h: Duties of the hot and cold side of SHX and IHX

Fig. 10 shows the system response to a +30 °C step increase in the temperature of the stream entering the cold side of the SHX (T_{ci}). Fig. 10a and 10d are the controlled variables for the SHX (T_{co}) and IHX (T_{ho2}), respectively. As shown, both the temperatures spike immediately after the disturbance. The manipulated variables – the hot side flow rate of SHX (F_h) and the hot side flow rate of IHX (F_{h2}) – decrease in response. Fig. 10b and 10c show the uncontrolled temperatures for the SHX (T_{ho}) and IHX (T_{co2}), respectively. The hot outlet temperature of the SHX (T_{ho}) increases by ~14 °C. After an initial increase of roughly 3.6 °C, the temperature of cold outlet stream of the IHX (T_{co2}) stabilizes at a temperature 2.5 °C higher than the initial value. Again, the manipulated variables are changed once a flow rate has reached the constraint of a change of $\pm 20\%$ in the initial value. In this scenario, the hot side flow rate of the IHX reaches this limit first (80%) at approximately 150 seconds as seen in Fig. 10e. At this time, the IHX switches to using the cold side flow rate (F_{c2}) as the manipulated variable. This is the same variable as the hot side flow rate of the SHX (F_h) and thus the SHX must also switch to using the cold side flow rate (F_c) because both controllers can not use the same manipulated variable. Fig. 10f shows the IHX cold side (SHX hot side) flow rate. It decreases by ~16.4% during the initial phase of control when employed for the control of the SHX, but then increases by 2.5% when it is switched to control the IHX. The overall change in the flow rate of this stream is -13.9%. The cold side flow rate of the SHX, seen in Fig. 10g, has an initial spike but eventually decreases by 0.4%. The system is in equilibrium at ~700 seconds after the disturbance is introduced, with a decrease in the thermal duty of ~2000 kW or -20% of the initial duty as seen in Fig. 10h.

Fig.10. Control of IHX and SHX with changing manipulated variables after +30 °C step increase entering the cold side of the SHX. a: SHX cold outlet temperature, b: SHX hot outlet temperature, c: IHX cold outlet temperature, d: IHX hot side outlet temperature, e: hot side flow rate IHX, f: hot side flow rate of SHX, g: cold side flow rate of SHX, h: Duties of the hot and cold side of SHX and IHX

3.4. Summary

The control system response to various disturbances is summarized in Table 6. As seen from the table, the system is able to establish a new steady state for step temperature disturbances in the process and primary streams.

Table 6

Summary of results for different disturbances

Loop	Disturbance	SHX flow rate change %	IHX flow rate change %	Change in Thermal Duty kW
Temperature Disturbances				
Process	-10 °C	$F_h = +6.8\%$	$F_{h2} = +6.7\%$	+650 (+6.5%)
	+10 °C	$F_h = -5.0\%$	$F_{h2} = -6.5\%$	-650 (-6.5%)
	-22 °C*	$F_c = -1.0\%$ $F_h = +20\%$	$F_{h2} = +13\%$	+1300 (+13%)
	+30°C**	$F_c = -0.4\%$ $F_h = -16.4\%$	$F_{h2} = -20\%$ $F_{c2} = +2.5\%$	-2000 (-20%)
Primary	-10 °C	$F_c = -9.5\%$	$F_{c2} = -6.3\%$	-1000 (-10%)
	+10 °C	$F_c = +10.3\%$	$F_{c2} = +8.5\%$	+1000 (+10%)

*System changes from using $F_{h2}/F_h \rightarrow F_{h2}/F_c$ **System changes from using $F_{h2}/F_h \rightarrow F_{c2}/F_c$

Other potential system disturbances involve changes in flow rates of various streams, arising from leakages or breakages in the piping system or a pump malfunction, etc. The control system described above does not include the dynamics of the nuclear reactor and its control. Further work is in progress to simulate the control system response incorporating the flow disturbances and the reactor dynamics along with feedback effects.

5. Conclusion

A control system architecture was developed for the control of coupled heat exchanger-nuclear reactor system, and the system behavior simulated by developing a MATLAB code. Two controllers were incorporated into the code to control the temperatures of the cold side outlet stream of the SHX (T_{co}) and hot side outlet stream of the IHX (T_{ho2}) by manipulating either the hot side flow rates (F_h/F_{h2}), cold side flow rates (F_c/F_{c2}), or combination of these. Transfer functions were used to tune the controllers and simulate the transient response of the control system to temperature disturbances in the process and primary loops, representing either a

problem in the process or the reactor. For a 10°C step change in the process, the hot side flow rates (F_h/F_{h2}) changed between 5% and 7% and the duty changed by ± 650 kW or $\pm 6.5\%$ to maintain the controlled temperatures at their set points. For similar disturbances in the primary loop, the cold side flow rates (F_c/F_{c2}) changed between 6% and 10% and the overall duty change was approximately ± 1000 kW, or 10% of the initial duty. The disturbances in the primary loop have an overall greater impact on the system. It may be best to have a control strategy in which the manipulated variables depend on where the disturbance occurs. For example, if the disturbance is from the process side then the hot side flow rates (F_h/F_{h2}) may be the desired manipulated variables. However, if the disturbance comes from the primary loop then using the cold side flow rates (F_c/F_{c2}) may produce better control. In addition, a control strategy that involved switching of the manipulated variable after a certain pre-set limit ($\pm 20\%$ change) was reached for that manipulated variable was investigated. This limit is reached for larger temperature disturbances in the system, which triggered a switching of the manipulated variables. The system was able to come to a new equilibrium state relatively quickly while successfully maintaining the controlled temperatures at their desired set-points, demonstrating the effectiveness of this approach.

Nomenclature

A : heat transfer area (m^2).

C_p : specific heat ($\text{J/kg}\cdot^\circ\text{C}$).

E : Error

F : Flow rate

G_c : Controller transfer function

G_v : Valve or pump transfer function

$G_{s/p}$: Process transfer function

k : overall heat transfer coefficient ($\text{W/m}^2\cdot^\circ\text{C}$)

K : Gain

M_w : Mass of metal (kg)

P : Output of controller

T/t : Temperature

T : Time constant (s)

Greek Symbols

α : individual heat transfer coefficients ($\text{W/m}^2\cdot^\circ\text{C}$)

τ : time delay

Subscripts

c : cold

D : derivative

h : hot

i : inlet

I : IHX

$\int$: Integral

o : outlet

P: proportional

S: SHX

w: wall

0: initial value

1: SHX

2: IHX

3: Reactor

Superscript

*: Set-point

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Appendix A: Transfer functions, gain, and time constants

Transfer functions for the hot side of the heat exchangers are shown below.

$$G_{s5} = \frac{\Delta T_{ho}}{\Delta F_{hi}} = \frac{K_{hFh}}{T_{hs} + 1} \quad (A-1)$$

$$G_{s6} = \frac{\Delta T_{ho}}{\Delta F_{ci}} = \frac{K_{hFc}}{T_{hs} + 1} \quad (A-2)$$

$$G_{s7} = \frac{\Delta T_{ho}}{\Delta T_{ci}} = \frac{K_{htc} e^{-\tau_{hs}}}{T_{hs} + 1} \quad (A-3)$$

$$G_{s8} = \frac{\Delta T_{ho}}{\Delta T_{hi}} = \frac{K_{hth}}{T_{hs} + 1} \quad (A-4)$$

The gains to changes are calculated by methods developed previously based on simple energy balance for various streams (Guomin et al., 2011). Temperature gains are as follows.

$$K_{ctc} = \frac{\Delta t_{co}}{\Delta t_{ci}} = \frac{\frac{F_c C_{pc} - 1}{F_h C_{ph}}}{\frac{F_c C_{pc} - B_c}{F_h C_{ph}}} \quad (A-5)$$

This is the gain for change in cold side outlet temperature due to changes in cold side inlet temperature.

$$K_{cth} = \frac{\Delta t_{co}}{\Delta t_{hi}} = \frac{1 - B_c}{\frac{F_c C_{pc} - B_c}{F_h C_{ph}}} \quad (A-6)$$

This is the gain for change in cold side outlet temperature due to changes in hot side inlet temperature.

$$K_{hth} = \frac{\Delta t_{ho}}{\Delta t_{hi}} = \frac{B_h - B_h \frac{F_h C_{ph}}{F_c C_{pc}}}{1 - B_h \frac{F_h C_{ph}}{F_c C_{pc}}} \quad (A-7)$$

This is the gain for change in hot side outlet temperature due to changes in hot side inlet temperature.

$$K_{htc} = \frac{\Delta t_{ho}}{\Delta t_{ci}} = \frac{1 - B_h}{1 - B_h \frac{F_h C_{ph}}{F_c C_{pc}}} \quad (A-8)$$

This is the gain for change in hot side outlet temperature due to changes in cold side inlet temperature.

These gains describe the change in outlet temperature with changes in the inlet temperatures. B_c and B_h are shown below.

$$B_h = e^{\frac{k_h A_h}{F_c C_{p_c}} - \frac{k_h A_h}{F_h C_{p_h}}} \quad (\text{A-9})$$

$$B_c = e^{\frac{k_c A_c}{F_c C_{p_c}} - \frac{k_c A_c}{F_h C_{p_h}}} \quad (\text{A-10})$$

In these equations k is the heat transfer coefficient, A is the heat transfer area, G is the flow rate and C_p is the heat capacity. Additionally there are gains to changes in flow rates and those are shown below.

$$K_{cFc} = \frac{dt_{co}}{dF_c} = \frac{t_{hi} - t_{ci}}{\left(B_c - \frac{F_c C_{p_c}}{F_h C_{p_h}}\right)^2} \left(B_c \frac{k_c A_c}{F_c F_h C_{p_h}} + B_c \frac{C_{p_c}}{F_h C_{p_h}} - B_c \frac{k_c A_c}{F_c^2 C_{p_c}} - \frac{C_{p_c}}{F_h C_{p_h}} \right) \quad (\text{A-11})$$

This is gain for change in cold side outlet temperature due to changes in cold side flowrate.

$$K_{cFh} = \frac{dt_{co}}{dF_h} = \frac{t_{hi} - t_{ci}}{\left(B_c - \frac{F_c C_{p_c}}{F_h C_{p_h}}\right)^2} \left(B_c \frac{k_c A_c}{F_h^2 C_{p_h}} + \frac{F_c C_{p_c}}{F_h^2 C_{p_h}} - B_c \frac{k_c A_c F_c C_{p_c}}{F_h^3 C_{p_c}^2} - B_c \frac{F_c C_{p_c}}{F_h^2 C_{p_h}} \right) \quad (\text{A-12})$$

This is gain for change in cold side outlet temperature due to changes in hot side flowrate.

$$K_{hFh} = \frac{dt_{ho}}{dF_h} = \frac{t_{hi} - t_{ci}}{\left(B_h \frac{F_h C_{p_h}}{F_c C_{p_c}} - 1\right)^2} \left(B_h \frac{k_h A_h}{F_h^2 C_{p_h}} + B_h^2 \frac{C_{p_h}}{F_c C_{p_c}} - B_h \frac{k_h A_h}{F_h F_c C_{p_c}} - B_h \frac{C_{p_h}}{F_c C_{p_c}} \right) \quad (\text{A-13})$$

This is gain for change in hot side outlet temperature due to changes in hot side flowrate.

$$K_{hFc} = \frac{dt_{ho}}{dF_c} = \frac{t_{hi} - t_{ci}}{\left(B_h \frac{F_h C_{p_h}}{F_c C_{p_c}} - 1\right)^2} \left(B_h \frac{k_h A_h F_h C_{p_h}}{F_c^3 C_{p_c}^2} + B_h \frac{F_h C_{p_h}}{F_c^2 C_{p_c}} - B_h \frac{k_h A_h}{F_c^2 C_{p_c}} - B_h^2 \frac{F_h C_{p_h}}{F_c^2 C_{p_c}} \right) \quad (\text{A-14})$$

This is gain for change in hot side outlet temperature due to changes in cold side flowrate.

The time constant (T) is described below. And the time delay is simply the time it takes for the fluid to flow through the heat exchanger or simply L/v where L is the flow length and v is the velocity.

$$T = \frac{M_w C_w}{\frac{C_{p_c} \alpha_c A_c}{C_{p_c} + \frac{\alpha_c A_c}{2 F_c}} + \frac{\alpha_h A_h F_h}{F_h + \frac{\alpha_c A_h}{2 C_{p_h}}}} \quad (\text{A-15})$$

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