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Real Time Performance Analysis and Fault Diagnosis in Heat Exchanger

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Abstract: The heat exchanger is a device used for transferring of heat from medium to another medium. They are widely used in petrochemical plants, air conditioning, chemical plants, thermal power plants and etc. Due to the change in process parameters the overall heat transfer rate will be severly affected. In order to increase the efficiency of overall heat transfer rate, the possible faults developed in the heat exchanger have to be identified. For this purpose, various fault diagnosis methods are available. Among them, the process history based method is here chosen. This method requires large amount of process data. The real time readings from a shell and tube heat exchanger is obtained for both normal and fault operating conditions. And a transfer function model is also derived using the real time data. The frequency response shows the occurrence of the resonance effect in the heat exchanger. By using suitable diagnosis methods with these real time data, the possibility of occurrence of faults can be diagnosed and remedial measures will also be recommended.
Keywords: Heat transfer coefficient, fault diagnosis, shell and tube heat exchanger, fault detection.

1. Introduction

In the heat exchanger two different or the same medium may be separated by a solid wall to prevent mixing or they may be in direct contact. They are widely used in refrigeration, air conditioning, power stations, chemical plants, natural gas processing, and sewage treatment. The classic example of a heat exchanger is found in an internal combustion engine in which a circulating fluid known as engine coolant flows through radiator coils and air flows past the coils, which cools the coolant and heats the incoming air. There are three heat transfer operations taking place in a heat exchanger [6]. They are: convective heat transfer from fluid to the inner wall of the tube, conductive heat transfer through the tube wall and convective heat transfer from the outer tube wall to the outside fluid.

2. Experimental Setup

There are many type of heat exchangers available among them the shell and tube heat exchanger is one. It is the most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher-pressure applications [1]. As its name implies, this type of heat exchanger consists of a shell with a bundle of tubes inside it. One fluid runs through the tubes and another fluid or steam flows outside the tubes but inside the shell to transfer heat between the two fluids.

Heat is transferred from one fluid to the other through the tube walls either from tube side to shell side or vice versa. The fluids can be either liquids or gases on either the shell or the tube side. In order to transfer heat efficiently, a large heat transfer area should be used, leading to the use of many tube. The real time setup of the shell and tube heat exchanger used for research work is shown in the Figure 1. From this the inlet temperature, outlet temperature, steam pressure, flow rate of water are noted and the overall heat transfer coefficient is calculated using various formula.

Figure. 1 Real Time Setup of Shell and Tube Heat Exchanger

The following Table 1 shows the specifications of the real time setup of the shell and tube heat exchanger.

Table 1: Specifications of Shell and Tube Heat Exchanger

S.No	Parameters	Values
1.	Shell inner diameter	0.155 m
2.	Length of the exchanger	0.985 m
3.	Pipe inner diameter	0.0065 m
4.	Pipe outer diameter	0.0095 m
5.	Number of tubes	24
6.	Thermal conductivity of material	55 w/mK

3. Modelling of Shell and Tube Heat Exchanger

To obtain the transfer function, usual steady-state assumptions of no axial conduction, no back mixing and constant fluid properties are made. And to limit the equation to second order it is assumed that there is no wall resistance and no capacity in the condensate film. If significant, the wall resistance could be split and added to the two film resistances, and the condensate film capacity could be added to that of the wall [7].

The energy balance equation for the fluid stream is written for a length dx is given as,

$$M_f C_f \left(\frac{\partial \theta}{\partial t}\right) dx + F' C_f \left(\frac{\partial \theta}{\partial x}\right) dx = h_1 A_1 dx(\theta_w - \theta) \quad (1)$$

$$M_w C_w \left(\frac{\partial \theta_w}{\partial t}\right) dx = h_2 A_2 dx(\theta_s - \theta_w) - h_1 A_1 dx(\theta_w - \theta) \quad (2)$$

Where,

M_f =Mass flow rate of cold water lb fluid/ft

C_f = heat capacity of fluid, Btu/lb(^{0}F)

h_1 = inside coefficient, Btu/(sec)(ft^2)(^{0}F)

A_1 =inside transfer area, ft^2/ft

v = velocity, fps

M_wC_W = Wall capacity, Btu/(^{0}F)(ft)

h_2 = outside coefficient, Btu/(sec)(ft^2)(^{0}F)

A_2 =outside transfer area, ft^2/ft

$$\frac{\theta}{\theta_S} = \frac{b}{a}(1 - e^{-ax/v}) \qquad (3)$$

where,

$$a = \frac{(T_1 s + 1)(T_{12} T_2 s + T_{12} + T_2) - T_2}{T_1 (T_{12} T_2 s + T_{12} + T_2)}$$

$$\frac{b}{a} = \frac{1}{T_1 T_2 s^2 + (T_1 + T_2 + T_1 T_2 / T_{12}) s + 1}$$

Where $\frac{x}{v} = L$, is the time for the fluid to flow through the tubes, which is time delay L.

$$\frac{\theta}{\theta_s} = \frac{b}{a}(1 - e^{-aL})$$

The equation (3) is the transfer function model of the shell and tube heat exchanger.

4. Real Time Data from Shell and Tube Heat Exchange

The Table 2 shows the real time data taken from shell and tube heat exchanger.

Table 2: Real Time Data taken from Shell and Tube Heat Exchanger

S.NO	Steam pressure kgf/cm^2	Steam pressure absolute kgf/cm^2	Steam temp ^{0}C	Temp cold water in ^{0}C	Temp cold water out ^{0}C	volume flow of cold water Lph	Volume flow of cold water m$^{3/}$/sec x10^4	Velocity of cold water m/sec	Mass flow rate of cold water kg/sec	Tc ^{0}C
1.	0.2	1.2	104.8	33	63	4	0.66	2.008	0.06526	48
2.	0.2	1.2	104.8	33	60	6	1.00	3.015	0.09894	46.5
…….	…….	…….	…….	…….	…….	…….	…….	…….	…….	…….
7.	0.4	1.4	109.3	32	58	8	1.33	4.010	0.1316	45
8.	0.4	1.4	109.3	31	54	10	1.66	5.005	0.1645	42.5

The Table 3 shows the overall heat transfer coefficients (Theoretical).

Table 3: Overall Heat Transfer Coefficients (Theoretical)

S.NO	T_w ^0C	T_f ^0C	ΔT LMTD	Properties at T_f				ΔT_0	hs W/m^2k	hi W/m^2k	U_0 Theoretical
				ρ_f Kg/m^3	μ_f NS/m^2 $x10^{-6}$	K_f Watt/m K	Cp J/Kg k				
1.	76.4	90.6	55.45	964.88	313.03	0.6801	4208.7	28.4	5445.1	11725.4	2932.00
2.	75.65	90.2	57.24	965.14	314.28	0.6800	4208.2	29.15	5404.05	16029.4	3236.26
…….	…….	…….	…….	…….	…….	…….	…….	…….	…….	…….	…….
8.	75.9	92.6	66.13	963.50	306.49	0.6807	4211.1	33.4	5248.55	23314.4	3496.61

The Table 4 shows the overall heat transfer coefficients (Experimental).

Table 4: Overall Heat Transfer Coefficients (Experimental)

S.NO	PROPERTIES AT Tc				N_{Re} Reynold's number	N_{pr} Prandtl number	vol flow of condensate for 5 Sec $m^3 x10^4$	vol flow of condensate m^3/sec $x10^4$	Mass flow rate of condensate kg/sec	λ_s J/Kg X 10^3	Q W X 10^3	U_0 exp
	ρ Kg/m^3	μ NS/m^2 $x10^{-6}$	K Watt/m K	Cp J/Kg k								
1.	988.84	570.28	0.6454	4174	22631.58	3.688	1.15	2.3	0.0227	2244.1	50.941	1904.4
2.	989.47	585.865	0.643	4174	33098.30	3.803	1.10	2.2	0.0217	2244.1	48.69	1844.84
……	……	……	……	……	……	……	……	……	……	……	……	……
8.	991.15	627.42	0.638	4174	51391.93	4.104	0.82	1.64	0.0162	2231.9	36.15	1596.84

The final values obtained from the above data are

- Overall heat transfer coefficient U_0(experimental) = 1786.7 W/m^2K
- Overall heat transfer coefficient U_0(theoretical) = 3247.699 W/m^2K
- Individual heat transfer coefficient(steam side) h_s = 5316.705 W/m^2K
- Individual heat transfer coefficient(cold water side) h_i = 17644.72 W/m^2K

5. Transfer Function Calculation

$$T_1 = \frac{M_f c_f}{h_1 A_1} = \frac{0.25628 \times 1}{3107.41 \times 0.2196} \times 3600 = 1.35\,\text{sec}$$

$$T_2 = \frac{M_w c_w}{h_2 A_2} = \frac{0.051918 \times 1.005}{936.325 \times 0.3162} \times 3600 = 0.634\,\text{sec}$$

$$T_{12} = \frac{M_w c_w}{h_1 A_1} = \frac{0.051918 \times 1.005}{3107.41 \times 0.2196} \times 3600 = 0.275\,\text{sec}$$

By substituting all these values in the equation (3) we get,

$$\frac{b}{a} = \frac{1}{0.8559 s^2 + 5.09 s + 1}$$

$$1 - e^{aL} = 1 - 0.4041 e^{-4s}$$

$$\frac{\theta}{\theta_s} = \frac{1 - 0.4041 e^{-4s}}{0.8559 s^2 + 5.09 s^2 + 1} \tag{4}$$

The equation (4) is the transfer function model obtained from the real time data.

6. Faults Detection

Types of faults considered in the heat exchanger are,

- Actuator fault
- Sensor fault
- Process fault
- Leakage in tubes present inside the shell of heat exchanger

These are the common faults that usually occurred in the heat exchanger [5].

A. Sensor Faults

A sensor is an object whose purpose is to detect events or changes in its environment, and provide a corresponding output. It is otherwise known as a transducer if it is provided with suitable signal conditioning unit.The following sensors available in the real time setup of the shell and tube heat exchanger are

- Rotameter – Flow Sensor
- Steam pressure gauge – Pressure Sensor
- Thermometer – Temperature Sensor

The gross errors usually occur with sensors. This could be due to the fixed failure, a constant bias, or an output range failure. A failure in any one of the instrument could cause the plant state variable to deviate beyond the acceptable limit unless the failure is detected promptly and corrective actions are accomplished in time.

B. Rotameter Fault

The rotameter is the type of flow sensor used for measuring the water flow rate in the heat exchanger. There is a possible fault when it is turning OFF the inlet water supply to the heat exchanger. It means that the water supply valve at the rotameter inlet section is in OFF condition and due to which, there will not be water flow to the heat exchanger through the rotameter. Under this condition, inlet steam to the heat exchanger is allowed and varied in steps. The corresponding temperature values at the outlet section of the heat exchanger are noted.

Table 5: Data under Rotameter Fault Condition

S.NO	Steam pressure kgf/cm^2	Temp cold water in ^0C	Temp cold water out ^0C	Volume flow of cold water Lph	Volume of condensate mL/sec
1.	0.2	31	70	2,4,6,8,10	0
2.	0.4	32	72	2,4,6,8,10	0
3.	0.6	32	75	2,4,6,8,10	0
4.	0.8	33	78	2,4,6,8,10	0
5.	1.0	34	82	2,4,6,8,10	0

Table 5 shows the temperature readings at both inlet and outlet sections along with values of the condensate. From the above readings, it is observed that during the normal working condition, the outlet temperature of the water has to be decreased but due to the rotameter fault (there is no water flow rate) the temperature increases. The volume of the condensate is also found zero as there is no water supply for converting the steam to condensate.

C. Steam Pressure Gauge Fault

The pressure gauge is used for measuring the steam pressure inside the shell of the heat exchanger. The possible fault is obtained by turning off the pressure gauge. And the readings are taken by changing the steam pressure and the liquid flow rate. Table 6 shows the temperature readings at both inlet and outlet sections along with the volume of the condensate.

Table 6: Data under Steam Pressure Gauge Fault Condition

S.NO	Steam pressure kgf/cm^2		Temp cold water in ^{0}C	Temp cold water out ^{0}C		Volume flow of cold water Lph	Volume of condensate mL/sec
	Indicated	Original		Indicated	Original		
1.	0.2	0.2	31	63	63	4	▲
2.	0.2	0.4	31	60	61	6	▼
3.	0.2	0.8	32	50	70	8	▲
4.	0.2	0.4	32	49	54	10	▼

From the above readings, it is observed that when the steam is constant and the inlet water flow rate is increased, the outlet temperature has to be decreased. But due to the steam pressure gauge fault (wrong indication of the steam) the outlet temperature gets fluctuated. The volume of the condensate also gets changed due to the deviation in the temperature.

D. Actuator Faults

The operation of a control valve involves positioning its movable part relative to the stationary seat of the valve. The purpose of the valve actuator is to accurately locate the valve plug in a position dictated by the control signal. The actuator accepts a signal from the control system and, in response, moves the valve to a fully-open or fully-closed position. The actuator fault is created by turning off the steam inlet flow rate valve. And the flow rate is increased as usual. And the readings are taken which is further listed in the Table 7.

Table 8: Data under Actuator Fault Condition

S.NO	Steam pressure kgf/cm^2	Temp cold water in ^{0}C	Temp cold water out ^{0}C	Volume flow of cold water Lph	Volume of condensate mL/sec
1.	0.2,0.4,0.6,0.8,1	31	31	2	0
2.	0.2,0.4,0.6,0.8,1	31	32	4	0
3.	0.2,0.4,0.6,0.8,1	32	32	6	0
4.	0.2,0.4,0.6,0.8,1	32	33	8	0
5.	0.2,0.4,0.6,0.8,1	34	34	10	0

From the above readings, it is observed that the water flow rate gets gradually increased and as there is no inlet steam flows, due to the actuator fault both the inlet and outlet temperatures are nearly same. And the volume of the condensate is found zero, as there is no steam to be converted as the condensate.

E. Leakage in Tubes Present Inside the Shell of Heat Exchanger

In the shell and tube heat exchanger, there will be tubes present inside the shell from which the liquid moves from the inlet to outlet direction. There may be some leakage in those tubes present[3]. If there is leakage in the tubes, then possible values are listed in the Table 9.

Table 9: Data during Leakage of Tubes Present Inside the Shell of Heat Exchanger

S.NO	Steam pressure kgf/cm^2	Temp cold water in ^0C	Temp cold water out ^0C	Volume flow of cold water Lph	Volume of condensate mL/sec	
					Normal	Leakage
1.	0.2	31	63	4	▼	▲
2.	0.2	31	60	6	▼	▲
3.	0.2	32	50	8	▼	▲
4.	0.2	32	49	10	▼	▲

From the above readings, it is observed that the steam pressure is kept constant and the inlet water flow rate is increased. If the leakage is present in the tubes then there will be no change in both the inlet as well as the outlet temperatures of the liquid. But the volume of the condensate will be higher when compared to the normal condition without any leakage.

F. Frequency Response Of The Heat Exchanger-Transfer

Function Model

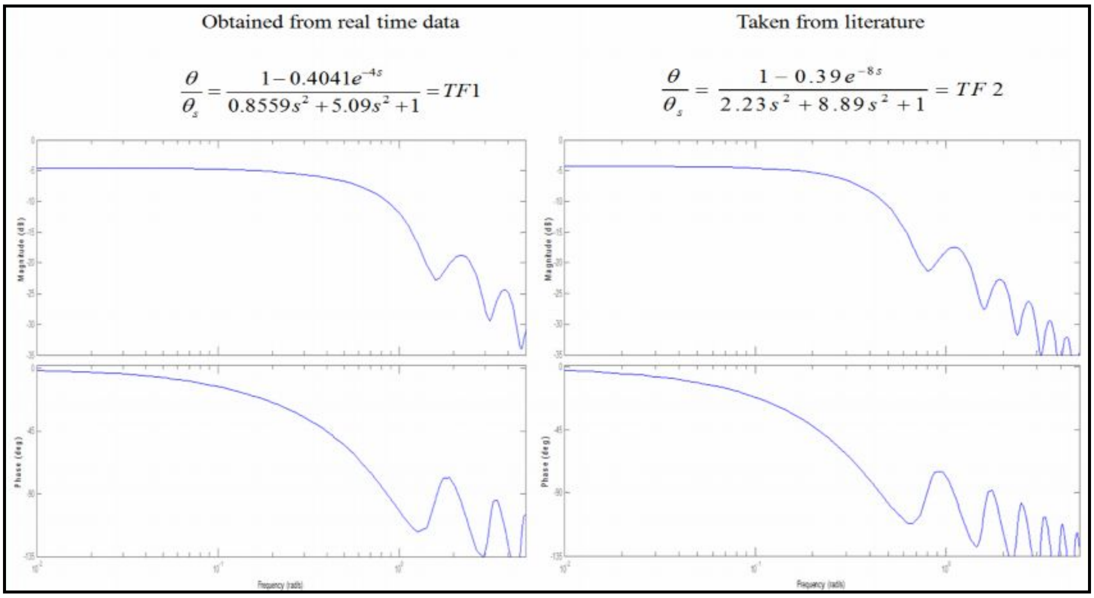

Figure 5.1 Bode Plot of the Transfer Function Model of Shell and Tube Heat Exchanger

The bode plot indicates the frequency response of the transfer function model of the shell and tube heat exchanger. The fluctuation produced in the response is due to the resonance effect [7]. The term $1\text{-}e^{-aL}$ shows regular fluctuations in magnitude and phase with frequency which leads to resonant peak. The usual procedure for determining the largest time constant can give incorrect results for the system forced in distributed manner.

For steam water exchanger, the time delay L is about equal to time constant which is based on overall coefficient. After a step change increase in steam temperature, the outlet temperature will gradually rise would be reached slightly more than L sec in practical case. Thus this time constant along with the vibration due to the water flow in inner tubes causes error and fluctuating term.

G. Effects of Various Faults in Heat Exchanger

Under various possible fault conditions, the performance of heat exchanger is to be analyzed.

Response During Flow Sensor - (Rotameter-Off) Fault Condition

Figure 5.2 shows the response of the heat exchanger during flow sensor (rotameter- OFF) fault condition

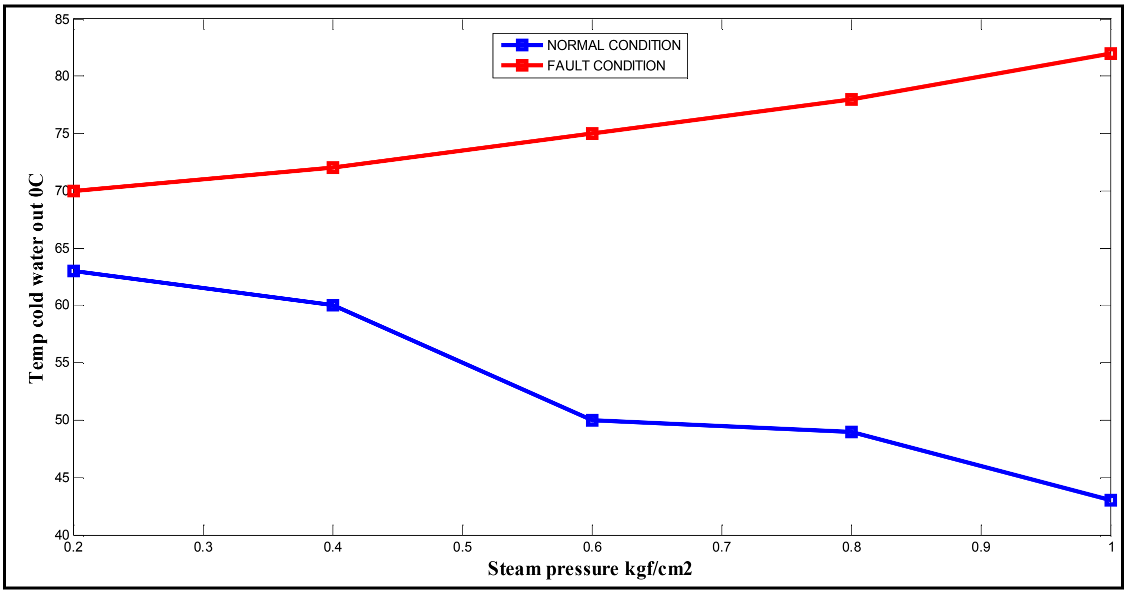

Figure 5.2 Response during Rotameter Fault Condition

This plot indicates the response during the flow sensor fault condition (rotameter OFF). The steam pressure is increased from the lower value gradually to some extent and at every point, the inlet water flow rate is also increased and thus the temperature has to be decreased during the normal operating condition. But with the presence of sensor fault (rotameter OFF) the temperature is found increased.

Response During Steam Pressure Gauge (Off) Fault Condition

Figure 5.3 shows the response of the heat exchanger during steam pressure gauge (OFF) fault condition

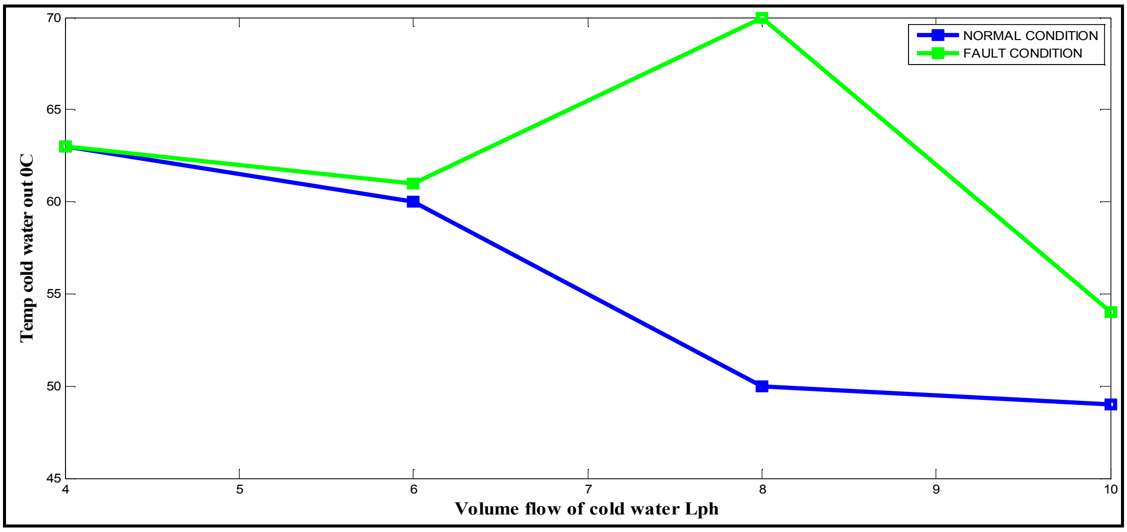

Figure 5.3 Response during Steam Pressure Gauge Fault Condition

This plot indicates the response of the heat exchanger during the steam pressure gauge fault condition. The steam pressure is kept constant and the inlet water flow rate is increased. The outlet temperature has to be reduced during normal operating condition. But due to the presence of steam pressure gauge fault, the temperature changes randomly.

Response During Steam Valve Closed Condition – Actuator Fault

Figure 5.4 shows the response of the heat exchanger during steam valve closed condition – Actuator fault.

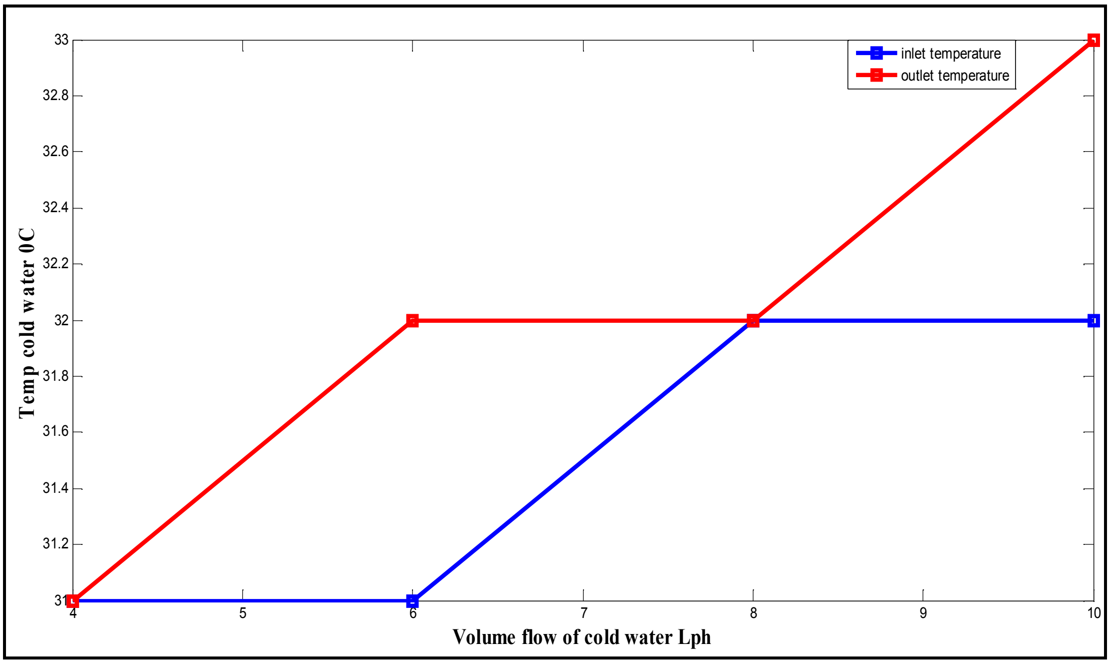

Figure 5.4 Response during Actuator Fault Condition

The above plot indicates the response of the actuator fault (steam valve OFF) condition. The water flow rate is increased and at every point the steam pressure is also increased and thus the temperature has to be increased during normal operating condition. But due to the steam valve fault (absence of steam flow) the outlet temperature is maintained relatively same as the inlet temperature.

7. Conclusion and Futuer Scope

From the shell and tube type heat exchanger setup, the real time data was obtained and from those data, it is derived the mathematical modelling by transfer function representation. The overall heat transfer coefficients both in theoretical and simulation were determined. Frequency response analysis of heat exchanger was also carried out by bode plot for theoretical transfer function taken from literature and practical transfer function derived for experimental setup.

Various possible faults such as sensor faults (flow sensor, pressure sensor), actuator fault (steam pressure gauge fault), and leakage in tubes present in shell and tube heat exchanger were considered. Under those fault conditions, the performance of heat exchanger is analysed along with the cause of fault. Using suitable intelligent techniques like neural networks, fuzzy logic and etc, the fault detection will be carried out accurately with minimum time duration.

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