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Critical Analysis of Heat Exchanger Cycle for its Maintainability Using Failure Modes and Effect Analysis and Pareto Analysis

Sayali Vyas, Atharva Desai, Shreyas Badave, Apurv Kulkarni, B. Rajiv

Abstract**—**The Failure Modes and Effect Analysis (FMEA) is an efficient evaluation technique to identify potential failures in products, processes, and services. FMEA is designed to identify and prioritize failure modes. It proves to be a useful method for identifying and correcting possible failures at its earliest possible level so that one can avoid consequences of poor performance. In this paper, FMEA tool is used in detection of failures of various components of heat exchanger cycle and to identify critical failures of the components which may hamper the system's performance. Further, a detailed Pareto analysis is done to find out the most critical components of the cycle, the causes of its failures, and possible recommended actions. This paper can be used as a checklist which will help in maintainability of the system.

Keywords**—**FMEA, heat exchanger cycle, Ishikawa diagram, Pareto analysis, risk priority number.

I. INTRODUCTION

HEAT exchangers (HEs) are devices which serve as a medium for heat exchange between two streams without mixing. In HEs, there are basically no work interactions, and changes in kinetic and potential energy are negligible for each fluid stream. The heat transfer between the two fluids takes place within the device and to avoid any heat losses to the surrounding medium, the outer shell is well insulated [1].

The purpose of the HE cycle discussed in this paper is to provide hot water which is achieved by heating water at ambient temperature with the help of steam. Such cycles are widely used in various industries such as hotel industry (hot water for geyser), food industry (hot oil for frying), brew industry (heat recovery systems), etc.

The performance of such a cycle is of utmost importance and it requires high maintenance. A plate type HE is used in the process.

FMEA is an analytical tool which is widely used to carry out the risk analysis of any process. Carrying out FMEA helps in identifying the various failure modes and the critical ones. This helps in achieving disturbance free operation of the system.

II. PROCESS DESCRIPTION

Referring to P&I (Piping and Instrumentation) diagram, the process flow is explained below.

The HE cycle is used to heat water with the help of steam. The cycle discussed in the paper proceeds as follows:

1) At the inlet of steam header, steam at the order of 15 barG is available.
2) Steam is made to enter the system with the help of a piston valve. The separator on the line serves the purpose of removing any moisture present in steam and sends pure steam ahead.
3) After the separator, a Pressure Reducing Valve (PRV) is used to reduce the steam pressure to 8 barG. This is required considering the pressure losses in the line and the requirements of steam pressure further in the line.
4) Just after the PRV, a safety valve is installed to ensure that 8 barG steam is sent ahead if the PRV fails. The safety valve's set-point is set to 8 barG and it relieves pressure when the set-point is crossed.
5) The maximum inlet pressure to the HE as per design is 3 barG. To achieve this, an electro-pneumatic control valve is used along with Proportional-Integral-Derivative (PID) controller (D-TRON, Forbes Marshall make). The feedback of pressure at downstream of control valve is given to PID controller which in turn controls the operation of the control valve to maintain 3 barG pressure.
6) Water at ambient temperature is pumped from a water tank. A normal water pump is used for this purpose. To achieve a stable flow, a piston valve is used to keep the flow constant.
7) The water gets heated through the HE. The feedback of the hot water temperature is given to a PID controller wherein a set-point is set. Depending on the feedback of temperature, the controller regulates the operation of the electro-pneumatic control valve.
8) After the steam passes through the HE, to conserve energy, a condensate recovery system is used to convert steam into condensate and then to pump it to the drain header.

Such is the process flow of the HE cycle. Several components play crucial role in maintaining optimum performance of the system.

Sayali Vyas is with College of Engineering, Pune as a Final Year B.Tech student pursuing stream – Production Engineering and Industrial Management, India (phone: +91 9552055158; e-mail: sayalijvyas@gmail.com).

Atharva Desai, Shreyas Badave, and Apurv Kulkarni are with College of Engineering, Pune as Final Year B.Tech student pursuing stream – Production Engineering and Industrial Management, India (e-mail: desaiam07@gmail.com, shreyas.badve@gmail.com, apurv.kulkarni95@gmail.com).

B. Rajiv is Head, Production Engineering and Industrial Management Department in College of Engineering, Pune, India (e-mail: rbh.prod@coep.ac.in).

International Science Index, Industrial and Manufacturing Engineering Vol:11, No:5, 2017 waset.org/Publication/10007174

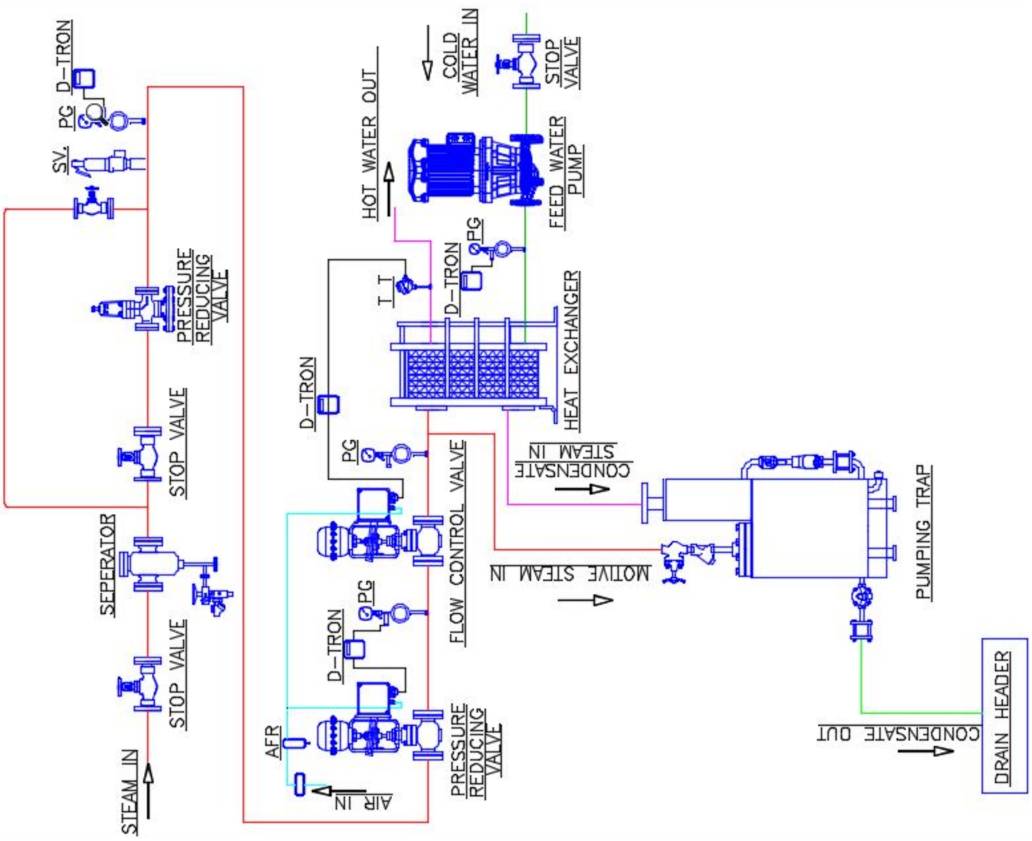

Fig. 1 P&I Diagram

III. FMEA ANALYSIS

FMEA is a useful tool for planning and performing preventive maintenance system in various industries. The technique for the first time by reliability engineers was based in the 1950s to assess safety of military systems. After this, the method quickly spread in the United States and France. The method was developed and applied in the early 1960s by NASA. Later in the 1980s, the Germans used this technique in its chemical and nuclear industries [2]. This method is widely used in electronics, chemical and other manufacturing sectors for identifying, prioritizing and resolving failures, defects and potential problems.

The FMEA method involves identification of failure modes of all components in the system and calculation of Risk Priority Number (RPN) for each failure and it is calculated from three factors: Severity (S), Occurrence (O), and Detection (S) [2].

$$RPN = O * S * D \tag{1}$$

Each of the three factors (O, S, and D) are rated on a scale of 1 to 10. Occurrence Probability (O) is indicating the possibility to occur an incident. Table I shows the criteria for the same.

Consideration of the severity level (S) is very important. If severity level is 9 or 10, regardless of RPN, its cause should be investigated immediately. Table II shows the criteria for deciding the severity of a failure mode.

TABLE I
CRITERIA FOR OCCURRENCE PROBABILITY [2]

Criteria to evaluate Occurrence Probability in FMEA method	
Description	**Scale**
Failure occurrence is very likely	10
Failure occurrence is likely	9
Failure occurrence possibility is very high	8
Failure occurrence possibility is high	7
Failure occurrence possibility is medium	6
Failure occurrence possibility is low	5
Failure occurrence possibility is very low	4
Failure occurrence possibility is rare	3
Failure occurrence possibility is very rare	2
Failure occurrence is unlikely	1

TABLE II
CRITERIA FOR SEVERITY [2]

Criteria to evaluate Severity in FMEA method	
Description	**Scale**
Complete failure of the system	10
Severe damage to the system	9
Damage to system is too high	8
Damage to system is high	7
Damage to system is medium	6
Damage to system is low	5
Damage to system is very low	4
Minor damage to system	3
Very minor damage to system	2
No damage	1

Detection probability (D) means how likely an incident or failure is discovered after the fact at a specified time. Table III shows the criteria for the same.

TABLE III
CRITERIA FOR DETECTION PROBABILITY [2]

Criteria to evaluate Detection Probability in FMEA method	
Description	**Scale**
No detection	10
Negligible	9
Very Low	8
Low	7
Modest	6
Average	5
More likely than average	4
High	3
Very high	2
Extremely high	1

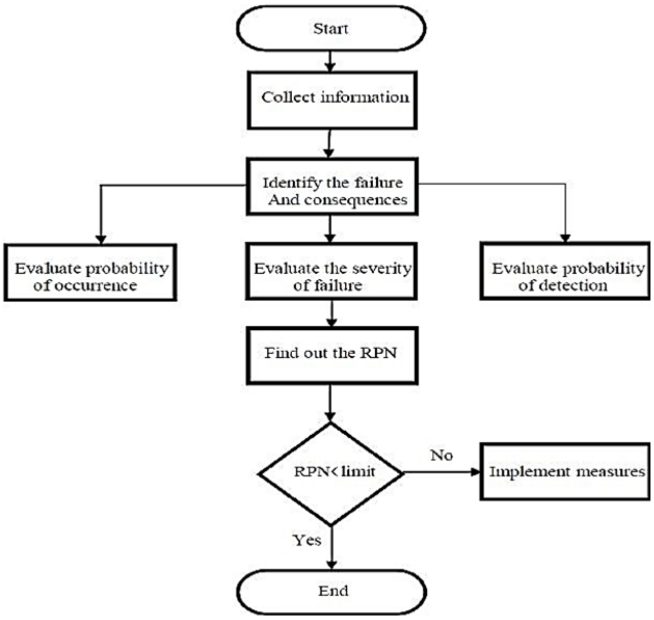

Fig. 2 Steps for FMEA [3]

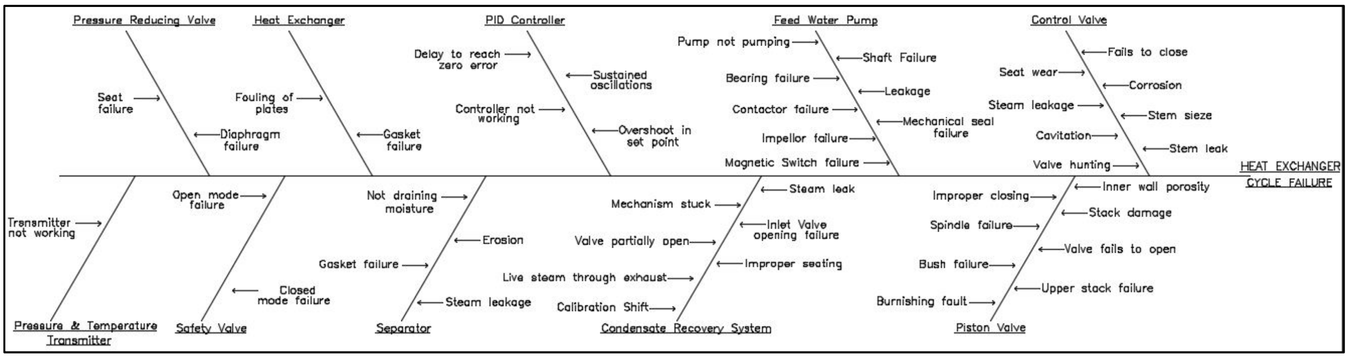

Fig. 3 Ishikawa Diagram of failures

The components that play significant roles in the HE cycle are as follows:

1. Control Valve
2. Piston Valve
3. Feed Water Pump
4. Condensate recovery system
5. PID Controller
6. Separator
7. HE
8. Safety Valve
9. PRV
10. Pressure Transmitter (PT) and Temperature Transmitter (TT)

The failures of each component are identified and enlisted and the same is represented in the form of an Ishikawa diagram as shown above. With the help of failures of components, the FMEA sheet is prepared. One of the significant features of the FMEA sheet is the RPN which is found based on S, O, D values. The values for S, O, D are based on judgment and are given with the help of guidance from industry experts in the same field. For the FMEA sheet prepared in this paper the RPN limit value is considered to be 125 assuming average value for each parameter S, O, D. From (1),

$$RPN = 5 * 5 * 5 = 125$$

The failures having RPN greater than 125 are considered for investigation.

Table IV is FMEA sheet of various failure of the components of the cycle. In the RPN column, the failure modes having RPN>125 are highlighted by orange color. The failure modes having RPN<125 with their severity of either 9 or 10 are highlighted by yellow. These highlighted failure modes are of importance and should be taken care of. Hence, recommended actions are given to assess these failures.

International Science Index, Industrial and Manufacturing Engineering Vol:11, No:5, 2017 waset.org/Publication/10007174

TABLE IV
FMEA SHEET OF HE CYCLE

Sr. No	Component Name	Part Function	Potential Failure Mode(s)	Potential Effect(s) of failures	Existing Conditions O	S	D	RPN	Recommended Actions
1	HE (HE)	Heat transfer between steam and water	Fouling of Plates	Increased Steam Consumption	7	7	3	147	Periodic cleaning of HE plates
			Gasket Failure	Fluid Leakage	3	6	2	36	
2	PID	Display parameter values and control operation of control valves	Delay to reach zero error	Delayed process outcome	6	7	2	84	
			Overshoot in set-point		6	8	2	96	
			Sustained Oscillations	No constant process outcome	7	8	3	168	Check the tuning parameters
			Controller not working	Set-point not achieved	6	8	3	144	Check wiring continuity and electrical connections
3	Separator	Separate moisture from steam	Not draining entrained moisture	Dry steam cannot be supplied	5	7	3	105	
			Steam leakage from separator	Energy losses, safety will hamper	2	6	9	108	
			Erosion of separator	Fluid leakage	2	7	3	42	
			Flange gasket damaged		3	7	3	63	
4	Control Valve	Control steam flow/pressure according to set-points	Fails to close	Redundant fouling of HE	5	5	7	175	Check and replace stem if necessary
			External & Internal Corrosion	Fluid Leakage	2	6	3	36	
			Seat Wear	Fluid leakage and valve recession	2	7	4	56	
			Stem seizes (sticky movement)	Increase packing wear rate and operating friction	3	8	6	144	Ensure smooth movement of stem
			Steam Leakage	Energy suit	2	7	3	42	
			Stem Leak	Steam loss	5	7	3	105	
			Valve Hunting	Constant Process o/p not achieved	5	8	3	120	
			Cavitation	Implosion of vapor cavities that produces impinging jets	5	7	3	105	
5	Feed Water Pump	Pump water from water tank to HE	FWP not pumping	No Inlet water	3	10	2	60	Check all components of FWP assembly, replace FWP if needed
			Shaft Failure		2	10	7	140	Replace shaft
			Bearing Failure	Noise from FWP	3	5	4	60	
			Contactor Failure	Irregular pumping	3	9	3	81	Replace contactor
			Magnetic Switch failure		5	9	3	135	Replace magnetic switch
			Impellor failure		4	9	3	108	Replace Impellor
			Leakage	Less water pumped	5	8	2	80	
			Mechanical Seal Failure		5	8	7	280	Ensure less vibration, proper lubrication, replace if necessary
6	Safety Valve	Release pressure in line above set-point	Open mode failure	Pressure beyond set-point	3	8	2	48	
			Closed mode failure	Set-point not achieved	3	3	2	18	
7	Piston valve	Isolation of outlet from inlet	Inner wall porosity	Leakage to outlet	3	7	4	84	
			Improper closing		5	7	4	140	Mention closing torque
			Stack damage		3	7	7	147	Replace softening stacks
			Valve fails to open	No flow at outlet	2	9	1	18	Check and remove dirt/burr on spindle
			Spindle failure		2	9	1	18	Apply grease, anti-seize for lubrication
8	PRV	Regulate pressure in line	Bush failure	Leakage to surrounding	3	8	3	72	
			Upper stack failure		3	6	5	90	
			Burnishing fault		3	6	5	90	
			Diaphragm failure	Inability of PRV to close	3	7	3	63	
			Seat failure		3	7	3	63	
9	PT/TT	Sense and transmit process values	Not working	Incorrect or no signals to controller	3	9	6	162	Replace PT/TT
10	Condensate Recovery system	Pumping of condensate using steam	Mechanism stuck	Valve does not operate	5	9	2	90	Check and replace failed component if any
			Live steam through exhaust		5	5	3	75	
			Improper valve seating	Exhaust valve partially open/close	6	5	4	120	
			Valve remains partially open	Inlet valve partially open/close	6	4	6	144	Clean dirt on valve seat and stem
			Inlet valve opening failure	Valve failed in close position	2	9	2	36	Keep steam motive pressure value below recommended value
			Calibration shift	Lower Flow rates	3	6	6	108	
			Steam Leak	Water hammer in discharge lines	5	6	4	120	

IV. PARETO ANALYSIS

Using FMEA, RPNs have been assigned to failures of all components. To identify the critical component which can hamper performance of HE cycle or lead to downtime, Pareto analysis is done. According to the Pareto principle, only few factors are responsible for producing most of the problems.

80/20 rule is applied in Pareto analysis which states that 80% of the key problems are produced by 20% causes. If these critical causes are tackled and necessary actions are taken, probability of success is higher [4].

Step I: Pareto analysis of components of HE cycle

To find out critical component that causes major problems in working of HE cycle, Pareto analysis is carried out. For that, count is made by taking RPN values > 125 & severity (S) of failures (Refer FMEA Sheet) equal to 9 or 10. The cumulative count and the % cumulative count are then calculated.

TABLE V
COUNT OF DEFECTS IN COMPONENTS OF HE CYCLE

Component Name	Count	Cumulative Count	% Cumulative Count
Feed Water Pump	6	6	31.58
Piston Valve	4	10	52.63
Condensate Recovery System	3	13	68.42
Control Valve	2	15	78.95
PID	2	17	89.47
HE	1	18	94.74
Pressure & Temperature transmitter	1	19	100
Separator	0	19	100
Safety Valve	0	19	100
PRV	0	19	100

From the above table, Pareto diagram of components of HE Cycle is plotted.

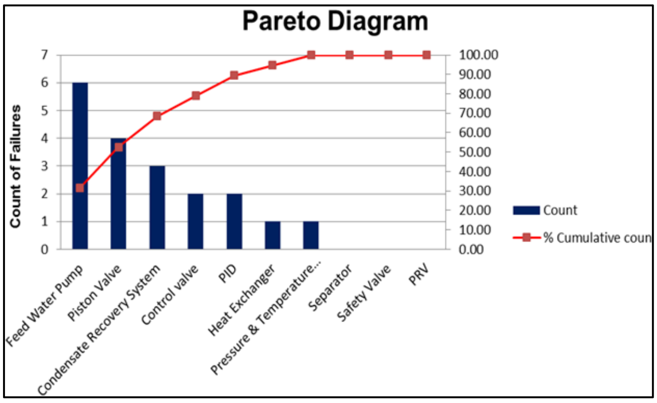

Fig. 4 Pareto analysis of components of HE cycle

From Fig. 4, it is observed that major problems are caused due to failure of feed water pump. Hence, the feed water pump is identified as the critical component of the heat exchanger cycle. In further steps, necessary actions have to be taken to overcome failure due to feed water pump.

Step II: Pareto Analysis of Failures of Feed Water Pump of HE Cycle

In this step, critical failure of feed water pump which is responsible for major problems of feed water pump and ultimately HE cycle is to be identified. For this purpose, RPN number is taken as count of failures from FMEA sheet. The cumulative count and the % cumulative count are then calculated.

TABLE VI
COUNT OF FAILURES OF FEED WATER PUMP

Failure of FWP	Count	Cumulative count	% Cumulative count
Mechanical Seal Failure	280	280	29.66
Shaft failure	140	420	44.49
Magnetic Switch failure	135	555	58.79
Impellor failure	108	663	70.23
Contactor failure	81	744	78.81
Leakage	80	824	87.29
FWP not working	60	884	93.64
Bearing failure	60	944	100

From Table VI, Pareto diagram of failures of Feed Water Pump is plotted.

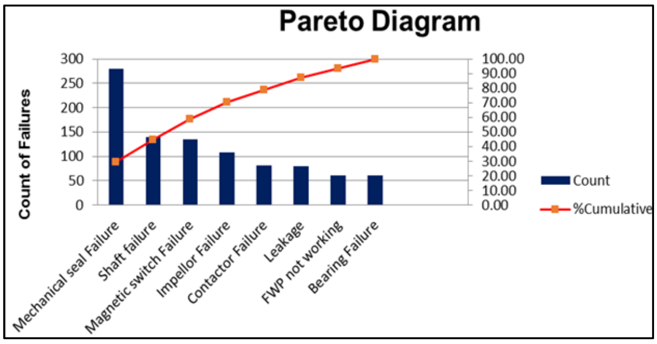

Fig. 5 Pareto analysis of failures

TABLE VII
RATING FOR CAUSES OF MECHANICAL SEAL FAILURE

Cause	Rating
Dry running of pump	9
Pump vibration	9
Poor Lubrication	8
Particle deposition like dirt	7
Poor Venting	8
Wearing of seal	7
Clogging of seal	6
High pressure in chamber than allowable limit	6
Excessive temperature due to friction	6

From Fig. 5, it is observed that one of the main causes of failure of Feed Water Pump is mechanical seal failure. Ultimately, mechanical seal failure is responsible of majority problems in the working of HE cycle.

Hence, 20% causes responsible for 80% problems of HE cycle are obtained using the above Pareto analysis.

Step III: To find causes of Mechanical seal failure

In this step, further 'Root Cause Analysis' is done to find out causes of mechanical seal failure of feed water pump. Major causes of mechanical seal failure of Feed Water Pump are [5]:

- Pump vibration
- Dry running of pump
- Poor lubrication
- Particle Deposition like dirt
- Poor venting
- Wearing of seal
- Clogging of seal

International Science Index, Industrial and Manufacturing Engineering Vol:11, No:5, 2017 waset.org/Publication/10007174

- High pressure in chamber than allowable limit
- Excessive temperature due to friction

Now, by rating these causes of failure on the scale of 1-10, priority can be given to overcome mechanical seal failure of feed water pump.

From Table VII, it can be concluded that, dry running of pump is a major cause of mechanical seal failure, and hence, necessary actions should be taken to overcome the same.

V. CONCLUSION

The work shows the FMEA study of HE cycle. With the help of Ishikawa diagram, the failures are listed for each component of the cycle. Based on the RPN analysis, it is evident that the feed water pump is the most vital component of the HE cycle and should be addressed first. Further Pareto analysis shows that the mechanical seal failure is the most critical failure in the feed water pump. All the possible causes of this failure are listed as per their rating. Thus, this paper can serve as a checklist for identification of failure modes, their effects and the causes of the most critical failures in the HE cycle. This would in return help in maintainability of the system.

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