Reliability Analysis of Heat Exchanger Cycle Using Non-Parametric Method

Apurv Kulkarni, Shreyas Badave, B. Rajiv

Abstract**—**Non-parametric reliability technique is useful for assessment of reliability of systems for which failure rates are not available. This is useful when detection of malfunctioning of any component is the key purpose during ongoing operation of the system. The main purpose of the Heat Exchanger Cycle discussed in this paper is to provide hot water at a constant temperature for longer periods of time. In such a cycle, certain components play a crucial role and this paper presents an effective way to predict the malfunctioning of the components by determination of system reliability. The method discussed in the paper is feasible and this is clarified with the help of various test cases.

Keywords**—**Heat exchanger cycle, K-statistics, PID controller, system reliability.

I.Introduction

HEAT exchangers are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various industries and they come in various designs. In heat exchangers, there are typically 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].

In this paper, main focus is given on steam heat exchangers i.e. the two fluid streams involved are steam and water. The two main types of 'Steam-to-Water' heat exchangers are 'Shell and Tube' and 'Plate' heat exchangers.

II.Process Description

In the heat exchanger cycle discussed in the paper, a plate heat exchanger is used over shell and tube. The main reason being the heat transfer efficiency in plate type is more. Other reasons favoring plate type are that there are moderate pressure losses, very small end temperature differences, fouling is less and the design is more compact, thus requiring less space [2].

The maximum allowed steam pressure at the inlet of plate heat exchanger is 3 barG as per the design considerations. The purpose of the cycle is to heat water at ambient temperature with the help of steam to a certain elevated temperature and ensure that water at that elevated temperature is provided for a prescribed period of time. The main components in the cycle are the manually operated pressure reducing valve, pneumatically actuated pressure reducing valve and pneumatically actuated flow control valve on the steam line. On the water line, the main components are the PID (Proportional-Integral-Derivative) controller (D-Tron, Forbes Marshall make) and manually operated stop valve.

Referring to the P&I (Piping and Instrumentation) diagram, the process requirements are vis:

a. Manually operated pressure reducing valve: At the steam header, steam pressure is usually of the order of 15 barG. To compensate for pressure losses along the steam line, it is imperative that pressure of the order of 8 barG is available after this valve. The actual output is observed on the PID controller (D-TRON 3).
b. Pneumatically operated pressure reducing valve: According to design requirements, maximum 3 barG pressure is to be supplied to the heat exchanger. This is achieved by using a PID controller (D-TRON 1) and the mentioned valve. Feedback of the downstream pressure is given to the controller which in turns controls the opening and closing of the valve by sending electrical current in the range 4-20 mA. The output is observed on the controller.
c. Water at constant load: To carry out the reliability analysis of the cycle, it is essential that water is available at constant load at the inlet of heat exchanger to ensure its long working life. This is achieved by the stop valve on the water line. To check the load of water, pressure along the line is measured and its output is observed on the PID controller (D-TRON 4).
d. Water at constant elevated temperature: To ensure constant elevated temperature is obtained, feedback is taken from the temperature transmitter on the water outlet line and same is given to PID controller (D-TRON 2), which in turn controls the operation of the pneumatically operated flow control valve on the steam line.

III.Reliability Aspect

For ensuring proper functioning of aforementioned cycle, it is imperative that the above described process requirements are met. Detection of malfunctioning of the critical components before they reach the state of failure will help in taking corrective measures to ensure smooth operation of the system.

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To detect the malfunctioning with ease without using any high end reliability software and for components whose failure rates are difficult to be determined, non-parametric reliability assessment proves to be a useful tool. Also, this technique can be used to determine reliability of an ongoing process.

Among the various non-parametric techniques available, K-statistics method is used to determine reliability in this paper. This is a well-established method and its implementation to assess reliability of the pre-defined system is explained. This technique is economical, as it does not involve the use of any software and consists of simple mathematical calculations and statistical terms.

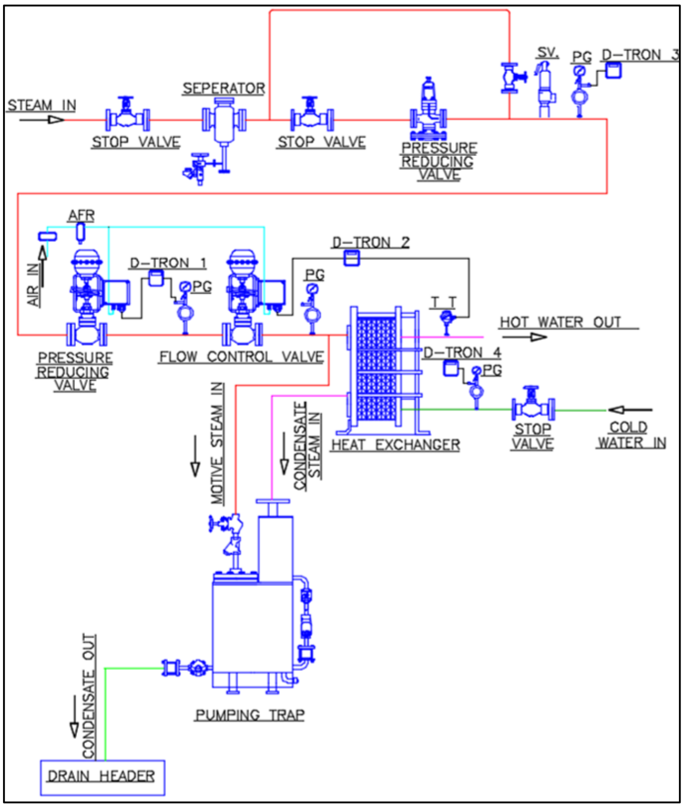

Fig. 1 P&I Diagram

This technique is helpful for small scale industries where it is not affordable to purchase the software and the system can be maintained in a better way by implementing this technique. For the cycle discussed in the paper, the critical components are as follows:

Component 1. Manually operated pressure reducing valve.

Component 2. Pneumatically actuated pressure reducing valve.

Component 3. D-TRON 1 which controls the operation of Component 2.

Note: Components 2 and 3 combined serve the purpose of maintaining 3 barG pressure at the downstream of Component 2.

Component 4. Manually operated stop valve on the water line.

Component 5. D-TRON 2 which maintains water at elevated temperature.

Component 6. Pneumatically actuated flow control valve.

Note: Components 5 and 6 combined serve the purpose of maintaining water at required set-point.

The RBD (Reliability Block Diagram) can be deduced from P&I diagram which contains these critical components in series as failure of any one component will lead to reduction in performance of the system. The RBD is as follows:

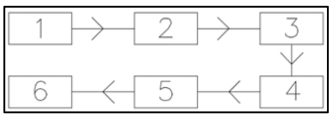

Fig. 2 RBD

For a system consisting of *n* components and are in series, the system reliability (R_s) is calculated as:

$$R_s = R_1 * R_2 * R_3 * \ldots * R_n \tag{1}$$

IV. K-Statistics

Reliability assessment activity is concerned with the comparison of the parameters or characteristics with a specification limit or with a pair of limits. The distribution of the characteristics is estimated or determined and the percentage of the distribution, which meets specification requirements, is calculated. The difference between the sample mean and the specification limit could be called safety margin of the mean. The comparison is done with the help of statistical parameter K given by Amstadter [3].

$$K = \frac{|L - \bar{X}|}{\sigma}$$

where $\bar{X}$ = mean of the sample data,

$$\text{Mean } (\bar{X} = \frac{\sum X_i}{n}) \quad (2)$$

n = sample size, σ = standard deviation for the sampled data

$$\sigma = \sqrt{\frac{\sum (X - \bar{X})^2}{n}} \quad (3)$$

The values of K for upper and lower limits of specified data are given by the equations as follows:

$$K_u = \frac{|L_u - \bar{X}|}{\sigma} \quad (4)$$

$$K_l = \frac{|L_l - \bar{X}|}{\sigma} \quad (5)$$

where K_u – statistical parameter related to upper limit, K_l – statistical parameter related to lower limit, L_u – upper limit, L_l – lower limit.

To determine reliability, it is necessary to compute K from the data and choose the appropriate table corresponding to the sample size and the desired level of confidence. The smaller amongst the two K values from (4) and (5) should be selected for further calculations.

For different sample size, different graphs are available which consist of a set of curves based on K value that show the relation between the reliability and confidence level.

In this paper, a sample size of 15 is considered for determining the reliability of the system and the graph corresponding to 15 sample sizes used.

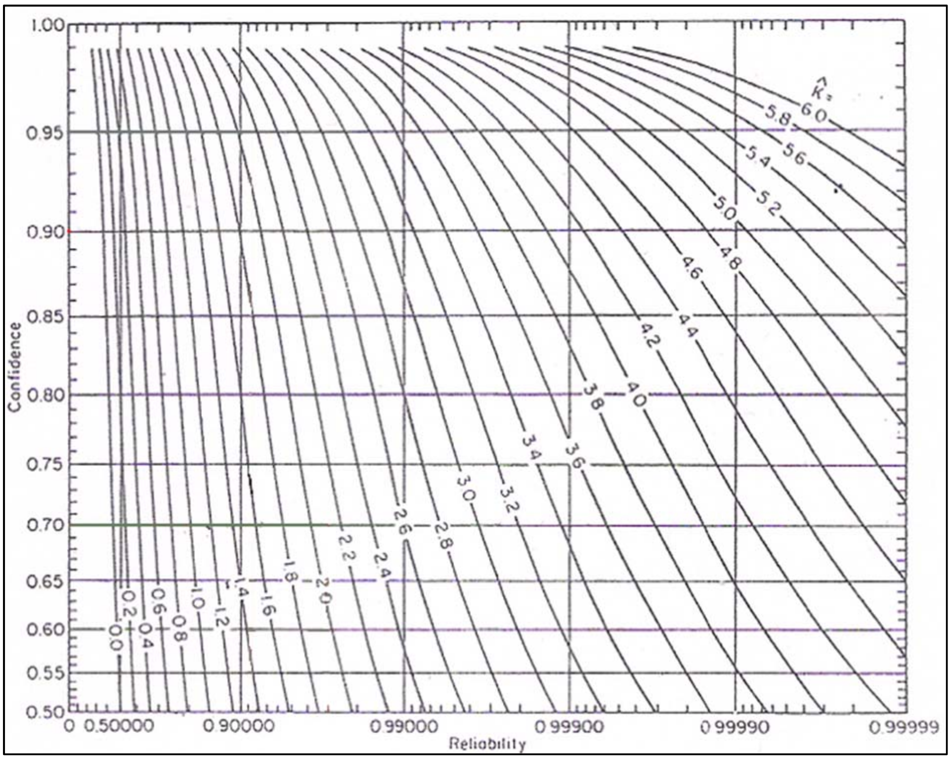

Fig. 3 Graph for determining reliability for 15 sample units [4]

V. Trial Specifications

As mentioned earlier, the purpose of the heat exchanger cycle is to provide hot water at a certain elevated temperature. For the test cases considered in this paper, the required hot water temperature set-point is 50 °C and reliability is determined.

To showcase the usefulness of this technique, two main cases are considered. In 'Test Case – A', a faulty Component 5 is used while in 'Test Case – B', Component 5 in good working condition is used. For both test cases, a constant water load at 0.4 barG pressure is used. The reliability calculations are performed assuming 90% confidence level. The lower and upper limits for each of the components are as follows:

Component 1: L_u = 8.2 barG, L_l = 7.8 barG

Components 2 and 3: L_u = 3.1 barG, L_l = 2.9 barG

Component 4: L_u = 0.5 barG, L_l = 0.3 barG
Components 5 and 6: L_u = 50.5°C, L_l = 49.5°C

The 90% confidence level is assumed taking into consideration the design and structure of the steam and water lines of the heat exchanger cycle. The upper and lower limits given above are decided based on the capabilities of the individual components and no calculations are done for determining the same.

Test Case – A

Sr. No.	Timestamp	D-TRON 3 (barG)	D-TRON 1 (barG)	D-TRON 4 (barG)	D-TRON 2 (°C)
1	17-01-17 13:35	7.95	3.05	0.38	46.5
2	17-01-17 13:36	7.98	3.02	0.36	47.4
3	17-01-17 13:37	8.02	2.98	0.42	49.7
4	17-01-17 13:38	8.07	2.96	0.45	50.8
5	17-01-17 13:39	8.11	2.98	0.41	52.2
6	17-01-17 13:40	8.08	3.00	0.3	52.6
7	17-01-17 13:41	8.13	3.02	0.44	41.1
8	17-01-17 13:42	8.16	3.04	0.43	49.4
9	17-01-17 13:43	8.08	3.06	0.39	47.3
10	17-01-17 13:44	8.01	3.06	0.39	46.1
11	17-01-17 13:45	7.99	3.07	0.49	49.6
12	17-01-17 13:46	8.00	3.02	0.41	50.7
13	17-01-17 13:47	8.01	2.96	0.5	51.9
14	17-01-17 13:48	8.00	2.91	0.48	49.8
15	17-01-17 13:49	7.99	2.89	0.42	47.2

Fig. 4 Data when Component 5 is faulty

For **Component 1**: Using (2), $\bar{X}$ = 8.04; using (3), σ = 0.06; using (4), $K_u = \frac{|8.2 - 8.04|}{0.06}$ = 2.61, using (5), $K_l = \frac{|7.8 - 8.04|}{0.06}$ = 3.86. Among K_u and K_l, K_u is chosen for further calculations.

Referring to Fig. 3, based on the confidence level and K value, the reliability of Component 1 (R_1) is:

$$R_1 = 0.9484$$

For **Components 2 and 3:** Using (2), $\bar{X}$ = 3; using (3), σ = 0.05; using (4), $K_u = \frac{|3.1 - 3|}{0.05}$= 1.81; using (5), $K_l = \frac{|2.9 - 3|}{0.05}$= 1.86. Among K_u and K_l, K_u is chosen for further calculations.

Referring to Fig. 3, based on the confidence level and K value, the reliability of Components 2 and 3 (R_2) is:

$$R_2 = 0.9$$

For **Component 4:** Using (2), $\bar{X}$ = 0.42; using (3), σ = 0.05; using (4), $K_u = \frac{|0.5 - 0.42|}{0.05}$= 1.58; using (5), $K_l = \frac{|0.3 - 0.42|}{0.05}$= 2.27. Among K_u and K_l, K_u is chosen for further calculations. Referring to Fig. 3, based on the confidence level and K value, the reliability of Component 4 (R_4) is:

$$R_4 = 0.8228$$

For **Components 5 and 6:** Using (2), $\bar{X}$ = 48.82; using (3), σ = 2.98, using (4), $K_u = \frac{|50.5 - 48.82|}{2.98}$ = 0.56; using (5), $K_l = \frac{|49.5 - 48.82|}{2.98}$= 0.23. Among K_u and K_l, K_l is chosen for further calculations.

Referring to Fig. 3, based on the confidence level and K value, the reliability of Components 5 and 6 (R_5) is:

$$R_5 = 0.5$$

Using (1), the system reliability is:

$$R_{sA} = 0.9484 * 0.9 * 0.8228 * 0.5$$
$$= 0.3512\ (35.12\%)$$

The above calculated system reliability may seem absurd as its value is very low, but it should be taken into consideration because of the product rule and the fact that each component has a reliability of success less than unity, the system reliability is less than the reliability of any one component. It also decreases as the number of components in the system increases and the reliability of the components decreases. This is illustrated in the graph below [5].

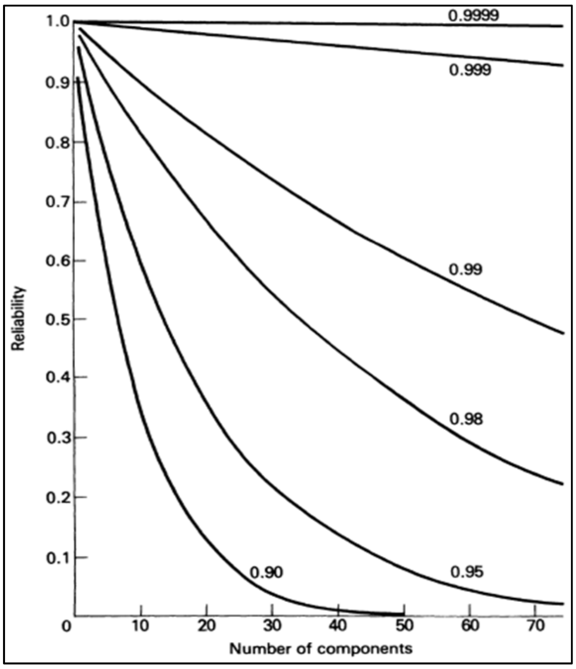

Fig. 5 R_s vs. number of components. The number on curves show reliability of each component

For **Component 1**: Using (2), $\bar{X}$ = 8; using (3), σ = 0.07; using (4), $K_u = \frac{|8.2 - 8|}{0.07}$ = 2.94; using (5), $K_l = \frac{|7.8 - 8|}{0.07}$ =2.9. Among K_u and K_l, K_l is chosen for further calculations.

Referring to Fig. 3, based on the confidence level and K value, the reliability of Component 1 (R_1) is:

$$R_1 = 0.9808$$

For **Components 2 and 3:** Using (2), $\bar{X}$ = 3: using (3), σ = 0.05, using (4), $K_u = \frac{|3.1 - 3|}{0.05}$ = 2.01; using (5), $K_l = \frac{|2.9 - 3|}{0.05}$ = 2.12. Among K_u and K_l, K_u is chosen for further calculations.

Test Case - B

Sr. No.	Timestamp	D-TRON 3 (barG)	D-TRON 1 (barG)	D-TRON 4 (barG)	D-TRON 2 (°C)
1	19-01-17 11:30	7.94	3.03	0.4	49.7
2	19-01-17 11:31	7.95	3	0.42	49.9
3	19-01-17 11:32	7.95	2.99	0.39	50
4	19-01-17 11:33	7.98	2.94	0.43	50
5	19-01-17 11:34	7.94	2.92	0.52	50.1
6	19-01-17 11:35	8.05	2.97	0.45	50.1
7	19-01-17 11:36	7.98	3.01	0.39	50
8	19-01-17 11:37	7.95	3.04	0.43	50
9	19-01-17 11:38	8.12	3.07	0.43	50
10	19-01-17 11:39	8.07	3.08	0.49	49.9
11	19-01-17 11:40	7.93	3.02	0.39	50
12	19-01-17 11:41	8.13	2.99	0.41	50.1
13	19-01-17 11:42	8.06	3.06	0.51	50.1
14	19-01-17 11:43	7.98	2.98	0.45	49.8
15	19-01-17 11:44	7.95	2.94	0.4	49.7

Fig. 6 Data when Component 5 is working in good condition

Referring to Fig. 3, based on the confidence level and K value, the reliability of Components 2 and 3 (R_2) is:

$$R_2 = 0.91$$

For **Component 4:** Using (2), $\bar{X} = 0.43$; using (3), σ = 0.04; using (4), $K_u = \frac{|0.5 - 0.43|}{0.04} = 1.54$; using (5), $K_l = \frac{|0.3 - 0.43|}{0.04} = 3.12$. Among K_u and K_l, K_u is chosen for further calculations.

Referring to Fig. 3, based on the confidence level and K value, the reliability of Component 4 (R_4) is:

$$R_4 = 0.7947$$

For **Components 5 and 6:** Using (2), $\bar{X} = 49.96$; using (3), σ = 0.14; using (4), $K_u = \frac{|50.5 - 49.96|}{0.14} = 3.99$; using (5), $K_l = \frac{|49.5 - 49.96|}{0.14} = 3.4$. Among K_u and K_l, K_l is chosen for further calculations.

Referring to Fig. 3, based on the confidence level and K value, the reliability of Components 5 and 6 (R_5) is:

$$R_5 = 0.992$$

Using (1), the system reliability is –

$$R_{sB} = 0.9808 * 0.91 * 0.7947 * 0.992 = 0.7036\ (70.36\%)$$

VI. Conclusion

Component 5 is the PID controller. For carrying out the tests, the tuning parameters of the controller were purposefully set wrong so that the proposed technique could be verified. It can be seen that R_{sA} is very much less than R_{sB} which should have been achieved pertaining to the condition of the controller. As the tuning parameters were set wrong, Component 6 underwent hunting and as a result the constant hot water temperature set-point could not be achieved. This resulted in poor performance of the cycle. Thus from the discussion, it can be inferred that reliability assessment by non-parametric assessment can be easily implemented to detect the malfunctioning of any component. This technique can be applied to more complex systems which involve components that are linked in combination of series and parallel connections.

VII. Future Scope

To take this idea to next level, the mathematical calculations to determine the K value and the system reliability can be done by a program. The use of such a program will be useful for complex systems and the identification of problems will be easier once the calculations are done. One such solution of a program using GNU Octave is currently undergoing a trial period by the authors.

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