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Heat Exchanger Reliability Analysis Based on Fouling Growth Model by Fault Tree Analysis

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The inherent reliability of heat exchanger in the design and manufacturing process, such as welding manner, yield strength, etc., has been the subject of many studies in the past. However, the operation reliability of heat exchanger, such as temperature, pressure and fouling resistance has received less attention. Herein, a novel heat exchanger reliability model involving the fouling resistance was established based on the Fault Tree Analysis (FTA). Moreover, a time-dependent progressively fouling growth model was also developed. In addition, Fouling Resistance Probability (*FRP*) was defined and calculated as a reliability indicator, which represents the failure probability of heat exchanger caused by fouling resistance. Subsequently, the well-established progressively fouling growth model was incorporated into the FTA model as a basic event. Ultimately, the heat exchanger reliability based on the FTA model was presented. Finally, maximum value of the heat exchanger failure rate originated from fouling growth was determined to be around 0.340 through three case studies in the literature, and minimum value of the heat exchanger unit reliability was estimated to be about 0.501. For this reason, the fouling resistance has a pronounced influence on the reliability of heat exchanger.

1. Introduction

Heat exchanger is an indispensable equipment in the heat exchange process. Once a heat exchanger fails, it will have immeasurable consequences for the whole production process. It is very necessary to effectively evaluate and predict the heat exchanger reliability (HER).

Many researchers have done much work on the reliability of heat exchanger network (HEN). For example, Sikos et al. (2010) proposed a methodology to use state-of-the-art commercial software tools for HEN reliability modelling and optimisation. It can be concluded that 30 % of maintenance costs can be substantially reduced by applying optimal reliability results. Lv et al. (2017) have simultaneously optimised system reliability and economics of HEN by NSGA-II, in which the HER was hypothesized as a constant (0.98). As a basic unit of heat exchanger network system reliability (HENR) calculation, HER has been seldom studied. In fact, heat exchanger can also be viewed as a system to compute reliability.

The HER generally refers to the probability of completing the specified function in the specified conditions and the specified time, which can be generally divided into three parts: inherent reliability, application reliability during operation and environmental adaptability. HER is an important indicator to measure the quality performance and safety performance of heat exchangers. Ma et al. (2011, 2012) proposed that the high temperature loads are the main reason to cause high stress and deformation in heat exchanger. The large stress is generated in the joint of inner fin and inner tube, which is only related to the inherent reliability of heat exchanger. Shi et al. (2015) applied FTA and Monte Carlo simulation (MCS) to a micro-grid case, in which the effect of each basic event on the reliability of the entire system was obtained over time. Moreover, a more accurate average failure time can be acquired by applying FT-MCS model. This method can also be extended to heat exchanger reliability. Purba et al. (2014) utilized a fuzzy reliability analysis method based on FTA model to obtain the failure probability of the basic event without quantitative historical failure data, in good agreement with the empirical values. Souza and Álvares (2008) evaluated the impact of the Reliability-Centered

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Maintenance (RCM) methodology on a power generating system and used the tools, i.e., Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) to conduct the investigations.
In addition to the vibration and the junction ways of the tube bundles, HER is correlated with the overall heat transfer coefficient. With the increase of time, fouling grows in the tube and shell wall of heat exchangers, which will decrease the overall heat transfer coefficient. Ebert et al. (1995) first proposed the concept of fouling threshold and afterwards improved the models several times to enhance the prediction accuracy of crude oil fouling. Radhakrishnan et al. (2007) established a neural network of fouling model according to historical operating data to predict the effect of fouling growth on the overall heat transfer coefficient in refineries. Previously, fouling resistance was calculated as fixed value. In stark contrast, Nakao et al. (2017) proposed a fouling rate model where the fouling resistance was calculated based on the thermofluidynamic design conditions.
In this work, a novel approach is presented for the analysis of HER based on fouling growth model by FTA, in which the fouling growth model has considered time and heat transfer coefficient of streams. Then a discrete model was established according to actual growth process. The fouling growth model was incorporated into the FTA model. The model is demonstrated by three cases study to show the efficiency and necessity.

2. FTA model

Fault Tree Analysis is a summarised-interpret reasoning law in the form of a tree diagram that describes the logical relationship between an accident and the various incidents that cause the accident. The top event of FTA is the main accident that may occur in the system. The various intermediate events are analysed down to the last layer referred to as the basic events.
Shell-tube heat exchangers are widely used in industrial manufacture and are selected as research objects in this work. The factors affecting the reliability of the shell-tube heat exchangers fall into two categories. One refers to the structural factors, including tube failure, nozzle corrosion, flange connection failure, tube bundle corrosion, etc. The other one refers to the operational factors, including the fluid temperature, flow rate, heat transfer coefficient, etc., which are all attributed to the fouling growth model.
The FTA model includes top events, intermediate events, and basic events. The upper and lower events are connected by AND gates and OR gates. The AND gates indicate that only if all the input events occur, then the upper output event takes place. The OR gates indicate that if one of the input events occurs, the upper output event will be set. The shell-tube heat exchanger failure is chosen as the top event. The first-level intermediate events that may cause the top event include tube failure, nozzle corrosion and flange connection failure. Each intermediate event continues to extend until the basic events. In this way, the FTA model that contains 15 intermediate events and 15 basic events is established as depicted in Figure 1. The basic events and intermediate events are shown in Tables 1 and 2 (Chen et al., 2015). In this work, fouling thermal resistance is proposed and added as a basic event (X1).

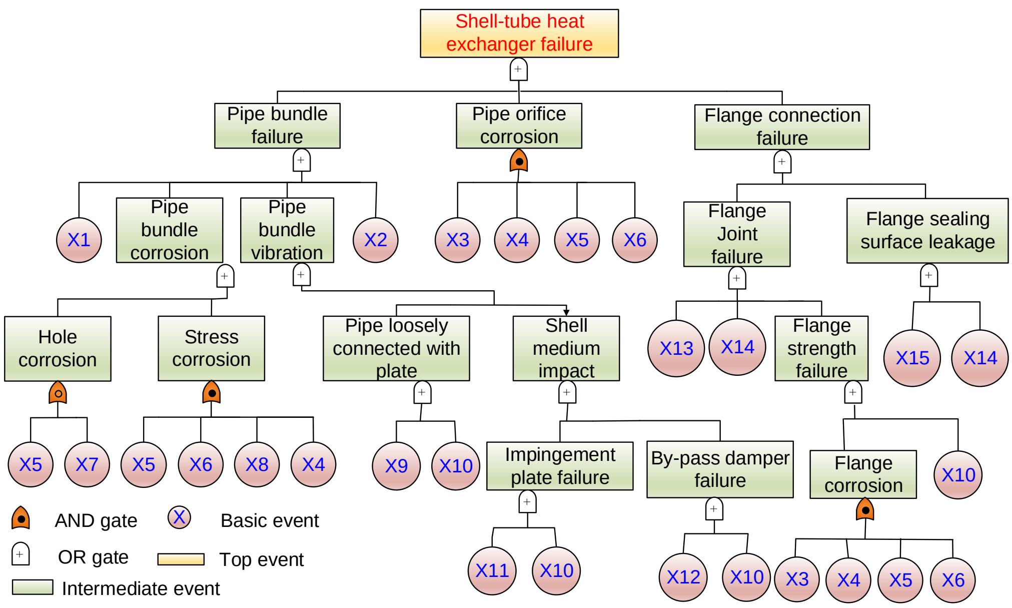

Figure 1: FTA reliability analysis model of Heat exchanger

Table 1: Basic events of FTA model

Number	Name	Probability
X1	Fouling resistance	unknown
X2	Medium erosion	0.02
X3	Stress concentration	0.02
X4	Poor corrosion resistance of materials	0.02
X5	Medium	0.015
X6	Service conditions	0.02
X7	Material defect	0.015
X8	pulling stress	0.006
X9	Thermal stress	0.03
X10	Confection defect	0.025
X11	Without impingement	0.002
X12	Without by-pass damper	0.002
X13	Bolt corrosion	0.001
X14	Spacer failure	0.001
X15	Uneven flange face	0.002

Table 2: Intermediate events of FTA model

Number	Name	Computational formula	Probability
M1	Pipe bundle failure	p(M1)=p(X1+M4+M5+X2)	0.129+p(X1)
M2	Pipe orifice corrosion	p(M2)=p(X3·X4·X5·X6)	0.00000012
M3	Flange connection failure	p(M3)=p(M6+M7)	0.03000012
M4	Pipe bundle corrosion	p(M4)=p(M8+M9)	0.000225036
M5	Pipe bundle vibration	p(M5)=p(M10+M11)	0.109
M6	Flange joint failure	p(M6)=p(X13+X14+M12)	0.02700012
M7	Flange sealing surface leakage	p(M7)=p(X14+X15)	0.003
M8	Hole corrosion	p(M8)=p(X5·X7)	0.000225
M9	Stress corrosion	p(M9)=p(X4·X5·X6·X8)	0.000000036
M10	Pipe loosely connected with plate	p(M10)=p(X9+X10)	0.055
M11	Shell medium impact	p(M11)=p(M13+M14)	0.054
M12	Flange strength failure	p(M12)=p(M15+X10)	0.02500012
M13	Impingement plate failure	p(M13)=p(X10+X11)	0.027
M14	By-pass damper failure	p(M14)=p(X10+X12)	0.027
M15	Flange corrosion	p(M15)=p(X3·X4·X5·X6)	0.00000012

The top event probability is defined as: p(M1)+p(M2)+p(M3)=0.159+p(X1). The fouling growth model to calculate the p(X1) is introduced in section 3.

3. Model of fouling resistance probability based on fouling growth model

Fouling resistance is a non-negligible problem in heat exchanger application. The main reason causing it is that solid dirt accumulates on the shell and tube surface of the heat exchanger, which decreases the thermal performance of heat exchangers. This effect is reflected on the overall heat transfer coefficient, which is also an important factor affecting the HER. The fouling growth model is the key of HER model.

The factors influencing fouling growth in heat exchangers are the following:

a. Operating parameters: the flow velocity and temperature of fluids;

b. Fluid properties: viscosity, concentration, heat capacity, etc.;

c. Equipment parameters: heat exchanger material, surface structure and type.

Four fouling growth types are shown in Figure 2 (Zubair et al., 1992). Curve 3 manifests that the fouling thermal resistance increases progressively with time. This is the ideal type of fouling growth and is widely used in research.

In other studies, the structural reliability and the fouling growth model of heat exchangers have been studied separately as two independent problems. Combining those two, a more comprehensive and convincing heat exchanger reliability model is constructed.

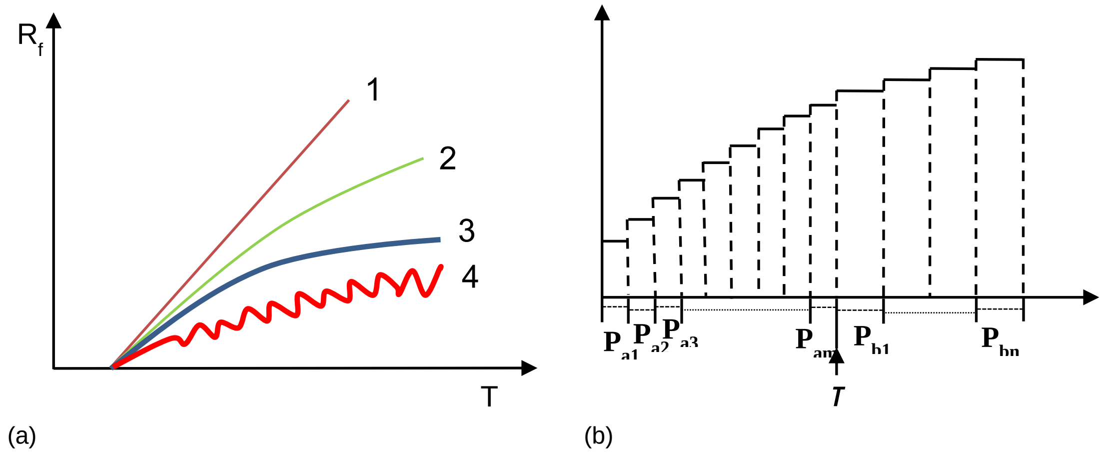

Figure 2: (a) The types of fouling growth model (Zubair et al., 1992); (b) Fouling growth discrete model

Heat exchanger fouling growth is a dynamic accumulation process. With time, the growth rate of fouling reduces until it reaches an asymptotic value (curve 3 in Figure 2a). Evaluating the fouling resistance as a function of time, a fouling growth model is represented by a discrete staged approach as shown in Figure 2b. The model is divided into two phases. The time constant τ is chosen as the critical point to separate these two phases. The term τ is the time when the fouling resistance reaches $0.8R_f^{\infty}$ (R_f^{∞} represents the utimate value of fouling resistance). In order to simplify the process, the fouling resistance at terminal point of each interval *P* is used for computing the *FRP* throughout the whole interval.

The expressions to determine the tube and shell fouling resistance as a function of time are shown below (Xiao, 2011):

$$R_{f_i}(P) = R_{f_i}^{\infty}(1-\exp(-t(P)/t_i)) \tag{1}$$

$$R_{f_j}(P) = R_{f_j}^{\infty}(1-\exp(-t(P)/t_j)) \tag{2}$$

Where, *i* and *j* represent tube side and shell side, *t* represents time, and *P* represents a certain time period. Ignoring the wall thermal resistance, the overall heat transfer coefficient with fouling is expressed as Eq(3), while the one without fouling can be expressed as Eq(4),

$$\frac{1}{K_f(P)} = \frac{1}{K_i} + \frac{1}{K_j} + R_{f_i}(P) + R_{f_j}(P) \tag{3}$$

$$\frac{1}{K_c} = \frac{1}{K_i} + \frac{1}{K_j} \tag{4}$$

Where, K_i and K_j represent the heat transfer coefficient of the tube side and shell side; K_c is the overall heat transfer coefficient of the heat exchanger without fouling; K_f represents the overall heat transfer coefficient with fouling. The reliability indicator *FRP* for a time interval *P* represents the failure probability of the heat exchanger caused by fouling and can be expressed as follows:

$$FRP(P) = \frac{K_c - K_f(P)}{K_c} \tag{5}$$

The *FRP (P)* is used to express the effect level of fouling resistance on the HER in time interval *P*. That is, the FRP (*P*) value is the probability of occurrence of fouling thermal resistance (the basic event X1).

4. Case study

According to the fouling growth model and Eq(1) to Eq(5), three examples adapted from the work of Xiao (2011) are used to calculate the FRP and HER. The stream parameters are shown in Table 3.

Table 3: Stream data of heat exchanger

Heat exchanger	Stream	$F_{cp}(\mathrm{kW \cdot K^{-1}})$	$h(\mathrm{kW \cdot m^{-2} \cdot K^{-1}})$	$R_f^{\infty}(\mathrm{m^2 \cdot K \cdot kW^{-1}})$
HE1	H1	7.03	1.4	0.286
	C1	6.10	1.5	0.333
HE2	H2	8.44	1.25	0.201
	C2	10.00	1.2	0.167
HE3	H3	30	2.0	0.410
	C3	20	1.5	0.190

Firstly, the fouling growth model is simply divided into four stages, which are bound by $0.2R_f^{\infty}$, $0.5R_f^{\infty}$, $0.8R_f^{\infty}$ and $1.0R_f^{\infty}$. From Eq(1) to Eq(5), the indicator *FRP* is calculated under different fouling growth stages as shown in Tables 4 and Table 5.

Table 4: FRP at the different fouling stages

	$FRP_{0.2R_f^{\infty}}$	$FRP_{0.5R_f^{\infty}}$	$FRP_{0.8R_f^{\infty}}$	$FRP_{1.0R_f^{\infty}}$
HE1	0.083	0.184	0.264	0.310
HE2	0.042	0.101	0.152	0.184
HE3	0.093	0.204	0.292	0.340

Table 5: HER at the different fouling stages

	$HER_{0.2R_f^{\infty}}$	$HER_{0.5R_f^{\infty}}$	$HER_{0.8R_f^{\infty}}$	$HER_{1.0R_f^{\infty}}$
HE1	0.758	0.657	0.577	0.531
HE2	0.799	0.740	0.689	0.657
HE3	0.748	0.637	0.549	0.501

From Figure 1, Table 1 and Table 2, the minimum cut sets of FTA can be determined; this includes 12 sets: (1) X1; (2) X2; (3) X9; (4) X10; (5) X11; (6) X12; (7) X13; (8) X14; (9) X15; (10) X3*X4*X5*X6; (11) X4*X5*X6*X8; and (12) X5*X7. The main reliability factors are determined based on the structural importance degrees of each basic event obtained by quantity calculation as follows: I(X15) = I(X14) = I(X13) = I(X12) = I(X11) = I(X10) = I(X9) = I(X2) = I(X1)>I(X5)>I(X7)>I(X6) = I(X4)>I(X8) = I(X3). When fouling is not considered, the failure probability and HER are 0.159 and 0.841, respectively.

Table 6: The HER of each stage of the three heat exchangers (HE1, HE2, HE3 represent the heat exchanger number)

HER	HE1	HE2	HE3	HER	HE1	HE2	HE3
Stage 1	0.8146	0.8258	0.8118	Stage 9	0.6034	0.7042	0.5782
Stage 2	0.7882	0.8106	0.7826	Stage 10	0.5770	0.6890	0.5490
Stage 3	0.7618	0.7954	0.7534	Stage 11	0.5678	0.6826	0.5394
Stage 4	0.7354	0.7802	0.7242	Stage 12	0.5586	0.6762	0.5298
Stage 5	0.7090	0.7650	0.6950	Stage 13	0.5494	0.6698	0.5202
Stage 6	0.6826	0.7498	0.6658	Stage 14	0.5402	0.6634	0.5106
Stage 7	0.6562	0.7346	0.6366	Stage 15	0.5310	0.6570	0.5010
Stage 8	0.6298	0.7194	0.6074				

In accordance with the discrete stage approach, choosing the value of τ as $HER_{0.8R_f^{\infty}}$ = 300 d, production period is usually thought as 720 d. The interval *t* = 0~300 d, where fouling grows fast, is divided into 10 segments, while the period *t* = 300 ~ 720 d, where the fouling growth rate slows down, is divided into 5 segments. The HER of each stage for the three heat exchangers is calculated. As shown in Table 6, in the first 10 segments, the HER reduction rate is significantly higher than that of the last 5 segments. HE2 has the highest HER through the whole period, while the HER of HE3 exhibits the lowest value. This is so since the fouling resistance of HE2 exhibits the lowest value, while the one of HE3 is the highest. It is assumed that the heat exchanger needs to be cleaned as the HER is reduced to 60%. For instance, HE1 needs to be cleaned when after stage 9 (270 d). Since the HER of HE2 is above 0.6, this unit does not need cleaning within a two-year period. In the case of HE3, after reaching stage 8 (240 d), a cleaning operation needs to be performed. This is an important guide in the design, manufacture and operation of heat exchangers.

5. Conclusions

A novel heat exchanger reliability model involving the fouling resistance is established based on the FTA. Fouling growth is added to the FTA model as a basic event. Calculation of the FTA model reveals the main basic events. Finally, the heat exchanger failure probability and HER without fouling are 0.159 and 0.841, respectively. Through the calculation of three heat exchanger examples with fouling growth, the heat exchanger failure probability caused by fouling can be as high as 0.340, while the HER considering fouling is reduced to a value of 0.501. Therefore, the HER considering fouling thermal resistance in industrial applications can guide the establishment of cleaning schemes of heat exchangers.

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References

Chen X., Zhao X., Pu J., 2015, Research on Failure Model of Stainless Shell and Tube Heat Exchanger Based on FTA, Pressure Vessel, 32(11), 64-68. (in Chinese)

Ebert, W., Panchal, C. B., 1995, Analysis of Exxon crude-oil-slip stream coking data (No. ANL/ES/CP-92175; CONF-9506406-3). Argonne National Lab., IL, USA.

Lv, J., Jiang, X., He, G., Xiao, W., Li, S., Sengupta, D., El-Halwagi, M. M. 2017, Economic and system reliability optimization of heat exchanger networks using NSGA-II algorithm, Applied Thermal Engineering, 124, 716-724.

Ma, T., Chen, Y., Zeng, M., Wang, Q., 2012, Stress analysis of internally finned bayonet tube in a high temperature heat exchanger, Applied Thermal Engineering, 43, 101-108.

Ma, T., Du, L., Zhang, D., Ji, Y., Zeng, M., Wang, Q., 2011, Study on reliability of high temperature heat exchangers, Chemical Engineering Transactions, 25, 351-356.

Nakao, A., Valdman, A., Costa, A. L., Bagajewicz, M. J., Queiroz, E. M., 2017, Incorporating fouling modeling into shell-and-tube heat exchanger design, Industrial & Engineering Chemistry Research, 56(15), 4377-4385.

Purba, J. H., Lu, J., Zhang, G., Pedrycz, W., 2014, A fuzzy reliability assessment of basic events of fault trees through qualitative data processing, Fuzzy Sets and Systems, 243, 50-69.

Radhakrishnan, V. R., Ramasamy, M., Zabiri, H., Do Thanh, V., Tahir, N. M., Mukhtar, H., Ramli, N., 2007, Heat exchanger fouling model and preventive maintenance scheduling tool, Applied Thermal Engineering, 27(17-18), 2791-2802.

Rodrigo de Queiroz Souza, Álvares, A. J., 2008, FMEA and FTA analysis for application of the reliability centered maintenance methodology: Case study on hydraulic turbines. InABCM Symposium Series in Mechatronics 3, 803-812.

Shi, X., Bazzi, A. M. 2015, Fault tree reliability analysis of a micro-grid using Monte Carlo simulations. In: 2015 IEEE Power and Energy Conference (PECI),1-5. Illions, USA.

Sikos L., Klemeš J., 2010, Reliability, availability and maintenance optimisation of heat exchanger networks, Applied Thermal Engineering, 30(1), 63-69.

Xiao F., 2011, Simultaneous optimisation of synthesis and cleaning schedule in flexible heat exchanger networks (In Chinese), PhD Thesis, Dalian University of Technology, Dalian, China.

Zubair, S. M., Sheikh, A. K., Shaik, M. N., 1992, A probabilistic approach to the maintenance of heat-transfer equipment subject to fouling, Energy, 17(8), 769-776.