PREDICTING THERMAL PERFORMANCE OF HEAT EXCHANGERS USING IN-SITU TESTING & STATISTICAL CORRELATION: COMPUTER CODE ST_XPERT

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ABSTRACT

This paper describes the methodology to ascertain the "heat transfer capability" of a tubular heat exchanger from steady state field test data. Periodic assessment of the heat duty capability of heat exchangers utilizing a fluid stream capable of inducing appreciable fouling and deemed to be critical to safety in operating nuclear power plants has become a common practice in the wake of USNRC's issuance of the Generic Letter 89-13. Since the measured test data invariably have a measure of uncertainty due to bias in the measurement instrumentation and errors in the measuring process and the heat transfer coefficient can only be calculated as an approximate value with an associated uncertainty, the calculation of the fouling factor must utilize concepts from statistics of multivariate random phenomena. For simplicity, and without loss of appreciable accuracy, all variables and measurement parameters are assumed to follow Gaussian probability distribution. The solution process permits and utilizes redundant measurements to improve the quality of the result.

Although work was specifically carried out to deal with the thermal performance safety issues raised by the U.S. Nuclear Regulatory Commission in 1989, it can be utilized in the performance assessment of any heat exchanger in any industrial application where in-situ testing is carried out. The methodology described herein is implemented in the computer code ST_XPERT, whose features are also described in this paper.

INTRODUCTION

Heat exchangers are typically designed with "fouling factors" assigned to both shell and tubesides. As the name implies, fouling factor is the recognition of the physical fact that the tube surface loses its luster and shine as foulants deposit on it with passage of time. There are numerous mechanisms of fouling; for our purposes here it is sufficient to state that the final outcome of fouling is the overlay of an insulating layer on the surface of the tube. The conductivity of the foulant layer and its thickness determine the overall resistance that it exerts against the transmission of heat across the tube wall. The heat exchanger designer is principally interested in the value of the thermal resistance of the fouling layer which, in the heat exchanger trade lexicon, is referred to as the "fouling factor". Typically, two discrete values of the fouling factor are specified, one for the inside surface of the tube (tubeside) and the other for the outside surface (shellside). The total fouling factor, R, for plain tubes, is given by

$$R = r_{fs} + \frac{d_o}{d_i} r_{ft} \tag{1}$$

where r_{fs} and r_{ft} are shellside and tubeside fouling factors, and d_o and d_i are the O.D. and I.D. of the tube, respectively.

At the time of design, the equipment specifier sets forth values of r_{fs} and r_{ft}, which are selected to ensure that the tubes will not foul beyond these values, or at least, the overall fouling resistance R will not exceed the design value. If the actual overall fouling resistance R were to indeed exceed the value assumed at the time of design, then theoretically the heat exchanger will be unable to deliver the heat duty expected of it. In reality, the heat exchanger designer leaves some additional margin in the equipment thermal design, and the heat transfer correlations used to determine the film coefficients themselves have a built-in margin of safety. As a result, in most heat exchangers, the total fouling resistance to heat transfer must exceed the design value before the thermal performance of the unit drops below the so-called "design point" value. When such an exceedance of fouling in a safety related exchanger occurs, then the nuclear plant must either clean the tubes immediately, or justify continued operability of the derated heat exchanger. Since those heat exchangers which utilize a natural cooling source are most apt to foul, in contrast to those which use highly purified demineralized water, the focus on the rate of fouling is rightfully directed to the former category of units in a nuclear plant. In other industries, such as food, pharmaceutical and petroleum plants, fouling of heat exchangers is seldom a safety concern, but invariably a matter of considerable economic consequence.

Generic Letter 89-13 issued by the USNRC alerted nuclear plant owners to the possibility of insidious and undetected increase in the total fouling and asked the owners to take appropriate steps to monitor it. This generic letter spawned efforts by EPRI and later the ASME to develop testing procedures to quantify the total fouling. These tests essentially require the performance test engineer to measure the terminal quantities, namely, the shellside and tubeside flow rates and the four terminal temperatures. Using these quantities, the engineer can compute the effective overall heat transfer coefficients, U_e, using the classical formula:

$$Q = U_e A F \Delta T \tag{2}$$

where Q is the total heat duty, A is the total effective surface area, ΔT is the "log mean temperature difference" (LMTD), and F is the LMTD correction factor. F is strictly a function of the flow rates and flow rate ratios for a given heat exchanger, and ΔT is defined by the terminal temperatures. Therefore, the effective value of U, denoted by U_e herein, for the test conditions is directly computed from Eq. (2).

Having determined U_e, the designer must next use the heat transfer correlations to determine the theoretical tube and shellside film coefficients. The theoretical "clean" coefficient is then given by

$$U_c = \frac{1}{\frac{1}{h_o} + (\frac{A_o}{A_i})\frac{1}{h_i} + R_W} \qquad \text{where } R_W = \frac{d_o}{24k}\left[\ln\frac{d_o}{d_o - 2t_m}\right] \tag{3}$$

where h_o and h_i are shell and tubeside theoretical film coefficients corresponding to the test flow rates, t_m is the tube wall thickness, and k is tube metal thermal conductivity. We note that U_c is calculated as a strictly theoretical number.

Having computed U_c, the theoretical fouling resistance follows from simple algebraic difference

$$R = \frac{1}{U_e} - \frac{1}{U_c} \tag{4}$$

The calculation of R would be a simple matter in the manner of the foregoing if all measured and calculated values were absolutely accurate. Unfortunately, all measured quantities have a degree of error associated with their value. Usually the temperatures are measured with much more accuracy than the flow rates, nonetheless, *every* measured temperature has some error. Additionally, the correlations for determining heat transfer coefficients, which are derived from empirical data, have an associated band of uncertainty. Finally, a minor contributor to uncertainty in the calculation of R is the tolerance on the tube wall thickness. It is necessary to devise a statistical procedure which enables us to compute the statistical scatter in the expected value of R. In fact, the specific task is to determine the value of R which bounds all possible values within n% confidence, where n can be as high as 95.

The mathematical procedure to solve this problem is presented in this paper. Before presenting the specific methodology we will review some facts in elementary statistics which are necessary to develop our formulation.

CONCEPTS FROM ELEMENTARY STATISTICS

Most random processes, such as observations of data, are known to follow the so-called "Gaussian probability distribution" or "normal distribution". This probability curve has the familiar bell-shaped form. The ordinate in this curve is the probability density function p(x) and the abscissa is the quantity of interest x (Figure 1). The fractional chance that the value of x will fall between x_1 and x_2 is given by

$$\epsilon = \int_{x_1}^{x_2} p(x)\, dx \tag{5}$$

ϵ will approach 1 if x_1 and x_2 tend to $-\infty$ and $+\infty$, respectively, i.e.,

$$\int_{-\infty}^{+\infty} p(x)\, dx = 1 \tag{6}$$

We note that p(x) has units of 1/x. The mathematical expression for this curve is given by

$$p(x) = \frac{1}{\sqrt{2\pi}\ \sigma}\ EXP\ [-\frac{1}{2}\ (\frac{x-\bar{x}}{\sigma})^2]; -\infty \leq x \leq \infty \tag{7}$$

It can be shown that Eq. (6) is satisfied for arbitrary values of σ. It can also be shown that this curve is symmetric about $x = \bar{x}$, i.e.,

$$p\ (\bar{x}+x) = p\ (\bar{x}-x) \tag{8}$$

$\bar{x}$, as indicated in Figure 1, is the mean value of x; it is the value of x where p(x) reaches its maximum value.

Let us define a dimensionless variable z, where

$$z = \frac{x-\bar{x}}{\sigma} \tag{9}$$

then

$$p\ (Z) = \frac{1}{\sqrt{2\pi}\ \sigma}\ EXP\ [\frac{-z^2}{2}]; -\infty \leq z \leq +\infty \tag{10}$$

$$If\ z_1 = \frac{x_1-\bar{x}}{\sigma}\ and\ z_2 = \frac{x_2-\bar{x}}{\sigma}$$

then the total probability that the value of z will lie between z_1 and z_2 is

$$I = \int_{x_1}^{x_2} p\ (x)\ dx$$

$$or\ I = \frac{1}{\sqrt{2\pi}} \int_{z_1}^{z_2} EXP\ [-\frac{1}{2}\ z^2]\ dz \tag{11}$$

This integral will have a defined value for each set of end conditions. From Eq. (9), when z = 1, $x = \bar{x} + \sigma$; where σ is known as the "standard deviation". Similarly, when z = 2, $x = \bar{x} + 2\sigma$. The integral I for values of z, ± 1, ± 2, and ± 3, is enumerated in Table 1.

Table 1; Cumulative Probability Values

z_1	z_2	Range of x	Value of I
-1	+1	$\bar{x} \pm \sigma$	0.6826
-2	+2	$\bar{x} \pm 2\sigma$	0.9544
-3	+3	$\bar{x} \pm 3\sigma$	0.9972

It is clear from the above table that nearly *all* data will lie within $\pm 3\sigma$ around the mean value. Therefore, if the range of uncertainty of a variable is defined, then the value of σ for that variable is readily inferred.

Another concept which requires exposition here is the so-called "confidence limit".

The confidence that the measured value of x will be less than X_{limit} is given by

$$y = I\ (-\infty, x_{limit}) = \int_{-\infty}^{z^*} EXP\ (-0.5z^2) \tag{12}$$

where

$$z^* = \frac{x_{limit}-\bar{x}}{\sigma} \tag{13}$$

This concept is important in heat exchanger testing where one is interested in determining the value of a quantity, say the fouling factor, which provides a certain confidence level.

Table 2 provides the value of y for different z. y is also known as the "one-sided cumulative probability function".

Table 2; Value of Cumulative Probability Function for Different z

z	0	0.5	1.0	1.5	2.0	2.5	3
y	0.5	.6915	.8413	.9332	.9772	.9938	.9987

Thus, for example, if it is required to compute the value of the fouling factor R with 95% confidence, interpolating from Table 2 gives

$$z = 1.5 + \frac{(.95\ -\ .9332)\ (0.5)}{(.9772\ -\ .9332)}$$

$$= 1.69$$

Therefore, the answer is

$$R = \bar{R} + 1.69\sigma_R$$

where R is the mean and σ_R is the standard deviation of the fouling factor probability distribution curve.

VALUE OF CLEAN COEFFICIENT AND ITS STANDARD DEVIATION

It is evident from the mathematical relationship for U_c (Eq. 3), that there are three quantities which are potentially subject to uncertainty in their values. These are: (i) shellside film coefficient, (ii) tubeside film coefficient and (iii) tube metal wall resistance.

The shellside coefficient is the parameter with the most uncertainty. This is due to the fact that the articulation of the shellside flow in the heat exchanger is very difficult due to the non-ideal flow geometry which exists in the shellside space. Standard heat exchanger rating codes account for the deviations from the "ideal crossflow" or "parallel flow" geometry by introducing penalty factors in the heat transfer correlations. These penalty terms are intended to bound the actual film coefficient from below, whereas the ideal coefficients bound from above. The same remark applies to the tubeside film coefficient, although the upper and lower bounds in this case are relatively close to each other.

Finally, the tube wall resistance is a function of the wall thickness of the tube and conductivity of the tube material. Whereas the conductivity of the tube material is known with considerable accuracy, the wall thickness of the tube can vary by as much as 10%. The uncertainty in the tube metal resistance arises principally from the variation in the tube wall thickness.

Since the maximum and minimum values of U_c can be computed if the upper and lower bound values of f_s, f_t, and t_m/k are known, it follows that the mean and standard deviation of U_c are readily obtained (by using the assumption that the upper and lower bound values are each 3σ removed from the mean).

The mean value and standard deviation of U_c computed in the manner of the foregoing are used later in the analysis to determine the fouling mean and standard deviations.

TESTING FOR CLEANLINESS EVALUATION

Thermal performance testing of a tubular heat exchanger entails measuring the flow rates of the two streams and their terminal temperatures. Out of the total of six quantities, one may omit measuring one and utilize the heat balance between the two streams to compute it. However, if all six quantities are measured they may not satisfy heat balance owing to errors in the measurements. Discarding one measured quantity based on intuitive feel removes the quandary at the expense of some legitimacy. It is far more preferable to take all six measurements into account when developing the profile of the fouling factor probability distribution. Table 3 below lists six possible combinations of measurements, each of which is sufficient to define the fouling factor.

Table 3; Sets of Measurement Quantities

Set #	Shellside Thermal Flow Rate, W_s	Shellside Inlet Temp., T_i	Shellside Outlet Temp., T_o	Tubeside Flow Rate, W_t	Tubeside Inlet Temp., t_i	Tubeside Outlet Temp., t_o
	x_1	x_2	x_3	x_4	x_5	X_6
1	√	√	√	√	√	-
2	√	√	√	-	√	√
3	√	√	√	√	-	√
4	-	√	√	√	√	√
5	√	-	√	√	√	√
6	√	√	-	√	√	√

The shellside parameters set the heat duty in the first three sets and in the last three, the duty is defined by the tubeside parameters. Any one of the six sets, therefore, allows us to compute the effective overall heat transfer coefficient. It is assumed that the mean and standard deviation of each of the variables including the contribution of instrument bias and measurement error, is known.

It is noted from Eq. (6) that the fouling factor R is a function of U_e and U_c. U_e is function of five measured quantities. Therefore, R is a function of six quantities; five measured variables and U_c.

A well known theorem in normal distribution theory holds that a quantity which is a function of several normally distributed quantities (i.e., a multivariable) is also a normally distributed quantity. Rigorous procedures to calculate the mean and standard deviation of the multivariable are available from the normal variation theory. A simplified approach based on partial derivatives is based on the principle of SRSS, which gives standard deviation in the fouling factor R, σ_R as

$$\sigma_R = \sqrt{\{\sum_{i=1}^{6} [\frac{\partial R}{\partial x_i}\sigma_{xi}]^2\}} \qquad (14)$$

The mean value of R is simply calculated by using the mean value of all variables.

$$\bar{R} = f(\bar{x}_i) \qquad (15)$$

The calculation process ends at this point if only five measured quantities were used. However, if all six variables were measured then we are faced with six values of $\bar{R}$ and σ_R, one computed from each of the quantities set in the six horizontal lines and U_c.

Furthermore, the testing may have been carried out at more than one set of conditions (flow rates and temperatures), giving the analyst six values of $\bar{R}$ and σ_R and one value of U_c for each set.

In order to develop the value of $\bar{R}$ and σ_R which utilizes the multiple values of $\bar{R}$ and σ_R, we utilize concepts from fuzzy logic. In the simplest form we reason that the "quality" of the fouling factor probability distribution curve is inversely proportional to its "spread" of which the standard deviation is a measure. Accordingly, we define a weighting function n_i defined as

$$n_i = \frac{\sigma_{\max}}{\sigma_i} \qquad (16)$$

where σ_i is the i-th fouling factor standard deviation (corresponding to data set i) and $\sigma_{\max}$ = AMAX [σ_i, i = 1....6]

The solution probability distribution curve for the fouling factor is given by the means $\bar{R}$ and standard deviation $\bar{\sigma}$ where

$$\bar{R} = \frac{\sum_{i=1}^{6} n_i R_i}{N} \qquad (17)$$

and

$$\bar{\sigma} = \frac{\sum_{i=1}^{6} n_i \sigma_i}{N} \qquad (18)$$

$$N = \sum_{i=1}^{6} n_i \qquad (19)$$

Having determined the mean and standard deviation of the fouling curve, the values of R for different confidence limits can be directly obtained using the data from Table 2.

EVALUATING DATA FROM TWO OR MORE INDEPENDENT TESTS

Data obtained from "independent" tests is far more valuable than from tests which are correlated to each other. It is important to recognize the notion of "independence" when configuring tests on a heat exchanger. At least one of the following three variables must be different between two tests in order for them to be considered independent:

(i) Tubeside flow rate
(ii) Shellside flow rate
(iii) Heat exchanger surface area

Heat exchanger surface area can be altered for a test by temporarily blocking some of the tubes with removable plugs, so as to create a smaller NTU exchanger during testing.

Practically speaking, a difference of at least 10% in at least one of the three variables would make two different tests independent of each other. Altering an inlet temperature does not produce an independent test, unless the temperature change is quite substantial (over 100°F for water).

As described earlier, the mean value and standard deviation of fouling factor, $\bar{R}$ and σ_R can be calculated for each independent test (equations 14 and 15). If all six variables were measured for any independent test, the $\bar{R}$ and σ_R are computed for each of the six discrete sets of data (as depicted in Table 3).

Implementing the concepts from fuzzy logic, the results of all of the independent tests are combined using equations 16 through 19, yielding a single mean fouling resistance and standard deviation.

ACCEPTANCE CRITERIA

In the foregoing sections, we established the algorithms for computing the mean fouling factor and standard deviation based on one or more sets of independent test data, with or without redundant test measurements. The fouling can then be presented as a function of confidence limit. However, the analyst must exercise caution when selecting the acceptance criteria for a test. Although the fouling factor is an excellent measure of the exchanger's degradation, if it has been computed based upon mean values of heat transfer coefficients rather than lower bound values as typically used in establishing the design criteria, it cannot be compared to the design value of fouling. The true acceptance criteria should be the value of the parameter which the heat exchanger was designed to meet, typically, a minimum heat removal rate. Often, the heat exchanger's design function is to maintain a fluid at a temperature less than a specified limit, in which case, the temperature may be used as the acceptance criteria. Whatever the acceptance criteria, it should be a parameter which can indicate whether the exchanger can perform its design function.

The performance of the exchanger under design conditions should be calculated using the fouling factor for a given confidence level as determined from test data and the mean value of heat transfer coefficients, not the minimum value as used in the design calculations. The results can then be presented as the acceptance parameter versus confidence limit.

COMPUTER CODE ST_XPERT

The concepts described in previous sections of this paper were implemented in the computer program ST_XPERT, which is an acronym for Shell and Tube Exchanger Performance Testing.

ST_XPERT requires as its input the geometric configuration of the shell and tube exchanger, at least one set of test data with associated uncertainties, and design basis conditions. The program output is a summary of projected design basis conditions, based upon the calculated value of fouling which corresponds to a 95% confidence limit, and a plot of projected design basis heat load versus percent confidence.

The statistical analysis methodology which has been presented in this paper was implemented in ST_XPERT. Computation of heat transfer coefficients was performed utilizing reliable correlations from empirical data.

The tubeside heat transfer coefficient is calculated using correlations appropriate for the operating flow regime; turbulent, transitional, or laminar. The tubeside correlations are fairly straightforward and can be carried out manually with relative ease.

Unlike the tubeside correlations, calculation of the shellside heat transfer coefficient can be quite complicated and extremely difficult to carry out manually. The analytical methodology should be one which completely characterizes the flow in the shellside of the exchanger. The Bell Delaware Method is one such methodology and has been implemented in ST_XPERT. The Bell Delaware Method is a design based method which, when implemented in a design program, the lower bound values would be used. Since the objective of the ST_XPERT is to perform a statistical analysis, the mean heat transfer coefficients can be used as long as the associated uncertainties are considered.

ST_XPERT also considers the tolerance of the tube wall in the thermal performance evaluation. It utilizes user friendly input/output screens for the program interface. The program can evaluate as many as 25 sets of test data, statistically combining the results to provide an accident heat removal capability with a specified level of confidence.

ANALYSIS OF FIELD TEST DATA

The service water (SRW) heat exchanger at a nuclear power plant has been selected as the sample heat exchanger to be used for illustrating the solution methodology and applications of ST_XPERT.

The SRW heat exchanger at Baltimore Gas & Electric Company's Calvert Nuclear Plant is a TEMA type, single tube pass tubular exchanger which is used to transfer heat from the plant to the ultimate heat sink (Chesapeake Bay). The heat exchanger has approximately 19,000 ft^2 of surface area, and the shellside baffle configuration is a modified triple segmental. This heat exchanger is known to have a history of fouling on its tubeside which contains the Chesapeake Bay water.

The performance testing was performed on the SRW heat exchanger under approximately steady-state conditions. The measured parameters are summarized in Table 4 along with the associated uncertainties in the measurements.

Table 4; SRW Heat Exchanger Performance Test Data

Parameter	Units	Tubeside	Shellside
Inlet temp.	°F	79.92 ±.13	95.19 ± .13
Outlet temp.	°F	85.65 ± .66	85.53 ± .37
Flow rate	gpm	20490 ± 500	12050 ± 440

The SRW heat exchanger was originally designed to remove 216.57 x 10^6 Btu/hr under the conditions set forth in Table 5.

Table 5; SRW Heat Exchanger Design Accident Conditions

Parameter	Units	Tubeside	Shellside
Inlet temp.	°F	90	170.03
Flow rate	lb/hr	8,369,460	3,362,770

The data was analyzed using ST_XPERT assuming a ± 10% tolerance on the tube wall thickness. The program indicated that the design heat load could only be removed with approximately 72% confidence (see Figure 2). At the 95% confidence limit, only 213.4 x 10^6 Btu/hr could be removed. Subsequently, a thorough review of overall system performance and a reevaluation of test acceptance criteria were required to clearly demonstrate that the system would perform its design functions.

Parametric Studies

Some analyses are performed herein to show the trends of the results as a given parameter is varied. The results will show that as the uncertainties are increased, the standard deviation of the fouling resistance will also increase thus, the heat removal rate with 95% confidence will decrease (see Figure 3). Note that the mean fouling will remain unchanged as the mean values of test data are also unchanged.

Using the mean test data as tabulated in Table 4, the heat removal rate Q_t, as calculated from the tubeside test data is 58.47×10^6 Btu/hr. The heat removal rate, Q_s, as calculated from the shellside test data is 58.28 Btu/hr.

Since the heat removal rate, Q_t, calculated from the tubeside data is in excellent agreement with Q_s (calculated from the shellside data), the calculated heat removal capacity will be nearly the same for the case where all six parameters are specified as for the case when only five parameters are specified. This is demonstrated in Figure 4 and 5 when all parameters are assigned a zero percent uncertainty.

As the uncertainty of a single parameter increases, the projected heat capacity, of course, decreases. The slope of the curve (Figures 4 and 5) is noticeably steeper for the case when only five parameters are specified. This study indicates that the effect of instrument inaccuracy on the calculated performance will be exaggerated if one parameter is computed from heat balance instead of being used as an input.

The above examples are only representative of the SRW heat exchanger for the given conditions. The purpose of the example is demonstrate the logic of the trends and the importance of using all known information. The actual effects of uncertainties of individual parameters depends upon the heat exchanger conditions which are being evaluated.

CLOSURE

A statistically consistent method to analyze the thermal performance of a heat exchanger from field test data has been presented. The method permits the analyst to include instrument bias, error in measurements as well as in mathematical correlations in establishing the probability distribution function for the output variable (such as the fouling factor or the heat duty). The analyst can then correlate the output variable as a function of confidence limit.

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