

HEAT EXCHANGER PERFORMANCE MONITORING

SCOPE

This document presents the method of determining dirt factor or fouling factor for shell and tube heat exchanger. Dirt factor in exchangers is an indication of the performance level of the exchangers. Low dirt factor indicates good performance. What important is to monitor dirt factor over time and study the trends.

DEFINITIONS

Dirt Factor – heat transfer resistance offered by a thin layer of scale deposition building up over time. It depends on type of fluid, nature of tube surface and operating conditions

REFERENCE

Binay K Dutta, *Heat Transfer Principles and Applications*, Prentice Hall

R K Sinnott, *Chemical Engineering Design*, Elsevier-Butterworth-Heinemann

Douglas L Erwin, *Industrial Chemical Process Design*, McGraw Hill

INTRODUCTION

In most process plants, poor performance of heat exchangers may eventually lead to loss of production due to inability of process to sustain throughput due to insufficient energy required by process or due to too high product rundown temperature to storage. This section describes the method normally used for effective performance monitoring of heat exchangers.

METHOD OF PERFORMANCE MONITORING

There are various methods could be used. Among them are listed below.

1. Outlet temperature trend
2. Heat exchanger efficiency trend
3. Pressure drop trend
4. Z-factor trend
5. Overall transfer coefficient trend
6. Dirt factor trend

Methods 1-3 are straight forward trending of actual plant data. Methods 4 & 5 require simple calculation but method 6 requires more complicated computation. The methods 1 to 5 are reliable at constant flowrate which is not always true in actual plant operations. Method 6 takes into account for flowrate variations; therefore it is more reliable and representative of exchanger performance. Only method 6 will be elaborated in this section.

DIRT FACTOR

Dirt factor which is also known as fouling factor is a sought-out value because it reveals how well the exchanger is performing in reference to its design. The smaller the dirt factor the smaller the fouling in the heat exchanger.

Fouling is a complex process that can be influenced by many variables. It can occur by a number of mechanisms operating either alone or in combination. These include:

Corrosion – corrosion products such as rust can gradually build-up on tube walls, resulting in reduced heat transmission and eventual tube failure. This type of fouling can be minimized or eliminated by the proper choice of corrosion-resistant materials of construction in the design process.

Crystallization – typically occurs with cooling water streams containing dissolved sulfates and carbonates. Since the solubility of these salts decreases with increasing temperature, they tend to precipitate on heat transfer surfaces when the water is heated, forming scale. This type of fouling can be minimized by limiting the outlet temperature to a maximum of 120°F.

Decomposition – Some organic compounds decompose when they are heated or in contact with a hot surface, forming carbonaceous deposits such as coke and tar. In cracking furnaces partial decomposition of the feedstock is the objective and coke formation is undesired but unavoidable by products.

Polymerization – reactions can be initiated by certain unsaturated organic compounds are heated or in contact with hot metal surfaces resulting in a tough plastic-like layer that can be very extremely difficult to remove.

Sedimentation – results from the deposition of suspended solids entrained in process streams such as cooling water and flue gases. Accumulation of sediments can be minimized by high velocity streams. Cooling water, for example, the velocity should be maintained higher than 1 m/s.

Biological activity – this type of fouling is caused by micro-organisms. Process streams such as cooling water, may contain algae or bacteria that can attach and grow on heat transfer surfaces, forming slimes that are very poor heat conductors. Metabolic products of these organisms can also cause corrosion. Biocides can be used to inhibit the growth of micro-organisms.

Dirt factor is computed from process stream data by correlation below:

$$R_d = \frac{U_c - U_d}{U_d U_c}$$

Where U_c = clean overall coefficients, $W/m^2 C$

U_d = dirty overall heat transfer coefficient, $W/m^2 C$

R_d = dirt factor, $m^2 C/W$

Overall Dirty Coefficient U_d

The dirty heat transfer coefficient U_d can be computed by using either conventional or effectiveness method.

Conventional Method

In this method U_d is determined by correlation given below.

$$U_d = \frac{Q_a}{A.LMTD_c}$$

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Where Q_a = actual heat duty, W

U_d = dirty overall heat transfer coefficient, $W/m^2\text{ }^\circ\text{C}$

A = total surface area, m^2

$LMTD_c$ = corrected log-mean-temperature, $^\circ\text{C}$

The actual heat duty is computed from the process streams data which is correlated by following equation:

For hot stream,

$$Q_h = WC(T_1 - T_2)$$

For cold stream

$$Q_c = wc(t_2 - t_1)$$

The actual heat duty is then computed by taking the average value from the above equations. If some data are suspected unreliable, reconciliation could be carried out. For water coolers the cooling water flowrate is normally unknown and computed from the heat balance. In this situation, accuracy of data shall influence the value of dirt factor.

$LMTD_c$ is computed by multiplying log-mean-temperature-difference with the correction factor F_c .

$$LMTD_c = \frac{GTTD - LTTD}{\text{Ln}\left(\frac{GTTD}{LTTD}\right)} F_c$$

Where $GTTD$ = greater terminal temperature difference

$LTTD$ = lower terminal temperature difference

The LMTD correction factor F_c can be determined graphically or by computing using correlation given below:

For 1-1 shell & tube exchanger or counter-current flow or either fluid is isothermal, then $F_c = 1$.

For N-2N shell & tube exchangers:

Let

N = number of shellside passes

$$R = \frac{T_1 - T_2}{t_2 - t_1} \quad P = \frac{t_2 - t_1}{T_1 - t_1}$$

Where T_1 = inlet temperature of shell side stream

T_2 = outlet temperature of shellside stream

t_1 = inlet temperature of tubeside stream

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$t_1 =$ outlet temperature of tubeside stream

For R unequal to 1, compute:

$$\alpha = \left(\frac{1 - RP}{1 - P} \right)^{1/N}$$

$$S = \frac{\alpha - 1}{\alpha - R}$$

$$F_c = \frac{\sqrt{R^2 + 1} \ln \left(\frac{1 - S}{1 - RS} \right)}{(R - 1) \ln \left(\frac{2 - S(R + 1 - \sqrt{R^2 + 1})}{2 - S(R + 1 + \sqrt{R^2 + 1})} \right)}$$

For $R = 1$, compute:

$$S = \frac{P}{N(1-P) + P} \quad F_c = \frac{S\sqrt{2}}{(1-S) \ln \left(\frac{2(1-S) + S\sqrt{2}}{2(1-S) - S\sqrt{2}} \right)}$$

Effectiveness Method

In this method, the dirty coefficient is computed from the heat exchange effectiveness which is defined as the ratio of heat duty to the maximum possible heat transfer. The latter is the rate of heat transfer that would occur in a counter-current flow heat exchanger having infinite heat transfer surface area. In such an exchanger, one of the fluid streams will gain or lose heat until its outlet temperature equals the inlet temperature of the other stream. The stream that experiences this maximum temperature change is the one that has the smaller value of $C = mC_p$, as can be seen from the heat balance equations from the two streams. Thus if the hot stream has the lower value of C then $T_2 = t_1$. The maximum possible heat transfer is given by:

$$Q_{max} = WC_p(T_1 - T_2) = WC_p(T_1 - t_1) = C_{min}(T_1 - t_1)$$

On the other hand, if the cold fluid has the lower value of C , then $t_2 = T_1$ and

$$Q_{max} = wc_p(t_2 - t_1) = wc_p(T_1 - t_1) = C_{min}(T_1 - t_1)$$

In either case

$$Q_{max} = C_{min}(T_1 - t_1) = C_{min} \Delta T_{max}$$

Where ΔT_{max} is the maximum possible temperature difference that can be formed from the terminal temperatures.

By definition, the effectiveness is given by,

If the hot stream has the lower value of C , then

If the cold stream has the lower value of C , then

$$\varepsilon = \frac{(T_1 - T_2)}{(T_1 - t_1)}$$

$$\varepsilon = \frac{(t_2 - t_1)}{(T_1 - t_1)}$$

For a given type of heat exchanger, ε depends only on two parameters, r and NTU where

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$$\varepsilon = \frac{Q}{Q_{\max}} = \frac{Q}{C_{\min} \Delta T_{\max}}$$

$$NTU = \frac{UA}{C_{\min}}$$

$$r = \frac{C_{\min}}{C_{\max}}$$

NTU stands for number of transfer unit. The relationships between effectiveness, r and NTU for shell & tube heat exchangers are given below.

For counter-current and $r < 1$

$$\varepsilon = \frac{1 - \exp[-NTU(1-r)]}{1 - r \exp[-NTU(1-r)]}$$

If $r = 1$ then

$$\varepsilon = \frac{NTU}{1 + NTU}$$

For co-current or parallel flow

$$\varepsilon = \frac{1 - \exp[-NTU(1+r)]}{1+r}$$

For 1-2 exchanger

$$\varepsilon = \frac{2}{\left[1 + r + \beta \frac{1 + \beta \exp[-\beta NTU]}{1 - \exp[-\beta NTU]} \right]} \quad \beta = \sqrt{1 + r^2}$$

For N-2N exchanger (N= number of shell passes) and $r < 1$,

$$\varepsilon = \frac{\left(\frac{1 - \eta r}{1 - \eta} \right)^N - 1}{\left(\frac{1 - \eta r}{1 - \eta} \right)^N - r}$$

If $r = 1$ then effectiveness is given by

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$$\varepsilon = \frac{N\eta}{1 + (N-1)\eta}$$

Where η is the effectiveness for a 1-2 exchanger with the same value of r but NTU is given by

The dirty overall coefficient is determined from the NTU correlation since the surface area and C_{min} are known. The correlation for 1-2 exchanger, for example, can be re-

$$NTU = \frac{UA}{NC_{min}}$$

arranged as shown below.

$$NTU = \frac{-1}{\beta} \ln \left[\frac{2/\varepsilon - (1+r) - \beta}{2/\varepsilon - (1+r) + \beta} \right]$$

Then U_d can be computed from

Overall Clean Heat Transfer Coefficient

Clean Heat Transfer Coefficient U_c is computed from the individual film heat transfer

$$U_d = \frac{NTUC_{min}}{A}$$

coefficient of the shellside and tubeside streams.

$$\frac{1}{U_c} = \frac{1}{h_o} + \frac{D_o}{h_i D_i}$$

The individual film heat transfer coefficients are computed either graphically or using correlation below:

For tubeside,

$$h_i = \exp \left(-4.287 + 0.85 \ln \left(\frac{D_i G_t}{\mu} \right) \right) \left(\frac{K}{D_i} \right) \left(c \frac{\mu}{K} \right)^{1/3} \left(\frac{\mu}{\mu_w} \right)^{0.14}$$

For cooling water, the following simplified correlation can be used.

$$h_i = \frac{4200(1.35 + 0.02T)}{D_i^{0.2}} U_t^{0.8}$$

Where h_i = tubeside heat transfer coefficient, $W/m^2 \text{ } ^\circ C$

T = average temperature, $^\circ C$

G_t = mass velocity, $kg/m^2 s$ per tube

U_t = water velocity, $m/s = G_t / \text{density}$

D_i = tube inside diameter, mm

The shellside film coefficient can be obtained from

$$h_o = \exp\left(-0.665 + 0.5195 \ln\left(\frac{D_e G_s}{\mu}\right)\right) \left(\frac{K}{D_e}\right) \left(c \frac{\mu}{K}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

The shellside equivalent diameter is computed as below”

For square pitch,

$$D_e = \frac{1.27}{D_o} (P_t^2 - 0.785 D_o^2)$$

For triangular pitch,

$$D_e = \frac{1.1}{D_o} (P_t^2 - 0.917 D_o^2)$$

The shellside mass velocity G_s is computed using correlation below.

$$G_s = W_s \frac{P_t}{(P_t - D_o)BS}$$

Where W_s = mass flowrate of shellside stream, Kg/s

P_t = tube pitch, m

B = baffle spacing, m

S = shell diameter, m

D_e = equivalent diameter, m

D_o = tube outside diameter, m

D_i = tube inside diameter, m

Dirt Factor Trending

Knowing the overall dirty coefficient and the clean coefficient then the dirt factor can be computed. For monitoring purposes, we can either plot the dirt factor over time period or alternatively the reciprocal of dirt factor over time.

Future performance of the exchanger can be predicted by determining the correlation that represents the relationship of dirt factor (or the reciprocal) versus time period (e.g. days).

Dirt factor of greater than the design value shall indicate fouling and deserves investigation especially if this occurs at the start-of-run. The performance of the exchanger is considered normal if the dirt factor remains below the design value over the monitoring period.

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