THE USE OF HOT WIRE TECHNIQUES IN FOULING TESTS
A WORD OF AWARENESS

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ABSTRACT

Hot metal wires have been used in fouling tests, mainly when corrosion or chemical reaction is present.
Most authors who have reported data obtained with hot wire techniques make no refence about the phenomenon related to the increase in surface area due to the accumulation of fouling layers. Yet this can cause problems of reverse insulation (critical radius), affecting the conclusions taken directly from the readouts.
The aim of this paper is to discuss this problem and show through a few selected cases the importance of this aspect in fouling resistance determinations using hot wire techniques.

INTRODUCTION

It is often impractical and even impossible to use field equipment for systematic fouling studies. Hence, some laboratory techniques were developed in order to evaluate the effect of pertinent parameters, on heat exchanger fouling, within appreciable ranges.

One of them is the hot wire probe test (HWP), which consists essentially of electrically heating a metal wire in contact with a fluid stream |1|.

Heat tranfer coefficients and thermal resistances can be calculateed knowing the heat flux, as well as the fluid and wire temperatures.

The wire temperature is a function of its electrical resistance, the latter being measured during the fouling tests.

Some improvements have been made in this technique; one, the U.O.P. Monirex Fouling Test (Figure 1) was designed by Universal Oil Products Co. to be comercially available for use in the laboratory as well as on a side stream of a particular process |2|.

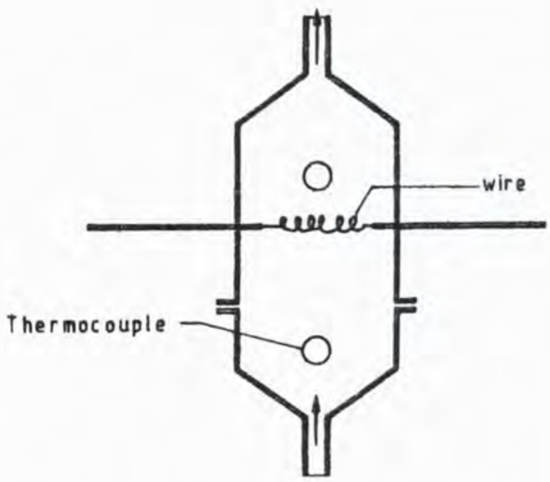

Figure 1 - Hot wire probe

The importance of this technique is due to some advantages:

- it is sensitive;
- by adjusting the operating conditions it can measure fouling in hours rather than months;
- it operates with small amounts of feedstock;
- it gives readouts in terms of heat-transfer coefficient:
- it easies the control of different parameters such as:

- temperature of the stream;
- temperature of the hot wire;
- flow rate of the stream;
- composition of the fluid.

The HWP has been used mainly when corrosion or chemical reaction is present and due to its particular features, is a pratical mean for stuying the dependence of fouling rate on wall temperature - an important parameter in many types of fouling.

In fact, despite the existence of a great number of listed fouling factors, published by **T.E.M.A.** - Tubular Exchanger Manufacturers Association - for a broad number of defined equipment and heat duties, they do not sufficiently account for the dependence of fouling on temperature, also making no allowance for its time dependence.

THE CRITICAL RADIUS

Fouling usually acts as an additional resistance to heat transfer; but in thin wires, and in some circunstances, this may not be true.

Assuming the wire as cilindrical, see **Figure 2**, the heat transfer rate from it can be calculated by:

$$q = \frac{(T_w - T_b)}{R} \cdot 2\pi \ell r_w \qquad (1)$$

Where:

q - heat transfer rate
T_w - temperature of the wall (wire)
T_b - bulk fluid temperature
ℓ - wire length
r_w - wire radius
R - total thermal Resistance = $R' + R_f$

and:

$$R' = \frac{r_w}{h_r}$$

R' - thermal resistance of the fluid

$$R_f = \frac{r_w}{k_f} \ln \frac{r}{r_w} \qquad (2)$$

R_f - thermal resistance of fouling layer
r - effective radius = $r_w + r_f$
r_f - fouling layer thickness
h - convective heat transfer coefficient
k_f - thermal conductivity of the deposit

and so

$$q = \frac{2\pi \ell (T_w - T_b)}{\frac{1}{hr} + \frac{1}{k_f} \ln \frac{r}{r_w}} \qquad (3)$$

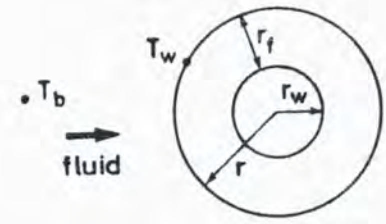

Figure 2 - Fouling layer on the wire

If the wire is very thin phenomena similar to reverse insulation |3| can be present. In fact, the accumulation of successive *cilindrical* layers of deposit results in a continuous increase in the surface area contacting the fluid; thus the total heat transfered may also increase if the area increases more rapidly than the thermal resistance.

A critical radius for the fouled wire can be determined knowing that for a maximum heat transfered the total thermal resistance is a minimum. The resistance is a minimum when the derivative of the sum of the resistances R' and R_f with respect to the radius r is set equal to zero:

$$\frac{dR}{d_r} = \frac{r_w}{k_f} d \ln \frac{r}{r_w} + \frac{r_w}{h} d \frac{1}{r} = \frac{r_w}{k_f r} - \frac{r_w}{h r^2}$$

for a minimum thermal resistance $\frac{dR}{dr} = 0$ and

$$r = \frac{k_f}{h} = r_c \qquad (4)$$

r_c being known as the **critical radius.**

An increase in heat transfer will be observed with increasing fouling thickness in the zone characterized by $r_w < r < r_c$, as can be seen from **Figure 3.**

Only at $r = r'$ will the heat transfer rate again equal the heat transfer from the initially unfouled wire.

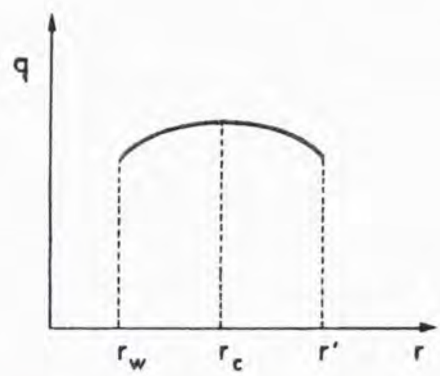

Figure 3 - Heat transfer rate versus wire radius

As from equation (4) $h = \frac{k_f}{r_c}$, equation (3) becomes

$$q = \frac{2\pi \ell \,(T_w - T_b) \times k_f}{\ln \frac{r}{r_w} + \frac{r_c}{r}}$$

EFFECTS OF THE CRITICAL RADIUS ON FOULING DATA

In the calculation of fouling resistances it is often assumed that no change in surface area occurs during fouling. However, this assumption is not valid for the HWP, where significant changes in the area can occur specially if the wire diameter is very small. For instances, if the wire radius is 0,1 mm, the increase in surface area caused by a fouling layer of 0,01 mm thickness is about 10%, but if the wire radius is 2 mm the same deposit produces an area increase of about 0,5%.

Experiments with the HWP under a constant heat flux are frequently carried out |6| by simply controlling the voltage to the wire. In this case, the following conclusions emerge from **Figure 4** and equation **(5)**:

- if $r < r_c$, increasing r decreses T_w;
- if $r > r_c$, increasing r increases T_w.

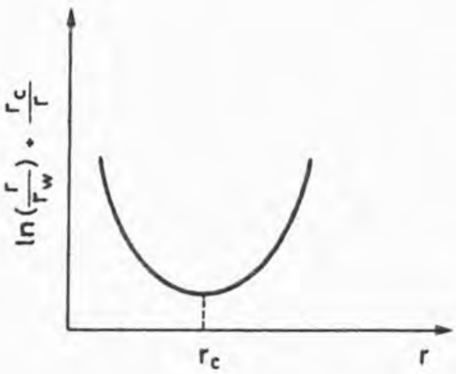

Figure 4 - Effect of radius change on the denominator of equation (5)

The consequences of these changes in T_w for two different types of data collection will be discussed below.

Fouling Resistance Versus Time Data

Frequently, the build-up of deposits with time in industrial heat exchangers tends to a maximum steady (asymptotic) value and, sometimes, presents an initial induction period where no fouling is detected. The shape of the fouling resistance versus time curves and, of course, the quantitative assessement of the deposit can be severely affected by the critical radius effect, as illustrated in the following example.

Suppose that: the wire on a HWP is 10 cm long, with a radius of 1 mm; the thermal conductivity of the deposited substance is 0,8 w/m k; the fluid and the initially clean wire temperature are, respectively, 15°C and 60°C; and the heat transfer rate (which will be held constant throughout the test) is 15 w. As deposition proceeds, T_w will change and, assuming constant h, the correct values of R_f can be calculated with equations (3) and (2). This R_f versus time data is shown in **Figure 5** - curve (a).

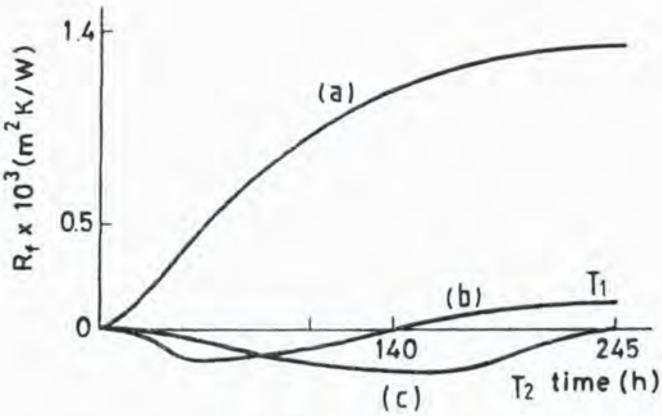

Figure 5 - Fouling curves.
(a) with critical radius correction.
(b) and (c) without correction.

However, when the change in surface area is not taken into account - for instance, if the thermal conductivity of the deposit is not known - R_f is simply evaluated by the expression:

$$R_f = R - \frac{1}{h} \qquad (6)$$

The fouling curve obtained with this equation (curve (b) in **Figure 5**) is quite different from curve (a) and leads to incorrect interpretation of the data, particularly when one tries to extrapolate these results to industrial situations.

Fouling Rate Versus Temperature Data

In the petroleum industry, fouling is very often due to the deposition of organic materials formed in chemical reactions that take place at high temperatures. A multitude of reactions can be present contributing to the overall fouling rate and so a complex dependence on temperature must be expected.

Most of the reports on the dependence of chemical reaction fouling on wall temperature refer a *breakpoint* temperature that is, a temperature above which fouling occurs at a significant rate.

The breakpoint temperature is characteristic for each sample under study and is a function of its chemical composition, oxygen concentration and other factors |4|.

The results obtained with the **WHP** mainly appear in the form of curves, like curve (a) in **Figure 6**.

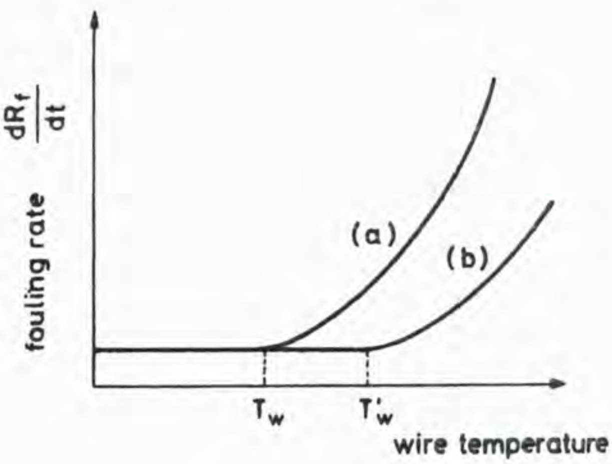

Figure 6 - Breakpoint temperature.
(a) with critical radius correction
(b) without correction

In these experiments the wire temperature is held constant, for a relatively long period, to check if for that temperature some deposit is formed. If the phenomenon of critical radius is present it is possible to operate the HWP at such temperatures that curves, like curve (b) or even curve (c) in **Figure 5**, may be obtained.

An erroneous interpretation of these curves can lead to the following:

- for the temperature at wich curve (b) was obtained (T_1), the induction period seems to be very long, and fouling relatively small;
- for the temperature at which curve (c) was obtained (T_2) no significant fouling seems to occur

during the operating time. So, this temperature appears to be below the breakpoint temperature, despite the actual presence of fouling.

Based on such an information, curve (a) in **Figure 6** would appear displaced to the right (curve (b)) and the value of the breakpoint temperature would be misrepresented - T_w' instead of T_w.

CONCLUSIONS

Most authors who have reported data obtained with the HWP seem not to be concerned with the phenomenon of critical radius, since they make no reference on calculations carried out to check wether reverse-insulation effects are present.

Nevertheless, to make a correct interpretation of experimental data, this effect must be checked out. If this effect is not taken into account, misleading results may be obtained, namely:

- values of thermal resistances of deposit lower than the real ones;
- induction periods and breakpoint temperatures greater than the actual ones.

Alternatively, when designing a HWP for a given duty the wire radius must be careffuly choosen to avoid the indesirable phenomenon.

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