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HEAT EXCHANGER FOULING - PREDICTION, MEASUREMENT AND MITIGATION

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ABSTRACT

The U. S. Department of Energy (DOE), Office of Industrial Programs (OIP) sponsors the development of innovative heat exchange systems. Fouling is a major and persistent cost associated with most industrial heat exchangers and nationally wastes an estimated 2.9 Quads per year. To predict and control fouling, three OIP projects are currently exploring heat exchanger fouling in specific industrial applications.

A fouling probe has been developed to determine empirically the fouling potential of an industrial gas stream and to derive the fouling thermal resistance. The probe is a hollow metal cylinder capable of measuring the average heat flux along the length of the tube. The local heat flux is also measured by a heat flux meter embedded in the probe wall. The fouling probe has been successfully tested in the laboratory at flue gas temperatures up to 2200 F and a local heat flux up to 41,000 BTU/hr-ft^2. The probe has been field tested at a coal-fired boiler plant. Future tests at a municipal waste incinerator are planned.

Two other projects study enhanced heat exchanger tubes, specifically the effect of enhanced surface geometries on tube bundle performance. Both projects include fouling in a liquid heat transfer fluid. Identifying and quantifying the factors affecting fouling in these enhanced heat transfer tubes will lead to techniques to mitigate fouling.

INTRODUCTION

The Advanced Heat Exchangers (AHX) Program of the DOE Office of Industrial Programs, sponsors technology development to advance the state-of-the-art in heat recovery and to expand energy conservation in American industry. OIP is concerned about the endemic energy cost of heat exchanger (hx) fouling. Consequently the AHX program sponsors projects to predict, measure and mitigate hx fouling. This paper briefly discusses the estimated costs associated with hx fouling and examines three AHX projects that concern hx fouling. Corrosion is a related problem. However, AHX projects to mitigate hx corrosion are beyond the scope of this paper.

BACKGROUND

Heat Exchanger fouling is a complex phenomenon. Heat exchanger fouling is defined as an undesirable solid or liquid deposit on a heat transfer surface. The insulating fouling layer decreases the overall heat transfer coefficient and thereby decreases the heat flux. Epstein (1) classifies fouling by six basic mechanisms:

1. Scaling: Salts precipitate from solution onto the heat transfer surface.
2. Particulate Fouling: Particulates suspended in the fluid stream deposit onto the heat transfer surface.
3. Chemical Reaction Fouling: Chemical reaction products form at the heat transfer surface. The actual surface material is not a reactant in this type of fouling mechanism.
4. Corrosion Fouling: A chemical reaction occurs at the heat transfer surface in which the surface reacts to form corrosion products.
5. Biofouling: Organisms gather at the heat transfer surface.
6. Freezing Fouling: A fluid solidifies on a heat transfer surface.

Regardless of the fouling mechanism involved, the net foulant mass transport rate determines the foulant accumulation. The net foulant mass transport rate is a function of: a) the foulant mass flux to the heat transfer surface, b) the attachment of the foulant to the surface, to include any chemical/biological reaction(s), and c) the detachment rate of the foulant mass. If a gas stream temperature is below the dew point of a constituent, condensation onto the heat exchanger tubes may increase the foulant accumulation through either particulate attachment or corrosion. The mass flux to the heat transfer surface is driven by the following mass transport phenomenon (2):

1. Particle Diffusion: Brownian forces and eddy diffusivity forces small particles, <1 um, in random directions, away from fluid streamlines (3).
2. Diffusiophoresis: The force caused by vapor condensation on a cool surface forces small particles, <1 um, towards a cool heat transfer surface (4).
3. Thermophoresis: The thermal gradient promotes fluid mixing and forces particles toward a cool surface. This phenomenon is significant for particles $0.05 \text{ um} < d_p < 0.5$ um. Thermophoresis also requires a temperature gradient between the surface and the gas stream of at least 200 F (5).
4. Electrophoresis: Friction or ionization imparts an electrostatic charge to a particle and forces diffusion along an electric field. This phenomena is insignificant for particles > 0.1 um (3).
5. Inertial Impaction: This phenomenon is only significant for particles > 1 um (6).
6. Ionic Diffusion: Ionic species in the fluid migrate and precipitate on the heat transfer surface (7).
7. Sedimentation: Gravity tends to remove the denser particles from the fluid stream when the settling velocity is comparable to the stream velocity.

Although it is convenient to characterize the fouling mechanisms and the mass transport processes, in industrial conditions many of these phenomena occur simultaneously. Consequently, fouling on a heat transfer surface is a complex function of many factors. Elements include the surface geometry, surface material, surface temperature, fouling deposit temperature, and fluid parameters, e.g., temperature, velocity. Often, as in this paper, fouling and corrosion are considered as separate issues. In fact, they are interrelated. Fouling often causes corrosion. In situ fouling is corrosion products formed at the heat transfer surface. Ex situ fouling is existing fouling material transported and deposited on the heat transfer surface. Similarly, corrosion products may foul the heat transfer surface themselves and also may attract additional fouling material from the fluid stream.

THE PROBLEM: FOULING COST

Although the cost to U.S. industry from heat exchanger fouling is difficult to quantify, the cost is substantial. The cost is primarily a function of two interrelated factors: the energy not transferred and hence lost because of the insulating fouling layer; and the increased capital cost involved in oversizing a heat exchanger to operate in a fouling environment. Other cost factors exist to a lesser extent, e.g., maintenance. Rebello (8) estimates the 1982 fouling cost to U.S. industry in lost energy at 2.9 Quads per year. Oversized heat exchangers cost industry an additional $180 million per year. Assuming an energy cost of $3/MMBTU, the total annual fouling cost would be about $9 billion. Rebello further analyzes the fouling cost to specific industries. He concludes (9) that fouling is most costly to the electric utility industry at approximately 2 Quads per year in lost energy and $65 million in increased capital costs. Again assuming an energy cost of $3/MMBTU, heat exchanger fouling annually costs the electric utility industry about $6 billion. The above calculations are based on 1982 data. Rebello further observes that the fouling effect on heat exchanger performance is a strong function of the overall heat transfer coefficient. The larger the heat flux, the more pronounced is the effect of any fouling. For example, in a gas-to-gas heat exchanger the overall heat transfer coefficient, U_c, is small, i.e., the heat transfer resistance is large. Because resistances are cumulative, a given amount of foulant influences a large resistance less, proportionally, than a small resistance (10). However, the fouling effect may be more pronounced with a larger U_c. For example, given a typical liquid-liquid shell and tube heat exchanger with a U_c of 100 BTU/hrft^{2}F, and a fouling thermal resistance, R_f, of 0.002 hrft^{2}F/BTU; a heat exchanger requires 20% more area to transfer the same amount of energy compared to a clean heat exchanger (9).

Improved methods of fouling mitigation and control may yield significant industrial energy savings. However, as Rebello comments (8), fouling mitigation techniques are often developed by the hx end user and are therefore proprietary. Probably no single well-defined body of technical knowledge exists in this area (11). DOE believes that government-sponsored research into heat exchanger fouling can result in significant national energy savings. However, because the general fouling phenomenon is so comprehensive and yet diverse, it is beyond the scope of any single program. Therefore, the Advanced Heat Exchangers Program seeks to understand, predict and control heat exchanger fouling in the three applications discussed below.

GAS-SIDE FOULING PROBE

JPL Fouling Probe Development

High-temperature flue gases are an untapped energy source in many plants because of corrosive compounds and fouling particulates in the flue gases. It is difficult to theoretically predict the effects of heat exchanger fouling without empirical data. If the fouling and corrosive potential of a given high-temperature waste gas stream could be measured, it may be possible to design a recuperator to capture waste heat. The Jet

Propulsion Laboratory (JPL) surveyed the state-of-the-art in gas-side fouling probes. In this study Marner and Henslee categorized existing gas-side fouling probes into five different types: heat flux meters, mass accumulation probes, optical devices, deposition probes, and acid condensation probes. However, they concluded that industry still needs a durable and versatile probe capable of measuring real time fouling resistances (12). Therefore, the Jet Propulsion Laboratory (JPL), with DOE funding, developed a fouling probe to determine the real time fouling potential of a gas stream (13). The National Engineering Laboratory, Glascow, Scotland, is currently conducting similar fouling probe research sponsored by the U.K. Department of Energy (3,4,6,14).

One purpose of the JPL fouling probe is to predict accurately the fouling thermal resistance as a function of time. This parameter supports efficient and economical heat exchanger design. The fouling probe may also predict the fouling effect on an existing heat exchanger resulting from a change in the gas-side operating parameters. For example, given a heat exchanger in an incinerator flue gas stream; the probe will determine the effect on the heat transfer rate if the operators modify the incinerator feed. The fouling probe may detect the change in the fouling resistance much more rapidly than the heat exchanger itself. The fouling probe is much smaller than most industrial heat exchangers. Therefore, a given amount of fouling will affect the tube-side fluid temperature difference of the fouling probe more than that of the industrial heat exchanger. Measuring the fouling thermal resistance as a function of time can also correlate fouling with unsteady-state process excursions. A given industrial process may not produce fouling under normal steady-state conditions and yet may create fouling when submitted to unsteady-state conditions.

The heat flux measurement in an industrial gas stream requires a portable and reliable instrument. The JPL fouling probe, Figure 1, consists of two concentric 304SS cylinders, as shown in Figure 2. Ambient air cools the probe interior to simulate an operating heat exchanger and to protect the probe from excessive stack gas temperatures. The cooling air enters and flows down the 0.5-in. OD inner cylinder, reverses direction, and flows along the 1.0-in. OD outer cylinder (13). A heat flux meter from International Thermal Instrument Company, Del Mar California, measures the local heat flux. Thermocouples are at three locations: the inside surface of the heat flux meter, the inside surface of the probe near the heat flux meter, and at the cooling air inlet and outlet. An average heat flux along the probe length is derived from the inlet and outlet temperatures of the cooling air.

The computerized probe control system controls the cooling air flow rate besides processing and recording the data. The controller maintains the tube-side of the heat flux meter at a constant temperature by regulating the cooling air flow rate. The system monitors the inlet cooling air volumetric flow rate and pressure in addition to the thermocouple and heat flux meter readings. The probe control system also contains a micro computer for data acquisition.

Given the above data from the probe control system and the gas stream temperature, calculation of the fouling thermal resistance (R_f) is relatively straightforward (15):

Average R_f over length of the probe:

$$R_f = \left[\frac{(T_g - T_{wi})A_o}{W_a Cp_a (T_{a2} - T_{a1})}\right]_{Fouled} - \left[\frac{(T_g - T_{wi})A_o}{W_a Cp_a (T_{a2} - T_{a1})}\right]_{Clean} \quad (1)$$

Local R_f from heat flux meter:

$$R_f' = \left[\frac{(T_g - T_{wi})}{(C_1 E + C_2)}\right]_{Fouled} - \left[\frac{(T_g - T_{wi})}{(C_1 E + C_2)}\right]_{Clean}$$

where: A_o = Effective outside surface area of fouling probe, ft^2
C_1, C_2 = Heat flux meter calibration constants
Cp_a = Specific heat of probe cooling air, Btu/lb^oF
E = Heat flux meter output, uV
T_{a1} = Probe inlet cooling air temperature, ^oF
T_{a2} = Probe outlet cooling air temperature, ^oF
T_g = Temperature of waste stream gas, ^oF
T_{wi} = Temperature of probe inside wall, ^oF
W_a = Mass flow rate of probe cooling air, lb/hr

JPL has successfully tested the fouling probe in a controlled laboratory environment (13,16). The laboratory test apparatus burned natural gas and injected the foulant, $Ca(OH)_2$, downstream. The test temperatures calcined the $Ca(OH)_2$ to CaO and H_2O. Table 1 lists the CaO particle size distribution along with other test parameters. At each test, T_{wi}, T_g, and the combustion gas velocity, V_g, were held constant. The change in cooling air temperature and mass flow rate, and the local heat flux were measured as a function of time. Figures 3 and 4 summarize the JPL test results. Both the average and local fouling thermal resistances, R_f, vary asymptotically with time. This, therefore, implies that at some time the mass of foulant attaining the surface and adhering equals the foulant mass detaching from the probe.

Table 1. Laboratory Test Parameters of the JPL Fouling Probe (13)

Parameter	Range
Gas Temperature, T_g	745 - 2214°F
Inside Wall Temperature, T_{wi}	270 - 1500°F
Average Gas Velocity, V_g	9.91 - 27.7 ft/sec
Local Heat Flux, q_{hfm}	3440 - 40,800 Btu/hrft^2
Average Heat Flux, q_a	5040 - 36,000 Btu/hrft^2
Test Duration, t	85 - 192 min
$Ca(OH)_2$ Foulant Feed Rate	1.2 lb/hr
Particle Size Distribution	
(5 Percent)	< 0.5 um
(11 Percent)	0.5 - 1 um
(34 Percent)	1 - 5 um
(34 Percent)	5 - 25 um
(16 Percent)	> 25 um
Gas Composition	
Oxygen, X_{O_2}	0.0308 - 0.176
Carbon Dioxide, X_{CO_2}	0.0152 - 0.0810
Water Vapor, X_{H_2O}	0.0305 - 0.162
Nitrogen, X_{N_2}	0.726 - 0.788

From the JPL tests, Marner and MacDavid conclude (13): 1) increased flue gas velocity produces increased shear stresses on the probe which decreases the fouling thermal resistance, 2) increased probe surface temperatures may, in some cases, bake the foulant onto the probe, which thereby decreases the foulant removal rate and increases the fouling thermal resistance, and 3) if inertial impaction does not dominate the fouling mechanism, then the foulant should deposit evenly around the probe circumference. In that case, the local fouling thermal resistance should approximately equal the average fouling thermal resistance. On the other hand, if inertial impaction dominates the fouling, the largest local fouling resistance will be at the forward stagnation point.

EER Fouling Probe Industrial Tests

Based on the successful JPL laboratory tests, the fouling probe was then tested to determine probe reliability in an industrial environment. For these industrial tests, the Idaho National Engineering Laboratory (INEL) constructed two fouling probes based on the JPL design. JPL was not involved on this test series. The Energy & Environmental Research Corporation (EER), Orrville, Ohio, ran the tests at the Richmond Power & Light Whitewater Unit 2 facility, Richmond, Indiana. DOE selected a boiler plant as the host site because it provided a high-temperature, fouling but comparatively benign industrial environment. The coal-fired boiler produces 540,000 lb/hr of 955°F, 1320 psig steam.

The test plan was designed to benefit from an EPA/EPRI solid sorbent trial concurrently scheduled by EER (15). The injection of the solid sorbent into the boiler, designed to reduce SO_x emissions, would also provide a highly fouling flue gas. Unfortunately, equipment problems prevented the solid sorbent tests from running concurrently with the fouling probe tests. Consequently, the flue gas was relatively clean.

EER tested the fouling probe in November 1988 and January/February 1989. The test port was between the primary and secondary superheaters where the flue gas can reach a maximum of 1900 F. To achieve a representative test, the probe was lengthened to 8 ft. This permitted the probe to reach the center of the duct. The working portion of the probe remained 2 ft long, with the 6 ft extension being insulated. During the November tests, the flue gas temperatures were 1650 - 1700 F, while the January/February tests saw a flue gas temperature of 1430 - 1490 F. The probe inside wall temperature was set at 1100 F for all tests. Regrettably, without the solid sorbent test, the flue gas was moderately clean. The small foulant amount deposited on the fouling probe did not generate a significant fouling thermal resistance. The average heat flux measurement exceeded the local heat flux measurement for all tests conducted. One or both measurements was apparently incorrect. INEL efforts to diagnose and correct the inaccurate probe measurements continue.

The EER fouling probe tests have been valuable shakedown trials. However, INEL must correct the probe before it can generate consistently reliable data. However, EER is enthusiastic about the probe (17). They believe that a commercial fouling probe application may be testing the fouling effects of coal in utility boilers. The probe can detect fouling more rapidly than the boiler steam tubes. A given amount of fouling will compress the tube-side fluid temperature difference of the probe more readily than that of the steam tubes. Therefore, if a utility contemplates changing coal, a short test with the alternate coal will yield fouling probe data to predict fouling effects from the change in fuel.

DOE plans another experimental series to test the fouling probe in a municipal waste incinerator - a high-temperature, highly corrosive, and highly fouling environment. This incinerator test series should correct the heat flux measurement problems noted in the boiler test series. In addition, the probe should yield useful design data for another project - the development of a ceramic heat exchanger for a Brayton-cycle cogeneration system.

FOULING ON ENHANCED HEAT EXCHANGER TUBES

Heat transfer enhancement is the process of improved heat transfer performance (18). Enhanced heat exchanger tubes may possess dramatically superior overall heat transfer coefficients compared to plain tubes. The difference in heat transfer coefficients may even exceed an order of magnitude. Heat transfer enhancement conserves energy by reducing the required temperature difference between the hot and cold streams. Heat transfer enhancement can reduce heat exchanger size or may increase the energy transfer in an existing heat exchanger. Reduced flow of one or both working fluids may also reduce the pumping power (9). Because of the substantial energy conservation potential, the DOE Advanced Heat Exchangers Program is funding two projects to develop and test enhanced heat exchanger tubes. The Rensselaer Polytechnic Institute (RPI) is conducting one project, "Enhanced Shell-and-Tube Heat Exchanger for Industry." Pennsylvania State University is conducting the other project, "Enhanced Tubes for Steam Condensers." These projects address the three major issues obstructing widespread industrial acceptance of enhanced heat exchanger tubes: 1) the inability to predict accurately the overall heat transfer coefficient improvement in an enhanced tube bundle given the performance of the single tube, 2) the inability to predict accurately the fouling effect on the enhanced surfaces, and 3) the inability to predict the enhanced surface effect on the boiling of a multicomponent mixture (19,20).

RPI, in cooperation with Wolverine Tube Inc. and Linde Division of the Union Carbide Corp., is investigating the shell-side boiling characteristics of two types of enhanced heat exchanger tubes with structured surfaces, the Linde High Flux tube and the Wolverine Turbo-B. Although both tubes are marketed now, industrial use is hindered because tube performance is not fully understood. RPI will initially screen single tube performance in pool boiling. RPI will then measure tube performances, to include heat transfer coefficients, in several horizontal tube bundles for both pool and forced convective boiling. The shell-side fluid will initially be pure refrigerant R-113. Subsequent experiments will include several binary mixtures of R-11 in R-113. RPI will then model the improved enhanced tube bundle performance in a kettle reboiler. The fouling work in this project is discussed below. This project should accelerate acceptance of heat exchanger tubes with structured surfaces, particularly in the chemical process and refrigeration industries.

Pennsylvania State University, in cooperation with Wolverine Tube Inc., is performing theoretical and experimental work intended to show that enhanced tubes can be successfully used in industrial steam condensers. The tubes will have enhanced surface geometries on both the steam and water sides. One of the candidate shell side enhancement geometries being evaluated for Cu/Ni and Ti tubes is shown in Figure 5. It is an integral fin tube with 19 fins/in. and 0.02 in. fin height. Figure 6 shows one of the candidate tube side enhancement geometries. This consists of a three dimensional array of protrusions on the inner tube surface. These protrusions would be formed in the Figure 5 finned tube by applying local tooling pressure on the outside of the tube. Control of water side fouling is a critical project issue and will be discussed below. This project promotes the introduction of enhanced heat exchanger tubes into industrial steam condensers, particularly in the electric utility industry.

Heat transfer enhancement has been systematically studied for over 25 years. Still, this subject is not well understood for many important enhancement techniques and heat transfer modes. One major technical obstacle is the understanding and the mitigation of fouling on an enhanced heat exchanger tube. As Professor A. E. Bergles, RPI, observes, "Fouling remains one of the unresolved problems in heat transfer. Since pure, clean fluids are rarely used in industrial practice, it is important to have the fouling characteristics of enhanced surfaces. In many cases, modest fouling can wipe out the high coefficients brought about by enhancement."(18)

RPI fouling research will afford a quantitative understanding of oil/R-113 fouling on the High-Flux and Turbo-B structured boiling surfaces. The research team selected oil as one foulant because oil/refrigerant contamination is the major fouling concern in the refrigeration industry. Tap water is the other fouling fluid under investigation. As the intermediate research goal, RPI will qualitatively identify the significant parameters influencing the shell-side fouling rate on the structured surfaces. A second experimental series will then systematically investigate the surface mechanism of fouling. This second experimental series, to include analytical modeling, will result in a quantitative understanding of fouling on a structured surface.

The initial, qualitative, experimental series examines the relationship between the structured surface and fouling. The test matrix contains: 1) three different pore sizes, 2) two different structured surfaces (High-Flux and Turbo-B), and 3) two different fouling fluids (oiland tap water). The test apparatus pertains to pool boiling, Figure 7.

After the research team qualitatively understands the fouling rate as a function of the structured surface and the fluid composition, the quantitative experimental series will commence. The RPI team will construct a large artificial cavity to simulate the structured surface of the heat exchanger tube. The initial foulant transport rate and attachment to the clean surface will be measured as a function of fluid composition and surface temperature. As the initial foulant layer blankets the clean surface, the surface characteristics alter. The surface affecting the fouling rate is now the upper foulant layer at the solid/liquid interface. The fluid observes an altered surface and consequently changes the fouling rate. The RPI test apparatus will permit measurement of the fouling rate as a function of the changing surface parameters. The research team anticipates using the results to construct a phenomenological model. The model will predict the shell-side fouling rate on the two structured surfaces in both a R-113/oil fluid and in tap water. It should also lead to a better understanding of fouling on structured surfaces in general. Experimental results are not yet available. The project is scheduled to conclude in September 1990 and a final report will be published at that time.

Pennsylvania State University is currently examining fouling on the tube side of enhanced steam condenser tubes. Figure 6 shows the water side enhancement geometry, on which particulate and biological fouling tests are being conducted. This enhancement consists of a three dimensional array of protrusions 0.015 in. high. Uncontrolled fouling quickly negates any improvement in the heat transfer coefficient from the enhanced tubes. The fouling apparatus circulates tap water through the test tubes under conditions that simulate those of a utility steam condenser. The equipment condenses R-114 on the outside of an 8 ft long 7/8 in OD enhanced tube. Figure 8 illustrates the apparatus. The test water is contaminated with particulate or biological organisms to cause accelerated fouling. The fouling resistance of the enhanced tube is measured as a function of time and compared with that of a plain tube. Once the effect of the tube-side enhancement on the fouling rate is established, the research team will attempt to mitigate the fouling with a sponge rubber ball cleaning device. This technique is effective in mitigating fouling in plain steam condenser tubes. The sponge rubber balls will enter the circulating fouling water and the cleaning effect on the fouling will be measured. Experimental results are not yet available. The project is scheduled to conclude in September 1990 and the final results will be published at that time.

SUMMARY

This paper has provided a review of the projects sponsored by the DOE Advanced Heat Exchanger Program in heat exchanger fouling. Substantial national energy losses are caused by heat exchanger fouling. The annual (1982) cost to U. S. industry of heat exchanger fouling was estimated at $9 billion or 2.9 Quads. Industrial heat exchanger fouling is far too complex to lend itself to a panacea. Progress in this field must be measured in slow, determined steps. Although the problem may seem intimidating, the opportunity for significant national energy conservation exists. Therefore, DOE will continue to work with industry and academia to reduce these energy losses to industry.

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