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ABSTRACT

Fouling is a complex phenomenon that (1) encompasses formation and transportation of precursors, and (2) attachment and possible removal of foulants. A basic understanding of fouling mechanisms should guide the development of effective mitigation techniques. The literature on fouling in complex flow passages of compact heat exchangers is limited; however, significant progress has been made with enhanced tubes.

INTRODUCTION

Compact heat exchangers and enhanced tubes are being increasingly used in the process, refrigeration, and utility industries. Plate-frame heat exchangers were developed primarily for single-phase applications in food processing, because they can be opened for routine cleaning and examination. The refrigeration industry was the major user of enhanced tubes, excluding finned tubes for air and gas applications. Fouling has been considered to be one of the major barriers to wide application of compact heat exchangers and enhanced tubes. As a result, these technologies were primarily considered for nonfouling conditions. We believe that the economic advantages, design flexibility, potential for eliminating process bottlenecks, and improved understanding of fouling mechanisms associated with compact heat exchangers and enhanced tubes will encourage other industries to use them. In the present review, the state of our knowledge about fouling in compact heat exchangers and enhanced tubes is examined. The key aspects of fouling mechanisms, threshold fouling conditions, and the effectiveness of mitigation techniques are discussed. Appendix A lists relevant literature on fouling in compact heat exchangers and enhanced tubes.

FOULING MECHANISMS

Major fouling mechanisms and the effects of two key parameters are summarized in Table 1. The interactive effects of transport of fouling precursors, chemical reactions, phase separation of insoluble salts or polymeric substances, and attachment of foulants to the tube wall are difficult to assess for many industrial fluids. Therefore, the designers and operators of heat exchangers are reminded to evaluate the effects of velocity and temperature together. On the basis of fouling data for plain tubes, wall shear rather than velocity should be used as a controlled parameter to evaluate the fouling propensity. The concept of threshold fouling conditions is being investigated, and the relationship between wall shear and wall temperature is being developed for precursors generated by chemical reactions, such as petroleum fluids and food products.

Table 1. Fouling Mechanisms and the Effects of Physical Parameters on the Fouling Propensity

Fouling Mechanisms	Parameters	Effects on Fouling Propensity
Biofouling	Temperature	High between 20 and 35 °C
	Velocity	Complex dependency
Particulate fouling	Temperature	↑ T ↓ weak deposits
	Velocity	↑ V ↓ asymptotic
Crystallization (scaling)	Temperature	↑ T ↑ inverse solubility
	Velocity	↑ V ↓ asymptotic
Chemical reaction	Temperature	Complex dependency
	Velocity	Complex dependency

Most heat exchangers are designed on the basis of the fouling resistance from one of the standards, such as TEMA (Tubular Exchanger Manufacturers Association). We believe that heat exchangers should be designed on the basis of the fouling rate, maintaining the thermal performance to meet the process requirements. Values from the standards developed for plain tubes cannot be directly used for compact heat exchangers. If someone does, the economic advantages of compact heat exchangers will quickly

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diminish. A brief summary of the recommended fouling resistance for plate heat exchangers (PHE) vs. TEMA standards is shown in Table 2.

Table 2.
Recommended Fouling Resistance vs. TEMA Values

Process Fluid	R_f – PHE m^2 / K kW	R_f - TEMA m^2 / K kW
Water		
Soft	0.018	0.18-0.35
Cooling tower water	0.044	0.18-0.35
Seawater	0.026	0.18-0.35
River water	0.044	0.35-0.53
Lube oil	0.053	0.36
Organic solvents	0.018-0.053	0.36
Steam (oil bearing)	0.009	0.18

COMPACT HEAT EXCHANGERS

The basic compact heat exchangers that are commercially available are the plate-frame (gasketed, welded, and brazed), plate-fin spiral, and printed-circuit types. These heat exchangers are used for single-phase as well as phase-change applications. Plate-frame, plate-fin, and spiral heat exchangers are commercially manufactured. Printed-circuit heat exchangers have niche applications, such as oil cooling on offshore platforms.

Fouling Characteristics

The fouling characteristics for each type of heat exchanger depend on the fouling mechanism and flow-passage geometry. A summary is provided here for the three leading compact-heat-exchanger types.

Plate-frame heat exchangers. Complex flow passages are perceived to have high fouling propensity. For some applications, less fouling was observed in plate-frame heat exchangers than in the shell-and-tube type. A basic understanding of fouling mechanisms should help in selecting the optimal plate configuration. The observations described below should provide some general guidelines.

Crystallization Fouling:

- Reduced fouling rate is typical due to combined effects of lower wall temperature and higher wall shear.
- Inlet and outlet flow distributors are prone to foul.

Biofouling:

- Fouling is minimal with appropriate on-line application of control measures, such as chlorination at the level used for plain tubes, or lower.
- Clean-in-place should be planned.
- Macrofouling in the manifold should be avoided because macrofouling can block flow passage, resulting in flow maldistribution (an observation port is recommended).
- Location of major fouling can change from summer to winter operation due to changes in water temperatures and biological activities.

Food Processing:

- Extensive data are available.
- Fouling deposition generally starts from the top, hot end and spreads downward.
- Controlling the wall temperature is a key to minimizing fouling.

Petroleum Fouling (welded plates):

- Lowering the wall temperature and increasing the wall shear reduces fouling in hydrotreating of gas oil.
- Deposit products can be cleaned with steam decoking.

Plate-fin heat exchangers. With fouling conditions, the plate-fin aluminum heat exchangers should have extruded multi-channel flow passages. Finned surfaces can then be used with nonfouling fluids for single-phase as well as phase-change applications. Some general observations follows.

Biofouling:

- Biofouling in rectangular flow passages can be controlled similar to that in a tube.
- Finned geometry is not recommended for water service because cavities may cause microorganism-induced corrosion (MIC).

Particulate Fouling:

- Wavy fins tend to have greater deposition propensity than straight fins.
- Deposition rates increase with velocity for straight fins and remain constant for wavy fins.

Biofouling and Particulate Fouling:

- Wavy fins seem to promote clay-type deposition.
- Pressure drop increases linearly for straight fins, while it reaches toward an asymptotic value for wavy fins.

Chemical Reaction:

- Plate-fin geometry can provide uniform temperature distribution and reduced dryout in reboiler applications.
- Plate-fin heat exchanger is used effectively as a reboiler in ethylene plants.

Spiral heat exchangers. Cross-flow configuration provides easy access to flow passages for cleaning. Fouling mitigation applicable to tubular geometry can be used for spiral heat exchangers. Spiral passages provide secondary flows which have shown to reduce fouling. However, flow passages can not be accessed, and clean-in-place should be planned.

Fouling Mitigation and Design Guidelines

Design and operation guidelines should be developed for fouling mitigation, because compact heat exchangers are increasingly being used under fouling conditions. Some of the design and operation features are summarized as follows:

- Design and operate units below threshold fouling conditions, such as solubility limits of calcium salts.
- Provisions should be made for clean-in-place operation.
- Fouling tends to begin in inlet or outflow distribution sections in plate-frame and plate-fin heat exchangers. Low-pressure-drop distribution sections are recommended for fouling conditions.
- Provisions should be made to clean inlet and outlet ports for plate-frame heat exchangers without opening the heat exchanger. Opening plate-frame heat exchangers for routine cleaning is not an option in most applications, except in food processing.
- Petroleum deposits can be removed from plate-frame heat exchangers by steam-air decoking.
- Extruded flow passages are recommended for high-fouling process streams in plate-fin heat exchangers.
- New mitigation techniques, such as pulse flow, should be developed for compact heat exchangers with complex, narrow flow passages. Pulse flow is also expected to increase the effectiveness of chemical cleaning methods.

ENHANCED TUBES

Enhanced surfaces can be applied to one side or both sides of tubes. The major categories of enhanced tubes being used by the industry are spirally indented, spirally finned/ribbed, low-fins outside, spirally fluted, axially fluted, and tube inserts. Spirally indented, finned, and fluted tubes are used for both single-phase and phase-change applications. Tube inserts are now being promoted for fouling mitigation in the refining industry.

The interactive effects of fouling and enhancement mechanisms determine the fouling propensity of enhanced tubes. The major enhancement mechanisms are (1) boundary-layer disruption, (2) swirling or secondary flows, (3) improved distribution of liquid and vapor phases, and (4) surface-tension-induced condensation and evaporation. The influence of enhanced surfaces on transport processes, shear-stress distribution, secondary flows in the vicinity of walls, phase distribution in multiphase flows, and wall temperature can alter the fouling process. Depending on the controlling step(s) for a given fouling mechanism, enhancement could increase or decrease the fouling rate. Moreover, enhanced surfaces may alter threshold fouling condition(s) and thereby expand operating conditions without a significant increase in fouling propensity.

Design Standards

Design standards are commonly used to obtain the fouling-resistance values for shell-and-tube heat exchangers. The same standards are also applied to design a heat exchanger with enhanced tubes. If fouling resistance is unrealistically high for a given fluid, the thermal and economic advantages of enhanced tubes are diminished. Some common standards that recommend design fouling-resistance values are the Tubular Exchanger Manufacturers Association (TEMA), the Heat Exchange Institute (HEI), the American Petroleum Institute (API), and the Air Conditioning and Refrigeration Institute (ACRI). Using values from these standards is a "safe" practice for the rating engineer. However, it is our judgment that these design fouling-resistance values have very little to do with actual fluid fouling characteristics. The standards do serve a very useful function: they guarantee that a similar percentage of additional heat transfer surface area is added to account for uncertainties in the heat-transfer prediction methods. If the standards truly represented the fouling characteristics, they would suggest fouling-resistance values of similar magnitudes for similar applications. In the example that follows, the values for the above four Standards differ by a factor of 30. The design fouling resistance for a cooling-water application varies from 0.05 to 0.72 m^2K/kW for the same tube-side velocity and water and heating-medium temperatures. Such discrepancies clearly demonstrate that the recommended values from the standards are not based solely on cooling-water fouling characteristics. A similar situation prevails with respect to petroleum products.

Fouling Characteristics

The major observations made are summarized below.

Biofouling:

- Fouling rates for spirally indented and spirally fluted tubes are comparable with those for plain tubes for moderate- fouling cooling waters.
- For waters containing high concentrations of microorganisms and nutrients, fouling rates for enhanced tubes are greater. However, for such fouling

conditions, some kind of fouling control methods would be used for both plain and enhanced tubes. In that case, the effective fouling rates are comparable.

- The increase in pressure drop for enhanced tubes due to fouling is generally less than that for plain tubes. However, the pressure drop for enhanced tubes is greater than that for plain tubes.

Crystallization Fouling:

- Higher heat-transfer coefficients lower the wall temperature and thereby reduce the fouling propensity.
- Asymptotic fouling-resistance values for finned and spirally indented tubes can be comparable with or lower than those for plain tubes, depending on fouling propensity of the fluid. Uneven deposition on enhanced surfaces tends to make deposits weaker than those on plain tubes.
- Axially fluted tubes are commonly used for multi-effect desalination, where salt deposition is chemically controlled.

Particulate Fouling:

- For low particulate concentrations and moderately high Reynolds numbers, fouling rates for plain and spirally indented tubes are comparable.
- For high concentrations and low Reynolds numbers, the rate of fouling for enhanced tubes can be significantly higher.
- Preferential deposition occurs, with high deposition in recirculation zones.

Chemical Reaction:

- Tube inserts of different types are used to mitigate fouling in petroleum processing. The increase in wall shear and reduction in wall temperature by the enhanced heat-transfer coefficient are primary reasons for reduced fouling rates.
- Spirally indented tubes reduce the fouling rate in petroleum processing, even with the same wall temperatures as those for plain tubes.
- Enhanced tubes have been shown to increase the fouling rate where diffusion of dissolved metals is believed to induce organic-fluid fouling.
- Uneven distribution of deposits from chemical reactions is expected; the extent depends on temperature and wall shear-stress distribution.

Fouling Mitigation and Design Guidelines

The development of mitigation techniques and proper design guidelines are key to industrial applications of enhanced tubes. We believe that with adequate designs, enhanced tubes can be used for low to moderate fouling conditions and can yield significant cost savings because of their high thermal performance. Some of the mitigation and design guidelines are as follows:

- The design method should follow three basic guidelines:
  1. Select the appropriate enhanced type for the particular fouling conditions,
  2. Conduct performance analysis for both clean and fouled conditions, and
  3. Provide methods for mitigation and cleaning.
- Uneven distribution of fouling deposition is expected. The effects of uneven distribution of the fouling deposits on the enhancement mechanism are not fully understood. In general, smoother enhancement profiles, similar to the spirally indented type, are recommended.
- Spirally indented tubes have been shown to be cleanable with hydrojets and brushes. Chemical cleaning is also effective for cooling-water applications.
- For spirally indented tubes, on-line sponge-ball cleaning maintains low fouling for cooling-water applications; however, long-term effectiveness has not been demonstrated.
- The interactive effects of wall temperature and wall shear stress should be examined for installing tube inserts in an existing tube bundle.
- Internally enhanced tubes and tube inserts tend to redistribute vapor and liquid phases for phase-change applications. In general, these enhancement devices reduce possible dryout and thereby reduce fouling in high-quality regions. This is particularly important for mixtures of hydrocarbons that have a wide boiling range.

SUMMARY

1. The interactive effects of fluid dynamics, heat/mass-transfer processes, and precursor formations determine the fouling propensity of compact heat exchangers and enhanced tubes.

2. Design and operation guidelines should be developed for application of compact heat exchangers and enhanced tubes in process industries with high-fouling conditions.

3. Compact heat exchangers and enhanced tubes are expected to show significant advantages for many industrial applications, provided that heat exchangers are designed on the basis of fouling rates rather than fixed values of the fouling resistance and different design options are compared on the basis of the total life-cycle costs instead of capital costs.

APPENDIX A

Relevant Literature

Plate-Frame Heat Exchangers

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