

DEP SPECIFICATION

FOULING MARGINS IN TUBULAR HEAT EXCHANGER DESIGN

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DESIGN AND ENGINEERING PRACTICE



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1. INTRODUCTION

1.1 SCOPE

This DEP specifies the practices to be followed during the design of tubular heat exchangers to provide allowances for fouling. The methodology and recommended margin values in this practice are based on experiences with a variety of fluids, for a wide range of flow velocities, operating temperatures, and fluid qualities like particulate content and corrosivity. The approach also includes ideas based on recent published work performed outside of Shell by organizations like HTRI (Heat Transfer Research, Inc.) and IHS ESDU International.

Values of allowances specified in this document should be suitably modified when a facility has specific experiences that are largely different.

This is a revision of the DEP of the same number dated December 1998; see [1.5] regarding the changes.

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This DEP is intended for use in facilities related to oil and gas production, gas handling, oil refining, chemical processing, gasification, distribution and supply/marketing. This DEP may also be applied in other similar facilities.

When DEPs are applied, a Management of Change (MOC) process should be implemented; this is of particular importance when existing facilities are to be modified.

If national and/or local regulations exist in which some of the requirements could be more stringent than in this DEP, the Contractor shall determine by careful scrutiny which of the requirements are the more stringent and which combination of requirements will be acceptable with regards to the safety, environmental, economic and legal aspects. In all cases the Contractor shall inform the Principal of any deviation from the requirements of this DEP which is considered to be necessary in order to comply with national and/or local regulations. The Principal may then negotiate with the Authorities concerned, the objective being to obtain agreement to follow this DEP as closely as possible.

1.3 DEFINITIONS

1.3.1 General definitions

The **Contractor** is the party that carries out all or part of the design, engineering, procurement, construction, commissioning or management of a project or operation of a facility. The Principal may undertake all or part of the duties of the Contractor.

The **Manufacturer/Supplier** is the party that manufactures or supplies equipment and services to perform the duties specified by the Contractor.

The **Principal** is the party that initiates the project and ultimately pays for it. The Principal may also include an agent or consultant authorised to act for, and on behalf of, the Principal.

The word **shall** indicates a requirement.

The word **should** indicates a recommendation.

1.3.2 Specific definitions

Term	Definition
Fouling Margin	The percent of excess surface area included in the design to enable the heat exchanger to perform the required heat duty in a fouled condition. Traditionally this margin has been provided by using design fouling resistances, which result in excess surface area.
Design Fouling Resistance	A measure of the ultimate additional resistance to heat transfer caused by deposits on the heat transfer surface. The deposits may include a corrosion layer on the tube surface(s). The ultimate resistance depends on the type of fluid, the presence of particulates and contaminants, the heat-transfer surface material, the temperature conditions, the flow velocities and the operating period between two successive cleaning actions. It is commonly denoted by the symbol R_f and has the units $[m^2 \cdot K/W]$
Fouling Coefficient	The reciprocal of the fouling resistance. NOTE: The use of the fouling coefficient has generally been abandoned, since it tends to be confusing that an increase in fouling results in a decrease in the fouling coefficient.

1.4 CROSS-REFERENCES

Where cross-references to other parts of this DEP are made, the referenced section number is shown in brackets. Other documents referenced by this DEP are listed in (4).

1.5 SUMMARY OF MAIN CHANGES

This DEP is a revision of the DEP of the same number dated December 1998.

This revision incorporates a major design methodology change by applying fouling margins, based on experience, and coupled with good design practices instead of using fouling resistances. A summary of the main, non-editorial changes since the last revision of this DEP are as follows:

Old section	New section	Change
TITLE	TITLE	Changed from FOULING RESISTANCES FOR HEAT TRANSFER EQUIPMENT to FOULING MARGINS IN TUBULAR HEAT EXCHANGER DESIGN
1.3.2	1.3.2	Added definition of fouling margin.
2		Old section APPLICABILITY AND BASIS OF DATA replaced with new section BASICS OF USING A FOULING MARGIN.
3		Old section APPLICATION OF LOWER FOULING RESISTANCES replaced with new section RECOMMENDED DESIGN METHODOLOGY.
4		Old section 5 REFERENCES renumbered to new section 4.

Old section	New section	Change
TABLES		Old section 4 FOULING RESISTANCE TABLES (1-22) replaced with Tables 1A and 1B defining fouling levels as very low, low, medium, high, or severe. Table 2 added to specify the amount of margin for fouling. Table 3 added for recommended minimum liquid velocities. Table 4 added to specify pressure drop multipliers. Old Table 1-1 for tube side cooling water velocities renumbered as Table 5. Old Table 1-2 Cooling Water Frictional Pressure Drop deleted.

1.6 COMMENTS ON THIS DEP

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1.7 DUAL UNITS

In this DEP, the International System of units (SI) shall be understood to prevail over US Customary (USC) units. USC units are provided in brackets following the SI units for information.

2. BASICS OF USING A FOULING MARGIN

2.1 DEFINITION OF FOULING MARGIN

Margin is defined as the heat transfer surface area in excess of what is required by a heat exchanger to perform the design heat duty. The margin can be for fouling or for other uncertainties in the design such as fluid properties or variable process conditions.

In terms of the overall heat transfer coefficients (U), the definitions are:

U_{clean} is the overall heat transfer coefficient as determined by the individual stream heat transfer coefficients and tube metal resistance, with no allowances included for fouling

U_{fouled} is the overall heat transfer coefficient, as determined by the individual stream heat transfer coefficients, tube metal resistance, plus the additional resistance as allotted for fouling (either as margin or as an additional resistance as described in [3.2].

U_{required} is the minimum overall heat transfer coefficient that is required for the heat exchanger to satisfy the prescribed process duty condition with the fixed heat transfer surface area which has been provided.

$$\text{Fouling Margin} = 100 * (U_{\text{clean}}/U_{\text{fouled}} - 1)$$

$$\% \text{ Overdesign} = 100 * (U_{\text{fouled}}/U_{\text{required}} - 1)$$

$$\% \text{ Total Excess Area} = 100 * (U_{\text{clean}}/U_{\text{required}} - 1)$$

where the clean, fouled (as calculated during design), and required coefficients are in the order:

$$U_{\text{clean}} \geq U_{\text{fouled}} \geq U_{\text{required}}$$

2.2 DEFINITION OF FOULING

In general, fouling is the process of deposition/accumulation of an undesired layer of solids on a heat transfer surface. The heat transfer resistance of this deposit is the fouling resistance. Fouling resistance is equivalent to deposit thickness divided by deposit thermal conductivity. Accumulation can happen due to deposition of particles carried with the fluid (such as catalyst in slurry), formation and sticking of solids due to chemical reactions (such as coke formation, polymerization, salt precipitation), corrosion of the tube surface itself, and a few other reasons.

2.3 HOW THE MARGIN IS PROVIDED AND SPECIFIED

There are two primary approaches to providing fouling margin during the design. The first approach is to assign a value of fouling resistance (called *fouling factor*) to each fluid using either field derived values or standard tables such as in the previous version of this document. The second approach is to design the exchanger without using fouling resistances but to instead add surface area to the design in terms of % Excess Area for Fouling (see definition above). The latter approach has commonly been used for non-tubular heat exchangers for more than 20 years.

The advantages of the first approach, especially if field derived values are used, is that the margin reflects the observed ultimate fouling resistance for that exchanger. The disadvantage is that there is no control over how much excess surface is being provided. The same values of fouling resistances might result in 15% excess surface for one design and 80% in another. Additionally, this method usually does not take into account operating conditions which commonly affect the rate of fouling, such as velocity, surface temperature, heat flux, or whether the fluid is on the shell side or tube side. The method may also penalize designs which are targeted at reducing fouling, for example through higher velocities. The fouling resistances used in the previous version of this document are included in Table 1B.

The second approach has the advantage of giving the designer control over the % excess area for fouling (with consideration for variables such as different velocities), but little guidance exists regarding how much this percentage should be and how it should be added

to the exchanger. For example, in a shell-and-tube heat exchanger (STHE) this margin can be provided by increasing the shell size, or tube length, or any combination of the two.

Both approaches have the inherent disadvantage that they have typically ignored the time element in fouling. Although the definition in [1.3.2] mentions that the resistance should depend on the time interval between two successive cleaning actions, standard tables contain no reference to this interval.

Two other aspects of the first approach are that fouling resistances are used for every fluid, regardless of whether it fouls, and, often an excessive amount of overdesign resulting from the assumed fouling resistances is accepted as a way to account for other design uncertainties.

2.4 PENALTIES FOR EXCESSIVE MARGIN

In addition to the obvious higher cost of larger exchangers (capital cost, weight, plot space, maintenance cost), oversized exchangers can also create operational problems. This applies whether the margin is provided to protect against fouling or for other reasons. A few examples are:

If extra surface area is incorporated by increasing the shell diameter, it can lead to lower velocities both on the shell and tube sides, which can accelerate fouling.

An oversized reboiler may provide excessively high heat duty in the clean condition, leading to film boiling and associated problems of low coefficients, dry wall situations and control problems.

An oversized condenser where too much cooling of the hot side is undesirable might need to be controlled by reducing cooling water flow leading to accelerated fouling on that side. Or, the control might be achieved by shutting off one of two or more parallel exchangers, leading to high shell side flow in the operational shells and possible vibration failures.

Where bypass control is used to control the process outlet temperature, an oversized exchanger can experience a large percentage of bypass at start-up or any time when the exchanger is in the clean condition, leading to low velocities through the side of the exchanger being bypassed. Accelerated fouling can result when the side being bypassed is a fouling fluid.

An oversized steam heated exchanger can have control problems, water hammer and flange leaks due to high levels of subcooled condensate.

2.5 EFFECT OF FOULING ON PRESSURE DROP

Since a fouling deposit creates reduced cross sectional area for flow, and at the same time often increases the surface roughness (and therefore the friction factor), the pressure drop at a fixed flow rate in a heat exchanger increases with fouling, or the flow rate might have to be reduced to stay within a pressure drop limit. Either situation could be unacceptable for operation, so an appropriate pressure drop margin should be provided in the hydraulic design of the overall system.

How to address pressure drop during design is discussed later in this document.

3. RECOMMENDED DESIGN METHODOLOGY

3.1 SEPARATE THE FOULING MARGIN FROM OTHER MARGIN REQUIREMENTS

Process considerations like uncertainties in operating conditions, physical properties, future expansions, and the state of upstream equipment might require a process design margin to be added to a heat exchanger. The process design margin should be included in the design process duty condition by the process designer. This design condition is usually established through the inclusion of an additional percentage applied to heat duty and stream flow rates or as a different set of outlet conditions, as opposed to an arbitrary margin on surface area alone which does not assure that such a heat duty can be achieved. The margin provided for fouling should be kept separate from any process margin. The fouling margin to be applied shall be based solely on the expected fouling propensity of the fluids; it shall not be arbitrarily increased to account for other design margins to be applied.

3.2 DESIGN PHILOSOPHY

Tables 1A and 1B categorize fluids into five fouling levels – Very Low (V), Low (L), Medium (M), High (H), and Severe (S).

For heat exchangers where both fluids fall under the V, L, or M categories, the heat exchanger sizing shall be determined based upon the fouling margin (value selected from Table 2) and no fouling resistance values shall be used. In no case, however, shall the resulting total equivalent fouling resistance (see [3.3.2]) be less than $0.17 \times 10^{-3} \text{ m}^2\text{-C/W}$ for carbon and low alloy steel tube materials or less than $0.088 \times 10^{-3} \text{ m}^2\text{-C/W}$ for high alloy and non-ferrous tube materials.

If one or both fluids are in the H or S category, then fouling resistance values from Table 1B shall be used for both streams. However, the excess area resulting from the use of these resistances shall not exceed 50% for shell and tube heat exchangers and 30% for air cooled heat exchangers. Designs with greater than these maximum excess area percentages for fouling shall be reviewed with the Principal.

The fouling margin is added as an “overdesign” for the reference design case, which is equivalent to having that amount of excess surface area and therefore translates to the difference between the “Actual” and “Required” overall heat transfer coefficients.

The fouling margins apply to shell and tube heat exchangers regardless of which side the fluid is on and for air-cooled heat exchangers on the tube side.

The detailed design of the exchanger geometry shall attempt to minimize fouling by satisfying the requirements of this DEP. For example: achieve the highest practical velocities for liquids; ensure that sufficient pressure drop is made available and maximize its use to obtain required velocities for medium/high/severe fouling services; avoid fouling threshold wall temperatures; and minimize dead zones on the shell side. Further, materials should be selected to minimize corrosion in problematic fouling services with a strong dependency on surface corrosion within the heat exchanger. Design practice requirements to minimize fouling are explained in the next section. Detailed guidance can be obtained from the Principal's heat transfer specialist

When the fouling margin in Table 2 is used and the good design practices to minimize fouling [3.5] are satisfied, the expectation is that the required heat exchanger cleaning time intervals will be reasonable when the overall economic total life cycle maintenance costs are considered.

The designer should also investigate the use of enhanced heat transfer technologies (EHT), including non-tubular exchangers, to most effectively minimize and/or address fouling. Guidance on use of EHT can be obtained from the Principal's heat transfer specialist or the EHT website (see References), and the final selection shall be approved by the Principal.

Experience shows that using higher fouling margins than shown in Table 2 commonly results in larger heat exchangers that provide little benefit in terms of extended cleaning frequency, improved thermal performance, or avoiding pressure drop limitations.

Since fouling usually obstructs flow paths and consequently increases pressure drop, a fouled exchanger will have a higher pressure drop than a clean one at the same flow rate. Therefore, the calculated clean pressure drops on both sides shall be multiplied by the factors shown in Table 4 to establish the pressure drops that shall be used in system hydraulic calculations such as pump sizing and cooling water flow balances.

3.2.1 Design and specification methodology

To use the fouling margin approach (V, L, or M streams on both sides), a zero fouling resistance shall be input to the design computer program and the surface area in the design shall be set such that the program reports a "% overdiseign" equal to or slightly greater than the fouling margin indicated by Table 2. The U_{actual} for the final design shall exceed U_{required} by the appropriate fouling margin. Note that since no fouling resistances are used, the design will have $U_{\text{actual}} = U_{\text{clean}}$. U_{required} is sometimes called U_{service} . The good design practices in [3.5] are required to deliver the premised most overall cost effective approach to reliable heat exchanger design.

U_{fouled} is the expected value of the overall heat transfer coefficient when the design fouling level is reached. Therefore, in designs with no margin other than fouling, $U_{\text{fouled}} = U_{\text{required}}$, within the small error due to the fact that there will not be an exact match to the values in Table 2.

The % overdiseign for fouling will be in addition to other margins that might be required [see 3.1].

3.2.2 Example of fouling margin design methodology

The following example shows the relationships of the various quantities, and design methodology using the formulas from Section 2.1:

Assume that a 15% fouling margin is required along with a 5% process margin on heat duty and flow rates.

Heat Duty = 12.381 MW x 1.05 = 13.0 MW, Mean Temperature Difference = 65 Deg. C

Suppose that for a specified heat exchanger geometry with a surface area = 643 m², the heat exchanger design program calculates;

$$U_{\text{required}} = \text{Heat Duty} / (\text{MTD} * A) = (13,000,000) / (65 * 643) = 311 \text{ [W/m}^2\text{-C]}$$

Then U_{clean} for this exchanger geometry must, as a minimum, provide an overdiseign equal to the fouling margin of 15%:

$$U_{\text{clean}} \geq (15/100 + 1) * 311$$

$$U_{\text{clean}} \geq 358 \text{ [W/m}^2\text{-C]}$$

If the heat exchanger design program, for example, predicts an actual clean overall heat transfer coefficient, U_{clean} , equal to 370 [W/m²-C] for the exchanger geometry, then the overdiseign requirement has been satisfied. If the predicted U_{clean} is $\leq$ 358 [W/m²-C], then the heat exchanger designer must modify the exchanger geometry, calculating a new U_{required} and U_{clean} until the condition is satisfied.

The final design margin (or excess surface) can be expressed as a Differential Resistance:

$$\text{The Total Equivalent Fouling Resistance} = 1/U_{\text{required}} - 1/U_{\text{clean}} = 1/311 - 1/370 = 0.000513 \text{ [m}^2\text{-C/W]}$$

Thus, the design is equivalent to a design with a total (hot side plus cold side) fouling resistance, or fouling factor, of 0.000513 [m²-C/W], with the 5% process margin applied to the heat duty and flow rates.

To complete the Shell EDRS, calculate U_{fouled} to match the fouling margin as above and enter on the EDRS.

$$U_{\text{fouled}} = 370 / (15/100 + 1) = 322 \text{ [W/m}^2\text{-C]}$$

Appendix 2 shows changes to the existing EDRS using the Shell & Tube EDRS as an example.

3.2.3 Cooling water heat exchangers

For cooling water service, tube material, wall temperature, and velocity should be used in selection of appropriate methodology for margins. In general, these exchangers have a very high heat transfer coefficient on the water side. When there is a relatively high coefficient on the other side, the use of a margin from Table 2 might result in an equivalent resistance that is too low compared to what is historically observed for these services.

When good design practices have been followed [3.5], minimum velocities are maintained (Table 5), and cooling water bulk and wall temperatures [3.5.2] are below recommended limits for cooling waters listed under the L or M fouling levels (Table 5), then the Table 2 margins are expected to be adequate. Corrosion resistant metallurgies such as Titanium further control the fouling mechanisms and lessen the need for high margins.

However, in cases where the water side falls under the H level, the design should be done using fouling resistances from Table 1B for both sides. If the fouling margin provided by these resistances exceeds 50%, the design shall be reviewed by the Principal.

The minimum and maximum velocities and maximum wall and bulk temperatures of Table 5 shall be satisfied for the design case conditions.

3.2.4 Other considerations

Additional considerations should be given during the design to facilitate cleaning of high and severe fouling category fluids. These include: bundle designs with 1" or larger straight tubes for tube side fouling and square tube layouts for shell side fouling, isolation valves and bypasses so that exchangers can be removed from service on the run for cleaning, and the use of installed spares where taking an exchanger out of service has a significant impact on operations.

If a new process unit has to be designed to be run without interruption to the heat exchangers for cleaning, spare exchangers might have to be provided so that the required duty can be maintained while one exchanger is out for cleaning. A spare can be avoided if it is acceptable to bypass a heat exchanger and operate with a reduced duty or throughput for a short time. Experience has shown that solely using higher fouling margins is unlikely to provide the necessary extra run length.

Sometimes it may be advantageous to specify a lower fouling margin if a reduced period between two successive cleanings is feasible. A lower fouling margin can also be achieved with the installation of an installed spare enabling cleaning at any time without shutdown. Alternatively, the design can incorporate parallel exchangers which can be isolated individually. In such an arrangement, one exchanger can be cleaned while running with reduced throughput. Prudent combination of one of these approaches with a fit-for-purpose monitoring program can provide significantly more cost effective CAPEX and operations and carbon and energy management performance.

If it is necessary to calculate tube wall temperatures at design conditions, then after the design is finalized the fouling margin should be converted to an equivalent resistance, as shown in [3.3.2], and that value should be used in the calculation of wall temperatures in the fouled condition.

3.3 PRESSURE DROP CONSIDERATIONS

For any design at a given flow rate, the hydraulics of the system determine the maximum pressure drop that can be consumed by the heat exchanger. This maximum pressure drop is that which may be achieved in the fouled condition, and shall be specified by the process engineer as the "allowable" pressure drop (ΔP_{allow}) on the heat exchanger data sheet. The design of the heat exchanger shall require the fouled pressure drop lower than the allowable.