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Value pricing of surface coatings for mitigating heat exchanger fouling

L. Gomes da Cruz[a,b], E.M. Ishiyama[c], C. Boxler[d], W. Augustin[d], S. Scholl[d], D.I. Wilson[a,*]

[a] *Department of Chemical Engineering & Biotechnology, University of Cambridge, New Museums Site, Pembroke Street, Cambridge CB2 3RA, UK*
[b] *Department of Chemical Engineering, Polytechnic School, University of São Paulo, Av. Prof. Luciano Gualberto, 380, trav. 3, 05508-010 São Paulo, SP, Brazil*
[c] *IHS Downstream Research, 133 Houndsditch, London EC3A 7BX, UK*
[d] *Institute for Chemical and Thermal Engineering, Technische Universität Braunschweig, Langer Kamp 7, 38106 Braunschweig D, Germany*

ABSTRACT

Surface modification has been proposed as an attractive mitigation strategy for combating heat exchanger fouling in the food industry and other sectors. Antifouling coatings manipulate the interactions between the surface and fouling precursors or fouling deposit to either extend the induction period before appreciable fouling starts and/or reduce the rate of deposition. A successful surface treatment should extend the time between cleaning operations, thereby reducing the operating cost of the system. A modified exchanger will, however, incur additional capital costs for replacement and this needs to be compared to the anticipated savings during operation. This paper considers the economic attractiveness of replacing existing exchangers by units with modified surfaces in a retrofit. Three cases are considered, which are modelled using fouling rates taken from studies in the literature. Antifouling performance is expressed in terms of (i) extended induction period before fouling starts, and/or (ii) reduced fouling rate. The annualised total cost (operating + annualised capital spend) is mapped for different combinations of these parameters to establish the economically favourable region for a coating at different coating prices. This allows the value pricing margin to be identified, where the expected benefits have to be split between the cost of the coating and the benefit to the manufacturer and operator. The case studies are (a) DLC-related surface modification to reduce aqueous crystallisation fouling; (b) fluorocarbon-based coatings which offer antifouling performance but can reduce heat transfer, for crystallisation fouling; and (c) fluorocarbon-based coatings in a dairy pasteuriser application. A novel strategy, of replacing stainless steel with fluorocarbon coated carbon steel, is also considered for case (b).

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1. Introduction

Fouling is a widespread problem in process heat transfer systems and necessitates regular cleaning and/or costly mitigation measures. It is a challenge for sustainable manufacturing as it incurs additional equipment, energy, treatment chemicals and downtime with associated costs as well as increasing the environmental impact of the process. Fouling can be mitigated (see Müller-Steinhagen et al., 2011) by modifying the process streams (e.g. softening hard water), manipulating process conditions (*e.g.* temperatures and flow rates/shear stresses, using alternative apparatus such as fluidised bed heat exchangers), and by modifying the heat transfer surface to reduce (or eliminate) fouling and/or

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* *Corresponding author*. Tel.: +44 1223 334 791; fax: +44 1223 331 796.
E-mail address: diw11@cam.ac.uk (D.I. Wilson).

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Nomenclature

Roman

A	heat transfer area (m^2)
C_{cl}	cost of cleaning (US$ unit^{-1})
c_E	energy cost (US$ J^{-1})
C_{equip}	cost of the uncoated equipment (US$)
C_H	cost of additional heating (US$)
C_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
C_r	heat capacity flow ratio (–)
E_{loss}	annual total energy loss (J)
E^*_{loss}	ratio of energy losses due to fouling (–)
h	film transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
n	number of cleaning cycles per year (–)
NTU	number of transfer units (–)
Q	heat duty (W)
R_{coat}	thermal resistance of the coating ($m^2\,K\,W^{-1}$)
R_f	thermal resistance of the fouling layer ($m^2\,K\,W^{-1}$)
$\dot{R}_f$	fouling rate ($m^2\,K\,J^{-1}$)
R_{metal}	thermal resistance of the tube metal ($m^2\,K\,W^{-1}$)
t	time (day)
t_{cyc}	optimum cycle time (day)
t^*_{cyc}	ratio of optimum cycle times (–)
T	temperature (K)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)

Greek

α	equipment cost multipilication factor due to coating (–)
δ_{coat}	thickness of coating (m)
δ_f	thickness of foulant (m)
δ_{metal}	thickness of tube (m)
ε	effectiveness (–)
λ_{coat}	thermal conductivity of coating ($W\,m^{-1}\,K^{-1}$)
λ_f	thermal conductivity of deposit ($W\,m^{-1}\,K^{-1}$)
λ_{metal}	thermal conductivity of tube ($W\,m^{-1}\,K^{-1}$)
ϕ^*	ratio of the total annualised cost for the coated unit over the uncoarted unit (–)
ϕ_{cap}	time averaged capital cost (US$ day^{-1})
ϕ_{op}	time averaged operation cost (US$ day^{-1})
ϕ_T	time averaged total annualised cost (US$ day^{-1})
τ	time taken to clean a unit (days)

Subscript

add	additional
c	cold stream
cl	clean
coat	coated
h	hot stream
hyg	hygienic constraint
in	inlet
ind	induction
LF	life time of the heat exchanger
max	maximum
min	minimum
opt	operating
out	outlet
p	processing period
unc	uncoated

Superscript

cl	clean state
r	required condition to achieve the same amount of heat as the clean state

enhance cleaning. The latter strategy, which may be labelled as the search for the 'Holy Grail' or antifouling surface, has attracted a considerable amount of research effort in recent years (Santos et al., 2013). Coating a surface to reduce fouling or other deposition processes involves modifying the interaction between the surface and the process fluid and thus the attachment, adhesion, retention and removal of depositing species. These interactions determine the strength of adhesion of any fouling layer and the cleanability of the surface. An ideal coating would prolong the fouling induction period, improving the plant operating efficiency. If deposition did occur, it would also require less effort for cleaning (lower concentration and temperature of cleaning solutions, shorter cleaning times), increasing the plant productivity and reducing the consumption of natural resources.

1.1. *Coatings*

There is a wide variety of processes available for coating metal substrates, including electrochemical deposition, thermal spraying, contact welding, plating, ion implantation or sputtering, physical and/or chemical vapour deposition, and hybrid methods. These differ in the deposition options (e.g. coating devices, coating species and precursors, coating rate), film properties (tribological and energetic properties, thickness and surface topography) and cost (equipment purchase and maintenance price, power consumption, space and personnel requirements).

The choice of coating material and method will depend on the nature of the surface to be coated as well as the nature of the species causing fouling. Tables 1 and 2 summarise the results of recent experimental studies on the effect of surface coatings on heat exchanger fouling in water scaling and milk-related liquids, respectively. These tables do not provide a comprehensive account of each study, as their purpose is to illustrate the breadth of types of coating tested, the range of fouling fluids (usually solutions), and the variety of outcomes. Details such as the method of manufacture, mode of heat transfer, and testing conditions can all be found in the original paper(s). The studies vary in terms of characterisation of the coatings (*e.g.* roughness, surface energy, thickness and uniformity), so comparing coatings is not always straightforward. A recent review of the effectiveness of different antifouling coatings has been published by Banerjee et al. (2011).

Some of the contradictory results in Tables 1 and 2 can be attributed to the diversity in experimental conditions, differences in methods for preparing coatings, composition of fouling solutions and monitoring/analytical methods. It is noteworthy that many workers have reported surface coatings to have a stronger effect on cleaning than on fouling. This indicates that assessments of surface coating performance should consider their contribution to the whole fouling-cleaning cycle.

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