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A semi-empirical correlation for crystallization fouling on heat exchange surfaces

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Abstract

Crystallization fouling experiments are reported in this paper. In general the results show four distinct time regions: a region where the fouling thermal resistance is zero, a region where the fouling thermal resistance is negative, a region where the fouling resistance increases steadily and a region where the fouling thermal resistance remains constant. Each of these regions can be matched with different development phases in the crystallization fouling process: nucleation phase (regions 1 and 2), growth phase and asymptotic phase. Overall the fouling curves exhibit an S-curve, characteristic of the logistic curve. A new correlation based on the solution of the logistic equation is formulated. The correlation parameters are evaluated and related to the crystallization parameters. The results of this work can find application in predicting the evolution of the fouling scale layer in heat exchangers that are in operation. The predictions can assist heat exchanger operators to plan cleaning schedules.

Keywords: Heat exchangers; Crystallization fouling; Logistic curve; Experiments

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1. Introduction

Fouling of heat transfer surfaces is a serious problem that affects the design and operation of heat exchangers. Fouling involves the formation of deposits of low thermal conductivity on heat transfer surfaces, leading to degradation in the rate of heat transfer. Fouling is a complex phenomenon and its prediction, based on the current knowledge is not accurate. At the design stage fouling is accounted for by increasing the heat transfer surface area. According to Garret-Price et al. [1] the general practice is to design heat exchangers with an average oversize of about 35%. Heat exchangers designed with excess surface area tend to be larger and heavier. This evidently results in extra costs to cover additional material, transportation and installation. To maintain the desired heat transfer rates during the operational stage of a heat exchanger periodic cleaning of heat transfer surfaces is a necessity. Periodic cleaning results in additional costs arising from loss of production and additional maintenance activities. It is not surprising that fouling related costs constitute a significant portion of the industry's running costs [2].

Fouling is usually classified into six categories depending on the key physical or chemical process essential to the particular fouling mechanism. The categories are crystallization, particulate, chemical, corrosion, biological and solidification [3]. Crystallization fouling accounts for over 25% of the fouling problems encountered. Crystallization fouling, or scaling, occurs when inverse solubility salts that are originally dissolved in the process fluid, deposit on heat transfer surfaces. A notable feature of inverse solubility salts is that their

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Nomenclature

A	area, m^2
A_0, A_1	constants in the logistic equation (Eq. 11) [units same as for growth variable]
b	constant (Eq. 14), –
C	concentration, kg/m^3
D_h	hydraulic diameter, m
ΔE	activation energy, J/mol
f_1	constant in Eq. (19), m^2/W K
f_2	constant in Eq. (19), m^2/W
f_3	constants in Eq. (19), m^2 K/W
K_n	reaction constant for nucleation (Eq. 14)
K_r	reaction constant, m^4/kg s
k_{rem}	proportionality constant for removal, m^3/kg s
k_{ro}	pre-exponential constant, m^4/kg s
k_{rough}	proportionality constant for surface modifying factor, –
m'	mass per unit area, kg/m^2
n	index in Eq. (2)
P	growth variable in the logistic equation (Eq. 11)
q''	heat flux, W/m^2
R_f	fouling thermal resistance, m^2 K/W
R_f^*	asymptotic fouling thermal resistance, m^2 K/W
R_g	gas constant, J/mol K
S	degree of supersaturation, –
T	temperature, °C
t	time, s
t_0	time to reach inflection point, s
t_{asy}	time to reach asymptote, s
t_{ind}	induction time, s

Greek symbols

β	mass transfer coefficient, m/s
δ	deposit thickness, m
ε	Surface roughness protrusion height, m
λ	thermal conductivity, W/mK
ρ	density, kg/m^3
σ	shear strength, N/m^2
τ	shear stress, N/m^2

Subscripts

asy	asymptote
b	bulk
dep	deposition
f	fouling
g	gas
i	interface
ind	induction
n	nucleation
r	reaction
rem	removal
rough	roughness
s	saturation
t	time
w	wall

solubilities decrease with increase in temperature. Salts that normally lead to scaling are usually sulfates, phosphates and carbonates of calcium. Calcium sulfate is one of the commonly encountered scale forming materials. Scale deposits due to calcium sulfate is found on surfaces in applications such as nanofiltration technology [4], desalination of seawater by reverse osmosis, handling of geothermal brines for energy production and water distillation [5].

The amount of deposits on a heat transfer surface can be quantified using fouling thermal resistance. Measuring the fouling thermal resistance can assist in extracting parameters that could be used for predicting fouling behavior in similar heat exchangers operating at similar conditions. How well the estimate depends not only on the physical model employed but also on the correlation method used. In this paper crystallization fouling experiments are reported. From the results, a semi-empirical correlation that can be used with operation parameters to predict the evolution of fouling on heat exchanger surfaces is formulated.

2. Theory

Crystallization fouling occurs when salts dissolved in the process fluid crystallize on a heat transfer surface. Three basic steps are necessary for crystallization to occur; attainment of supersaturation, formation of nuclei and growth of crystals.

The degree of supersaturation, S, is often used as a measure of supersaturation and is expressed as a ratio of the bulk concentration, C_b, to the saturation concentration, C_s. In heat transfer equipment supersaturation may be achieved by either evaporating a solution beyond the solubility limit of a dissolved salt or heating a solution containing a dissolved salt of inverse solubility nature to a level above its solubility temperature.

Nucleation refers to the process by which the smallest stable aggregates of a crystalline phase are formed in a crystallizing system. These minute particles then act as building blocks for crystal formation. The process of nucleation may either occur spontaneously or be induced artificially. When induced artificially the energy