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Theoretical Study on Heat Transfer in the Presence of Fouling

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Abstract

The fouling depositions of crude oil stream were studied theoretically in a shell and tube heat exchanger to investigate the effect of depositions on the heat transfer process. The employed heat exchanger was with steam flowing in the inner tubes and crude oil in the shell at different velocities and bulk temperatures. It is assumed that fouling occurs only on the heated stream side (crude oil). The analysis was carried out for turbulent flow heat transfer conditions with wide range of Reynolds number, bulk temperature and time. Many previously proposed models for fouling resistance were employed to estimate a new model for fouling rate. It is found that the fouling rate and consequently the heat transfer coefficient were affected by Reynolds number, Prandtls number, film temperature, activation energy, and time.

The results obtained showed that fouling resistance decreased with the increasing of Reynolds number and Prandtls number, and increased with the increasing of film temperature and time. The analyses of results were compared with some experimental work and a reasonable agreement is attained.

Keywords

Heat exchanger, Shell and tube, Fouling rate, Crude oil

Introduction

The term fouling is defined as the deposition of unwanted material on heat transfer equipment, which results in an increase in thermal resistance to heat transfer and subsequent loss of equipment thermal efficiency [1].

Fouling leads to reduce heat transfer, increase pressure drop, block process pipes, and these effects are costly. The cost factors include higher heat exchanger requirements, increase fuel consumption, reduce throughput and increase maintenance. In addition to the operation losses, fouling forces significant capital expenditure, these fouling factors are taken into consideration.

Reported causes of fouling from crude oils include [2]:

i) Impurities such as water, rust and other particulates.
ii) Gum or polymeric species formed through oxidation of reactive species in the oils.
iii) Insoluble asphaltenes from self-incompatible oils or from blending.
iv) Iron sulphide formation.
v) Coke formation due to reactions of polar fractions.

These factors (i) to (v) become progressively more important as the oil temperature is raised, i.e., factor (i) can predominate at lower temperatures in the preheat train, whereas factors (iv) and (v) become more important near the furnace inlet temperature.

Scaling of the heat exchanger surfaces has been of most concern because of the breakage of the fragile impregnated graphite tubes. Figure 1 shows a fouled heat exchanger.

Fig.1, Graphite shell and tube heat exchange.

As scaling becomes more serious, maintenance costs and downtime increase, while the production rate decreases. After some time of operation, the internal surfaces of equipment in contact with crude oil are covered with scale, which is removed by washing at high velocity. This descaling action is partly by dissolution and partly by abrasion. The main equipments which require regular washing are: flash chamber, heat exchangers, and acid pipework [3].

Parameters Affecting the Fouling

The fouling characteristic of a fluid in contact with a heat transfer surface depends on the following main parameters [4]:

1. Flow velocity of the fluid.
2. Surface temperature.
3. Fluid bulk temperature.
4. Material and geometry of the heat transfer surface.
5. Characteristics of the fouling fluid.

Fouling Characteristics

Many types of fouling can occur on the heat transfer surfaces. Based on the different physical and chemical processes involved, it is convenient to classify the fouling main types as [4, 5]:

Precipitation Fouling: Crystallization of dissolved salts due to solubility changes with temperature, and subsequent precipitation onto the heat transfer surface.

Particulate Fouling: Deposition of suspended particles in the process stream onto the heat transfer surfaces.

Biological Fouling "bio-fouling": This type occurs in raw water due to the attachment and growth of macro organisms on the heat transfer surfaces.

Chemical Reaction Fouling: Is a result of chemical reactions between reactants in the flowing fluid in which the surface material itself is not a reactant.

Corrosion Fouling: Due to chemical or electrochemical reaction between the heat transfer surface itself and the fluid stream to produce corrosion products.

Solidification Fouling: Due to freezing of a pure liquid or a higher melting point components of a multi-component solution onto a cooler surface.

This paper covers the impact of shell side fouling on the thermal performance and economics of shell and tube heat exchangers employed in the refinery and petrochemical plant processes.

Fouling Curves

The fouling process is indicated by the fouling resistance, R_f which is measured either by a test section or from the decreased capacity of an operating heat exchanger [٤].

The results are presented by R_f versus time curve. The delay time, t_d indicates an initial period of time that can elapse where no fouling occurs. The most important fouling curves (Fig. 2) are:

i) **The linear fouling curve:** In this mode, the mass of deposition rate, m_d increases linearly with time and there is no deposition removal, m_r, or $m_d - m_r =$ constant. The fouling curve in this case takes the form of:

$$Rf = a\,(t - t_d) \qquad \ldots (1)$$

Where "a" is the slope of the line as shown in Fig. 2

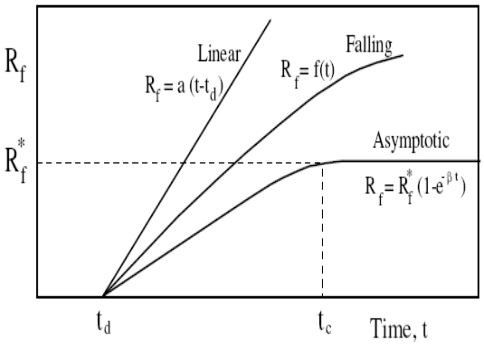

Fig.2, Fouling curves [4]

ii) **The asymptotic fouling curve:** In this mode, the rate of fouling gradually increases against time, until a steady state is reached when there is an asymptotic fouling resistance, R^*_f is obtained. In practical industrial situations, the asymptote may be reached in a matter of hours, weeks or months depending on the operation conditions. The general equation describing this behavior takes the form

$$R^*_f = (1 - e^{-\beta t}) \qquad \ldots (2)$$

This mode is the most widely existed in the industrial applications

iii) **The falling rate fouling curve:** In this mode, the mass of deposit increases with time nonlinearly and without reaching a steady state of asymptotic value, i.e., $m_d - m_r = f\,(t)$ and takes the form

$$R_f = f\,(t) \qquad \ldots (3)$$

Crude Oil Fouling Models

A large number of models for crude oil fouling have been presented. Ebert and Panchal (1995) have presented a fouling model that is expressed as the average (linear) fouling rate under given conditions as a result of two competing terms, namely, a deposition term and a removal term [5, 6, 7, 8, 9].

Fouling Rate = (deposition term) - (removal term)

$$\frac{dR_f}{dt} = \alpha\,\mathrm{Re}^{\beta}\,\exp\left(\frac{-E}{RT_f}\right) - \gamma\,\tau_w \qquad \ldots (4)$$

Where α, β, γ and E are constants to be determined from experimental data. And τ_w is the tube wall shear stress and can be given by.

$$\tau_w = \frac{f}{2}\,\rho\,u^2 \qquad \ldots (5)$$

The friction factor can be calculated from the Blasius equation [9]:

$$f = 0.0791\,\mathrm{Re}^{-0.25} \qquad \ldots (6)$$

The relationship in Eq. (4) points to the possibility of identifying combinations of temperature and velocity below which the fouling rates will be negligible. Ebert and Panchal present this as the “threshold condition”. This model suggests that the heat exchanger geometry which affects the surface and film temperatures, velocities and shear stresses can be effectively applied to maintain the conditions below the “threshold conditions” in a given heat exchanger.

Ebert and Panchal model assumes all the chemical reactions to be included by the Arrhenius term in Eq. (4). In addition, it ignores the effects of crude oil thermal conductivity and specific heat and only considers the impacts of crude oil density and viscosity as presented by Reynolds number. To modify this correlation, Prandtl number was also incorporated into the model by Polley etal. (2002) as shown by Eq. (7).

$$\frac{dR_f}{dt} = \alpha \operatorname{Re}^{\beta} \operatorname{Pr}^{-0.33} \exp\left(\frac{-E}{RT_w}\right) - \gamma \operatorname{Re}^{0.8} \quad \ldots (7)$$

The model differs primarily in the use of wall temperature, Tw, in the deposition term and Reynolds number rather than wall shear stress in the removal term.

Saleh et al. (2003) proposed a model that can only be able to predict fouling without considering the effect of fluid velocity on the removal term as follows:

$$\frac{dR_f}{dt} = \alpha P^{\beta} u^{\gamma} \exp\left(\frac{-E}{RT_f}\right) \quad \ldots (8)$$

The latest threshold fouling model (Eq. (9)) has been developed by Nasr and Givi (2006) Which, is independent of Prandtl number.

$$\frac{dR_f}{dt} = \alpha \operatorname{Re}^{\beta} \exp\left(\frac{-E}{RT_f}\right) - \gamma \operatorname{Re}^{0.4} \quad \ldots (9)$$

Nasr has estimated the constant parameters of Eq. (9) using the experimental data, measured by Saleh et al.

It should be mentioned that to extend the model for the other type of crude oil the constant values have to be recalculated correspondingly.

The Proposed Model

To propose a new model the experimental results reported by Polley, Nasr, and Ebert were used. The new model can be expressed by the following equation:

$$\frac{dR_f}{dt} = \alpha \operatorname{Re}^{\beta} \operatorname{Pr}^{\delta} \exp\left(\frac{-E}{RT_f}\right) \quad \ldots (10)$$

Film temperature can be obtained by the following equation:

$$T_f = 0.32 \times T_b + 0.68 \times T_w \quad \ldots (11)$$

The activation energy was obtained by drawing ln(dR_f/dt) versus 1/Tf. The following constants were used in the proposed model:

α =36.71 (m2 K/ kW hr)
β = -0.085
γ = -1.14
E = 22.618 (kJ/ mol)
The correlation coefficient was 0.943.

Results and Discussion

The study was carried out to examine the effect of operating conditions on fouling of crude oil. The following ranges of conditions were covered: velocity of 0.25 to 0.4 m/s, surface temperature of 177 to 245^{o}C, bulk temperature of 79 to 120^{o}C.

Effect of Reynolds Number

Velocity effects provide a key to understanding the fouling mechanism. If fouling rates increased with velocity, transport of fouling species is likely important. If fouling rate decreases with increasing velocity the dominant step is likely to be adhesion of foulants at the surface or chemical reaction.

As Reynolds number was raised from 4051 to 6233, the fouling rate decreased from 0.002543m^2.K/kW. hr to 0.002443 m^2.K/kW. hr for bulk temperature of 79°C and surface temperature of 245°C. Figure 3 shows the relationship between fouling rate and time at different values of Reynolds number.

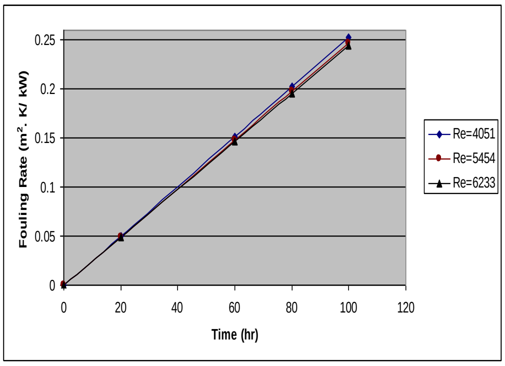

Fig.3, Effect of Reynolds number on fouling resistance at Tb= 79°C, Tw = 245°C

Effect of Film Temperature

i) Effect of Wall Temperature

As shown in Figure 4 fouling rates were most intensive at highest wall temperature. Fouling rates ranged from 0.005435 m^2 K/kW. hr at wall temperature of 177°C to 0.01037 m^2 K/kW. hr at wall temperature of 245°C for bulk temperature of 79°C and Reynolds number of 3895.

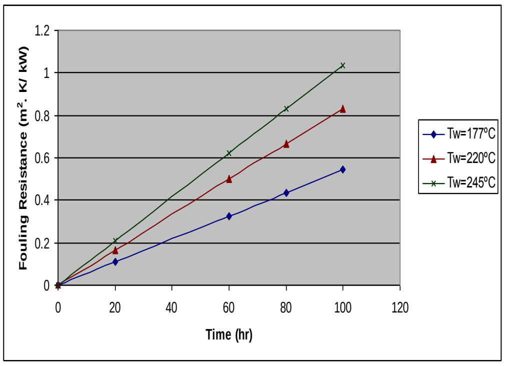

Fig.4, Effect of wall temperature on fouling resistance at Tb= 79°C, Re = 3895

ii) Effect of Bulk Temperature

Figure 5 shows fouling resistance versus time for three bulk temperatures of 77, 79 and 120°C, with fixed wall temperature of 177°C and Reynolds number of 5924.

By increasing the bulk temperature from 77 to 120°C, and hence the film temperature from 145 to 158.8°C, the fouling rate was increased from 0.001204 to 0.00222 m^2 K/kW. hr.

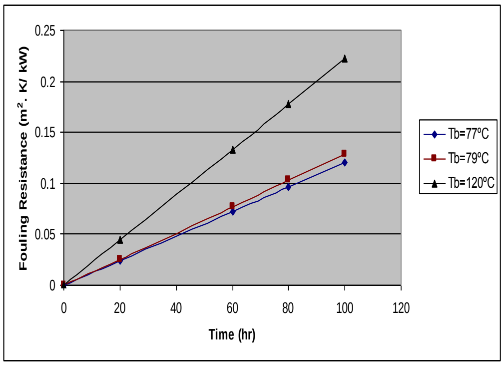

Fig.5, Effect of bulk temperature on fouling resistance at Tw= 177°C, Re = 5924

Effect of Prandtls Number

Figure 6 shows that as Prandtls increased from 10.46 to 14.92 the fouling resistance decreased from 0.003449m^{2}K/kW. hr to 0.002301 m^{2}K/kW. hr for the same values of film temperature and Reynolds number.

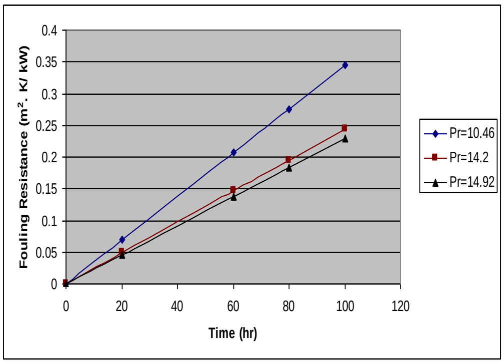

Fig.6, Effect of Prandtls number on fouling resistance at Tf= 191.24°C,Re = 5924

Comparison of the Results with Proposed Models

The results of the proposed model were compared with other proposed models carried out at the same conditions for Tb= 77°C, Tw= 242°C and Re= 5924, see Fig.7.

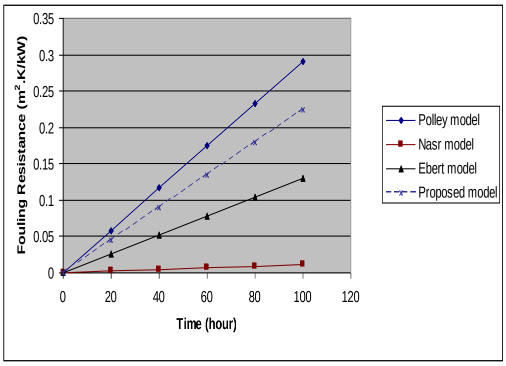

Fig.7, Comparison of the fouling resistance versus time for the proposed model with other models at Tb= 77°C, Tw= 242°C and Re = 5924

Conclusion

A study of fouling at bulk liquid temperatures of 77-120°C, surface temperatures in the range 177-245°C and Reynolds number in the range of 3895-6233 has shown that:

1. Fouling rates increase strongly with both the surface and the bulk temperature.
2. Surface temperature has a major impact on fouling rates. Fouling rate is correlated using a modified film temperature, which gives more weight to the surface temperature than to the bulk temperature.
3. Fouling rate decreases as Reynolds number increases to the power -0.085.
4. There is a linear dependence of the fouling resistance on time.
5. Bulk temperature effect can not be separated from the flow effects, since as the bulk temperature increases, the Reynolds number goes up slightly at fixed velocity.
6. Fouling rate decreases as Prandtls number increases to the power -1.14.

Nomenclature

E	activation energy, kJ/mol
f	friction factor, dimensionless
P	pressure, kPa
R_f	fouling resistance, m^2 K/kW
Re	Reynolds number, dimensionless
t	time, h
t_d	delay time, h
T_b	bulk temperature, K or °C
T_f	film temperature, K or °C
T_w	wall temperature, K or °C
u	fluid velocity, m/s

Greek symbols

α	constant parameter in Eqs. 4, 7, 8, 9 and 10
β	constant parameter in Eqs. 4, 7, 8, 9 and 10
δ	Constant parameter in Eq. 10
γ	constant parameter in Eqs. 4, 7, 8 and 9
ρ	density, kg/m^3
τ_w	wall shear stress, N/m^2

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