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Effect of Flow Oscillation on Surface Fouling

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ملخص البحث

تأثير السريان المتذبذب على الترسيبات فوق أسطح إنتقال الحرارة

معظم الدراسات التي تمت على الترسيبات المتكونة على أسطح إنتقال الحرارة قد تم دراستها تحت ظروف تشغيل ثابتة من حيث ظروف السريان. في هذه الدراسة قد تم دراسة تأثير بعض العوامل على هذه الترسيبات لسريان ترددي داخل المواسير. فقد تم إعداد دراسة نظرية لدراسة تأثير كل من الضغط المتذبذب و كذلك شكل موجة الضغط على معدل الترسيب على سطح إنتقال الحرارة وكذلك القيمة النهائية لهذا الترسيب. وأيضا تم دراسة تأثير سرعة السريان على معدل الترسيب. ومن ناحية شكل الموجة فقد تم دراسة خمس أشكال هي الجيب-المستطيل-المثلث-شبه المنحرف-سن المنشار. ويلاحظ أن جميع العوامل التي تم دراسة تأثيرها قد تم وضعها في صورة لا بعدية. الهدف الرئيسي من هذه الدراسة هو توظيف مثل هذا النوع من السريان للحد من هذه الترسيبات. ونتيجة هذه الدراسة فقد أستخلص أن وجود أي قيمة متذبذبة مسموح بها من المصمم أو المشغل مهما كانت صغيرة فإن لها تأثير ملموس على الحد من هذه الترسيبات ومن ناحية أخرى إذا كانت القيمة المتذبذبة كبيرة فإن الحد من الترسيبات يكون أكبر.

Abstract

A fundamental fouling model is developed in the light of oscillating flow dynamics. Flow oscillation inside tube is considered to study the effect of the dynamic aspects on the particulate fouling. A mathematical model for flow oscillation has been employed in conjunction with the fouling model to elaborate their mutual effects.

A parametric computational study has been carried out to study the effect of oscillating flow parameters such as pressure amplitude, frequency, and wave form on the fouling rate and its asymptotic value. The effect of Reynolds number on the dynamic characteristics has been investigated as well. Five different periodic pressure gradients wave forms namely sine, step, triangular, trapezoidal, and saw teeth, have been used in this investigation. All parameters are represented in non-dimensional forms.

The dynamic flow has been exploited to mitigate the fouling evolution. It is found that any marginal flow oscillation that can be tolerated by the equipment designer or operator has a fair effect in favor of fouling reduction. On the other hand, if the flow oscillation is deliberately exist, a pronounced fouling reduction could be obtained.

Nomenclature

Latin symbols

c	foulant concentration, *gram/kg*
f	frequency, *Hz*
i	imaginary constant, $\sqrt{-1}$
J_o	Bessel function of first kind of order zero
J_1	Bessel function of first kind of order one
k_1	deposition constant.
k_2	removal constant.
K	pressure gradient, *Pascal/m*
p	pressure, *Pascal*
Q	flow rate, m^3/sec
r	radial coordinate, *m*
r_o	pipe radius, *m*
Re	Reynolds number
R_f	fouling factor, W/m^2K
t	time, *sec*
t_c	time constant, *sec*
u	axial flow velocity, *m/sec*
x	fouling thickness, *m*
z	axial coordinate, *m*

Greek symbols

μ	dynamic viscosity, *kg/m.sec*
ν	kinematic viscosity, m^2/sec
ω	circular frequency, *rad/sec*
ρ	fluid density, kg/m^3
τ	shear stress, *Pascal*

Subscripts

d	pipe diameter
f	fouling
max	maximum
s	steady state
w	wall

Superscripts

$*$	asymptotic value

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1. Introduction

Fouling of heat transfer surfaces is one of the most important problems in heat transfer equipment. Fouling can occur on any fluid-solid interface and has adverse effects on the unit performance, in which it leads to decrease production, efficiency, and life of the unit. On the other hand, fouling leads to increase both of the capital and operating costs. Overcoming fouling is therefore essential for technical and economic considerations. Solution of the problem requires a better understanding of the physical processes causing fouling.

According to many investigators, fouling can be considered as the single most unknown factor in the design of the industrial equipment. This situation exists despite the wealth of operating experience accumulated over the years and accumulation of fouling literature. This lack of understanding almost reflects the complex nature of the phenomenon by which the fouling occurs in industrial equipment. The wide range of process streams and operating conditions present in industry tends to make most fouling situation unique, thus rendering a general analysis of the problem is difficult.

The interest in fouling research has increased greatly over the past twenty years. Many efforts were paid to decrease and prevent fouling, develop cleaning methods, and overcome the fouling effects. Some success has been obtained in every goal, but up to date, there is no clear and sufficient way that can be used to mitigate the fouling or the fouling effects. Some of the earliest papers on fouling appeared in the early 1920's and there were few additions to the literature up to 1960. Fouling was one of the major areas selected for investigation by the Heat Transfer Research Incorporation, (HTRI), in 1960. It was described as "the major unresolved problem in heat transfer". HTRI developed a measurement technique and obtained a large amount of data on the fouling characteristics of cooling tower water, seawater, and crude oil. Since 1960 there has been a significant increase in the literature on fouling and a considerable increase of interest in the subject. A review by Epstein (1983) contained over 150 references on fouling has been published between 1960 and 1977.

The International Conference on the "Fouling of heat transfer equipment" held in August 1979, objected to critically assess the present status of fouling research, review methods for the prediction of fouling, and identify the important directions for future research. In this conference, it was demonstrated that the basic mechanisms of many types of fouling are similar and that the theories used to explain one type of fouling might be indeed by used as a basis to explain other types.

Many investigators have studied the fouling phenomenon theoretically and experimentally. Kern and Seaton , 1966, have cited the first and the pioneer mathematical model for surface fouling. They stated that the fouling rate could be estimated as the difference between the deposition and removal rates. Also, they proposed that the deposition rate is proportional to the product of foulant concentration and flow rate whereas the removal rate is proportional to the shear stress and the instantaneous thickness of the deposit. In this model, if the removal term is small and always less than the deposition term, the fouling factor may increase indefinitely until the flow path is plugged. If the removal term is significant, a point may be reached where deposition and removal rates become equal and the fouling reaches asymptote value which is called asymptotic fouling factor.

Taborek. et.al., 1972, introduced the water characterization factor to the deposition term to account for the effect of water quality. They expressed the deposition rate by the so-called *Arrhenius* type equation. The removal term was postulated to be a function of shear stress, deposit thickness, and bonding strength of the deposit.

Watkinson, et.al., 1974, obtained a set of experimental fouling-time curves and compared their results against the fouling model proposed by Kern and Seaton, 1966. It was found that, the asymptotic fouling resistance was inversely proportional to the squared mass flow rate. Also it was found that, the initial fouling rate was inversely proportional to the mass flow rate and dependent exponentially on the initial wall temperature. They proposed a deposition term which equal the product of the foulant mass flux normal to the surface, j, and the sticking probability, p, which in turn is proportional to the adhesive force binding a particle to the surface, and inversely proportional to the hydrodynamic forces at the interface. The proposed removal term was formulated similar to that of Kern and Seaton.

Beal, 1978, described a new and potentially promising method for predicting the deposition of particles entrained in turbulent flow as a function of concentration gradient in normal direction times the sum of molecular and eddy diffusivity.

Watkinson, 1980, reported experimentally the effect of fluid velocity on the asymptotic fouling resistance for three different operating foulants and obtained a correlation for each.

Reitzer, 1981, considered the rate of scale formation in tubular heat exchangers. He assumed that fouling factor is linearly dependent on time, therefore no asymptotic fouling had been reached. He concluded that an additional removal mechanism is required to physically represent a complete fouling model.

Knudsen, 1986, composed the fouling models due to Kern and Seaton, 1966, and Taborek, et.al., 1972, and proposed a deposition - removal model based on the *Arrhenious* theory for both asymptotic factor and time constant.

Epstein, 1988, proposed a simple model to describe the asymptotic fouling type. He assumed that the deposition rate is constant, where the removal rate is proportional to the thickness of the deposited layer.

Recently, Webb and Li, 2000, investigated the effect of internal tube enhancement on the fouling rate for cooling tower water. They found that the enhancement parameters such as helix angle and number of starts have significant effects on the fouling mechanism. It is observed that, fouling increases as the number of starts and helix angle increases.

Li and Webb, 2000, extended their pervious work to study the effect of different fouling types. A comparison between pure particulate fouling and combined precipitation and particulate fouling had been carried out. They found that, the fouling resistance due to pure particulate fouling is less than that due to the combined precipitation and particulate fouling.

Forster and Bohnet, 2000, analyzed the influence of interfacial energies between two materials on adhesion based on van der Waals and hydrophobic interactions. They introduced a new anti-fouling strategy dealing with molecular interactions at the interface crystal /heat transfer surface to reduce the corresponding adhesive strength favoring the removal process due to the wall shear stress.

Schwarz, 2001, reported a long-term evolution of heat transfer performance of steam generators in many Siemens pressurized water reactors. It is concluded that, the iron deposition has drastically reduced and consequently, the fouling increase has almost stopped. This reduction occurred in all plants that have started under phosphate treatment for a long term of operation and their feed water chemistry have been converted to H-AVT treatment (all volatile treatment with hydrazine dosing to assure high pH-values). In plants, which operate under H-AVT from the beginning, no significant fouling factor increase has been observed. Hence, H-AVT treatment is preferred for feed water chemistry, not only from a corrosion prevention point of view but also from a heat transfer performance as well.

Kim, *et al*, 2001, investigated the effect of electronic anti-fouling (EAF) technology on fouling mitigation in a heat exchanger in an open cooling tower systems. They found that, the fouling resistance with EAF treatment was about 70% less than that without EAF treatment, at the end of 270-hr tests.

In the light of the above review, the effect of dynamic aspects of flow is not considered. In the present work, the effect of flow oscillation on the fouling parameters in pipe flow is investigated. A modification of Kern and Seaton model has been introduced to assess the dynamic effects due to flow oscillation.

2. Computational Methodology

2.1. Governing Equations

The momentum equation for unsteady, incompressible, fully developed oscillating flow in a circular tube has been reduced to;

$$\rho\frac{\partial u}{\partial t}=-\frac{dp}{dz}+\mu\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}\right) \tag{1}$$

In which the given oscillating pressure gradient is given by;

$$\frac{dp}{dz}=-\rho K e^{i\omega t} \tag{2}$$

The solution of Eq.(1) subjected to the harmonic pressure gradient of Eq.(2) along with the non-slip boundary conditions at the tube wall, yields the oscillating velocity distribution. This velocity distribution can be expressed in terms of the Bessel function of the first kind of order zero in radial direction, and has a harmonic dependence in time as follows:

$$u(r,t)=\frac{K}{i\omega}e^{i\omega t}\left\{1-\frac{J_o\left(r\sqrt{-i\omega/\nu}\right)}{J_o\left(r_o\sqrt{-i\omega/\nu}\right)}\right\} \tag{3}$$

The associated shear stress distribution can be found upon differentiation of Eq.(3) as;

$$\tau(r,t)=\rho\frac{K}{\sqrt{-i\omega/\nu}}e^{i\omega t}\left\{\frac{J_1\left(r\sqrt{-i\omega/\nu}\right)}{J_o\left(r_o\sqrt{-i\omega/\nu}\right)}\right\} \tag{4}$$

Following Kern and Seaton postulate, the fouling model, can be expressed as;

$$\frac{dx}{dt}=k_1\,Q(t)\,c-k_2\,\tau_w(t)x \tag{5}$$

The above equations have been normalized by the following reference parameters: for length, r_o (pipe radius); velocity, $u_{max,s}=\frac{r_o^2}{4\nu}K_s$ (steady state centerline velocity); and for time, $\frac{r_o^2}{\nu}$

The derived reference parameters are: circular frequency, $\frac{\nu}{r_o^2}$ and shear stress, $\frac{1}{2}\rho\, u^2_{max}$

Upon normalizing each variable with its corresponding reference parameter, a system of non-dimensional equations is obtained as follows:

(from now on, each symbol represents a non-dimensional variable)

$$u(r,t)=-\frac{4i}{\omega}\frac{K}{K_s}e^{i\omega t}\left\{1-\frac{J_o\left(r\sqrt{-i\omega}\right)}{J_o\left(\sqrt{-i\omega}\right)}\right\} \tag{6}$$

$$\tau(r,t)=\frac{-16}{\sqrt{-i\omega}}\frac{1}{\mathrm{Re}_d}\frac{K}{K_s}e^{i\omega t}\left\{\frac{J_1\left(r\sqrt{-i\omega}\right)}{J_o\left(\sqrt{-i\omega}\right)}\right\} \tag{7}$$

$$\tau_w(t) = \frac{16}{\sqrt{-i\omega}} \frac{1}{\mathrm{Re}_d} \frac{K}{K_s} e^{i\omega t} \left\{ \frac{J_1\left(\sqrt{-i\omega}\right)}{J_o\left(\sqrt{-i\omega}\right)} \right\} \quad (8)$$

From the above review, and following Kern and Seaton model, the fouling rate is the outcome of two essential processes. The first is the deposition process, which is proportional to the amount of flow rate and the concentration of foulant material in the stream. The second is the removal process which is proportional to the wall shear stress and the fouling thickness x. In case of steady flow, in which both flow rate and wall shear stress are approximately invariant with the fouling thickness x, it can be easily found that the fouling reaches an asymptotic value x^*.

As it is well known, the effect of the dynamic forces is greater than that of the corresponding steady state. Therefore, to enhance the removal force, a dynamic flow application is sought. On the other hand, the dynamic flow will reduce the foulant settlement on the surface. Subsequently, the overall dynamic flow effects are in favor of fouling reduction. However, the operations of industrial equipment are designed on steady flow state, a marginal dynamic flow could be tolerated. In fact, the notion of steady state operation is quite an assumption rather than a reality.

In the presenr work, the dynamic aspects that affect the fouling mechanism are embedded in Kern and Seaton Model by replacing the steady state flow rate and shear stress by their instantaneous value from Eqs.(6 and 8). The other dynamic effects lie in the proportionality constants k_1 and k_2. In fact, it is assumed that the major effect of oscillating flow on the fouling is the enhancement of these constants in favor of minimizing the deposition term and maximizing the removal term. This dynamic effect is taken to be the ratio of the maximum amplitude of the wall shear stress to that of the steady flow. This ratio is always greater than unity for any dynamic flow parameters.

From the above discussion the dynamic fouling model due to the flow oscillation can be written as;

$$\frac{dx}{dt} = k_1\, Q(t)\, \mathrm{Re}_d\, c - k_2\, \tau_w(t)\, \mathrm{Re}_d^{\,2}\, x \quad (9)$$

Equations (6 to 9) have been coded in a FORTRAN program and the results are obtained at each time step for each harmonic. For any given periodic function representing the pressure gradient, a Fourier transform is used to get its frequency spectrum and Eqs.(6 to 9) have been solved for each harmonic component and added to yield the equivalent solution.

Five different periodic pressure wave forms namely sine, step, triangular, trapezoidal, and saw teeth, have been used in this investigation to study the effect of dynamic flow parameters such as: dynamic pressure amplitude, frequency and Reynolds number on fouling characteristics.

3. Results and Discussion

A parametric computational study has been carried out to study the effect of oscillating flow parameters such as pressure amplitude, frequency, and wave form on the fouling rate and its asymptotic value. The effect of Reynolds number on the dynamic fouling characteristics has been investigated as well. All parameters are represented in a non-dimensional forms.

A sample of the output results is displayed in Fig.(1). It can be seen that the wall shear stress is lagging the given pressure sine wave by a phase of about $\pi/4$ where the flow rate is lagging by about $\pi/2$. This can be drawn from Eqs.(6 and 8) in which the time phase angles are represented by the argument of the complex amplitude of both velocity and wall shear stress. These angles are the arguments of i and $i^{\prime\prime}$ for both velocity (flow rate) and wall shear stress.

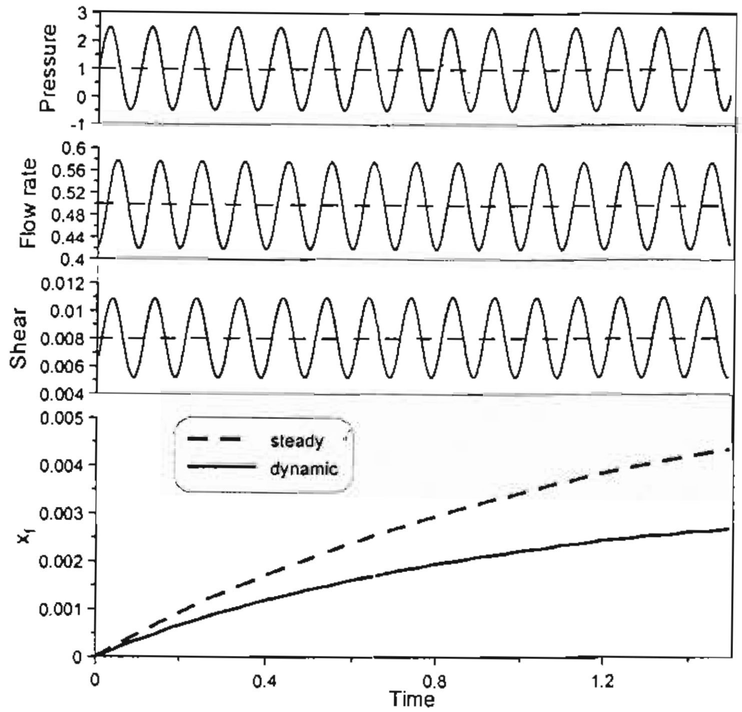


Fig.(1) Dynamic flow parameters for pressure sine wave form, at $f=10$, $K/Ks = 1.5$

The fouling thickness, x for both dynamic and steady flow are also displayed. It is clearly shown that, the dynamic fouling thickness and fouling rate are reasonably smaller than their corresponding steady values. This could prove that, the oscillating flow, in fact, alleviate the fouling problem. The asymptotic value of fouling for both dynamic and steady flow have not reached in this plot because of the non dimensional run time is small just to show the details of the dynamic flow parameters.

In Fig.(2), the pressure wave form and fouling curves for the other wave forms are illustrated. From this figure it is seen that, the dynamic fouling thickness and rate are less than their corresponding steady values for all wave forms. Figure (3) has been illustrated to show the effect of pressure wave form on the fouling parameters. In Fig.(3.a), the result of all five wave forms is summarized and their asymptotic trend is clearly displayed. In this figure the run time is long enough to reach the asymptotic fouling thickness x^*. A bar chart representing the asymptotic values, shown in Fig.(3.b), illustrates that the best shape is the step wave form and the poorest one is the saw teeth.

All test runs from now on will be done with enough time such that the asymptotic fouling thickness has been reached.

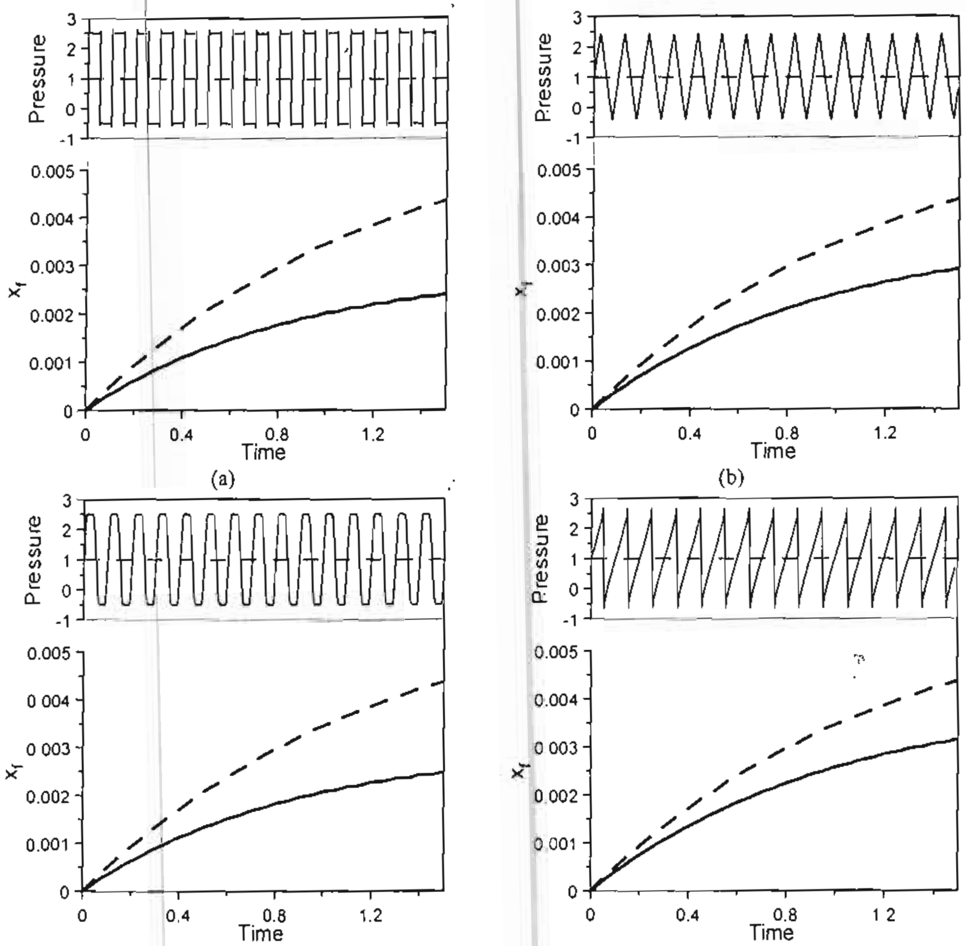
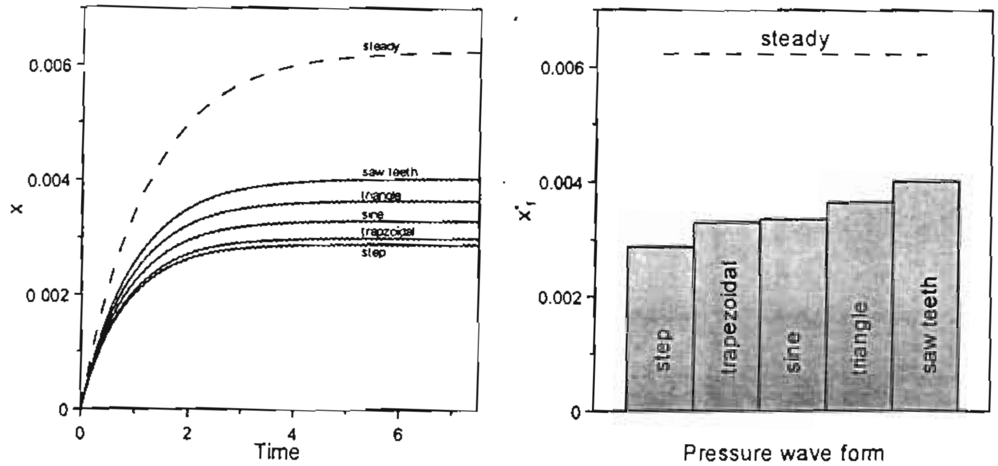


Fig.(2) Pressure wave form, at $f = 10$, $K/Ks = 1.5$
(a) step, (b) triangular, (c) trapezoidal, and (d) saw teeth
—— dynamic ------ steady

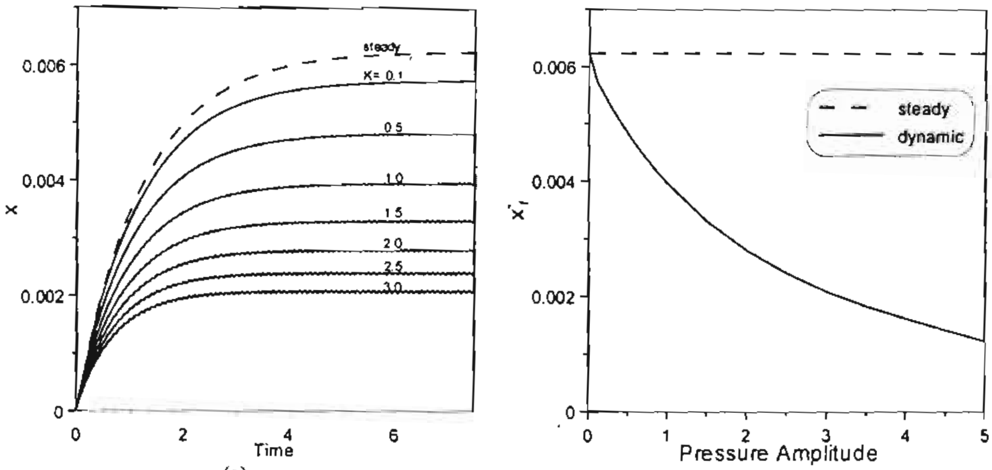
To investigate the effect of pressure wave amplitude on the fouling parameters, Fig.(4) has been illustrated for the sine wave shape. From this figure, it is seen that, the wave amplitude has a drastically effect on the fouling rate and its asymptotic value. The fouling rate and the asymptotic value are decreased by increasing the wave amplitude, that is due to increase of dynamic effects which increase the removal rate and may decrease the deposition one. From Fig.(4.b), it can be drawn that, the rate of fouling reduction is much pronounced at low amplitudes than at higher amplitudes. This could be beneficial in the industrial applications whenever any small marginal flow oscillation can be tolerated.

Figure (5) shows the effect of pressure wave frequency on the fouling parameters. From the figure, it can be seen that, increasing the wave frequency increases the fouling rate and the asymptotic value. Increasing the wave frequency decreases the dynamic effects. In the limit, for a very high frequency the flow approaches the steady state condition. From Fig.(5.b), it can be drawn that the wave frequency has a very limited effect on the fouling reduction at high frequencies.



(a) (b)

Fig.(3) Effect of pressure wave form on the fouling parameters, for $f=10$, $K/Ks = 1.5$



(a) (b)

Fig.(4) Effect of pressure amplitude on the fouling parameters, for sine wave at $f=10$

Figure (6) has been presented to show the effect of flow Reynolds number on the fouling parameters. For a given pressure wave amplitude and frequency, the major effect of Reynolds number is decreasing the fouling rate or time constant as Reynolds number increase as shown in Fig.(6a). On the other hand, Reynolds number has no effect on the asymptotic fouling thickness. In fact, the change of the Reynolds number does not affect the asymptotic fouling thickness because of the flow and fouling model in this study are based on laminar flow theory. The corresponding time constant t_c is shown in Fig.(6b). From this figure the time constant for both dynamic and steady conditions are quite different at low Reynolds number, and approach the same small value at high Reynolds number. This could be stated as the dynamic flow fouling is quite decelerated at low Reynolds rather than at high values.

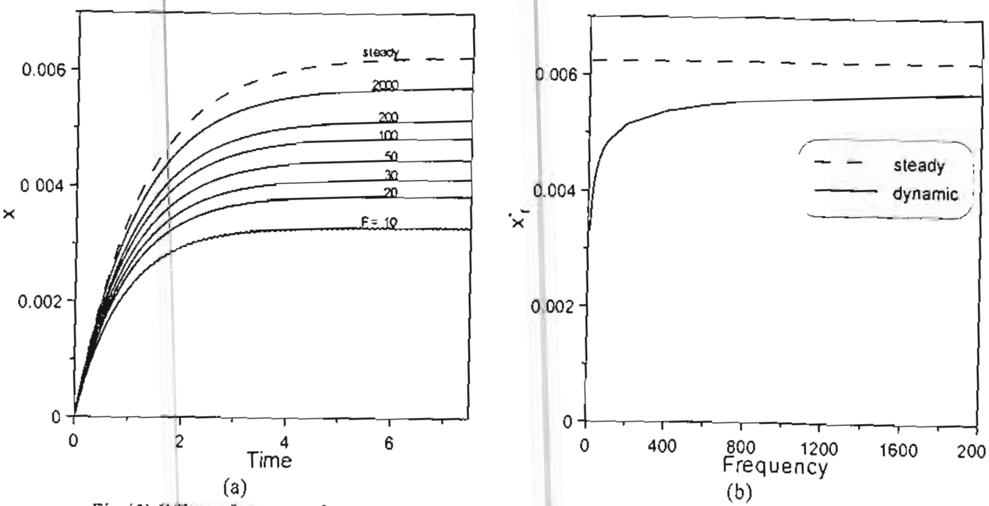


Fig.(5) Effect of pressure frequency on the fouling parameters, for sine wave at $K/Ks = 1.5$

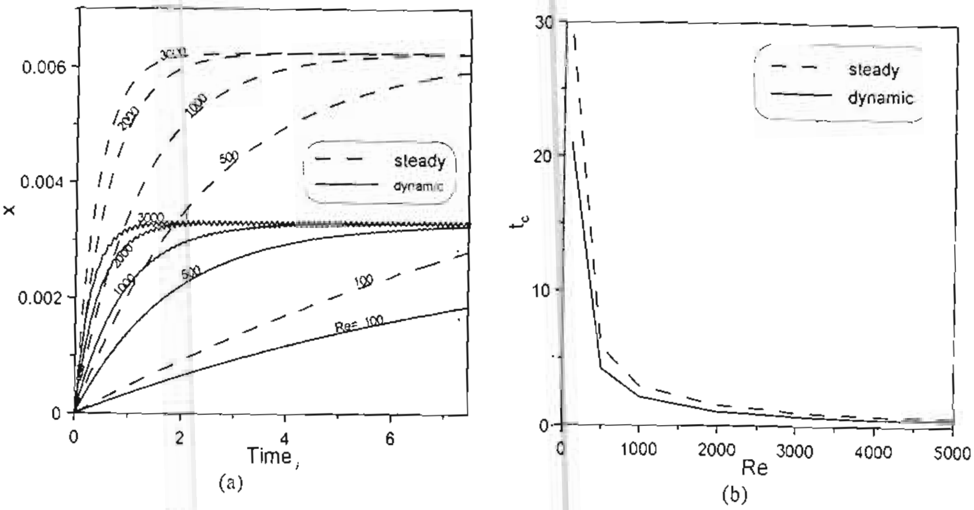


Fig.(6) Effect of Reynolds number on the fouling parameters, for sine wave at $f = 10$ $K/Ks = 1.5$

4. Conclusions and Recommendations

A fouling model accommodating the effect of flow dynamics has been developed. The effect of flow oscillation parameters has been investigated. However, the operation of industrial equipment usually, designed with the notion of steady state operation, a small marginal dynamics can not be avoided. In the light of this fact and the aforementioned discussion, a reasonable fouling reduction has been found.

For all investigated pressure gradient wave forms, It is found that the fouling problem has been alleviated. The step wave form has the greatest effect to mitigate the fouling, where the saw teeth wave form has the smallest effect. A typical reduction is found to be *54%* for step wave form and *34%* for the saw teeth.

An oscillating pressure gradient of sine wave form has been used to test the dynamic flow parameters on the fouling in flow inside tube. The effect of pressure oscillation amplitude is found to have a pronounced fouling reduction. At very low marginal amplitude, the fouling is quite mitigated. A great reduction is found to be *36%* for pressure gradient amplitude ratio as high as one and *8%* for a value as less as *0.1*.

The pressure wave frequency has a quite effect on the fouling reduction at low wave frequencies, where this effect diminishes as the frequency increases enough such that the steady state is reached. The reduction is found to be *46%* for frequency of *10* and *22%* for *100*.

The increase in flow Reynolds number reduces the fouling rate but has no effect on the asymptotic fouling thickness.

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