Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

Interfacial Phenomena in the Filtration/Separation of Petroleum Products

Rajan A. Jaisinghani[a]
[a] AMERICAN FILTRONE CORPORATION CORPORATE RESEARCH AND DEVELOPMENT, RICHMOND, VIRGINIA

To cite this Article Jaisinghani, Rajan A.(1983) 'Interfacial Phenomena in the Filtration/Separation of Petroleum Products', Separation Science and Technology, 18: 12, 1295 — 1322
To link to this Article: DOI: 10.1080/01496398308059928
URL: http://dx.doi.org/10.1080/01496398308059928

SEPARATION SCIENCE AND TECHNOLOGY, 18(12&13), pp. 1295-1322, 1983

Interfacial Phenomena in the Filtration/Separation of Petroleum Products

RAJAN A. JAISINGHANI

AMERICAN FILTRONE CORPORATION
CORPORATE RESEARCH AND DEVELOPMENT
P. O. BOX 34668
RICHMOND, VIRGINIA 23234

ABSTRACT

The increased dieselization of the internal combustion engine and other energy related considerations are the impetus for higher performance, longer life petroleum product filters. A better understanding of the role of interfacial phenomena, in the non-aqueous filtration applications, is needed for improved products. This review paper focuses on the effect of interfacial phenomena in the coalescence and separation of water emulsions from fuel oil and on the removal of fine suspended solids from petroleum hydrocarbons, for conditions relevent to end-of-line cartridge filtration applications. Work, during the last two decades, specifically concerned with these interfacial effects has been reviewed in this paper.

INTRODUCTION

The increased dieselization of internal combustion engines and the simultaneous decline in fuel quality has focused attention on the end-of-line filtration/separation of dispersed water and solids from petroleum fuels and lubricants. Fine solids and water with dis-

0149-6395/84/1812-1295$3.50/0

solved and undissolved metallic oxides have been the cause of both catastrophic and steady failure of injectors and transfer pumps. The main mechanisms are wear due to corrosion and erosion.

A current trend, has been the blending of heavy residual fuels with No. 2 distillate fuels for the operation of marine and industrial medium and low speed diesel engines. This can result in a savings of $0.25 MM - $1.00 MM per year per ship depending on the type of operation. Currently, there have been "successful" operations at, as high as, 80% No.6-20% No.2 fuel oils blends for low speed engines. These successful experiences are not without additional maintenance cost (1). A major problem is the presence of cracking catalyst fines, not adequately removed by current filtration systems.

Over the last decade, the hydraulic component of the fluid power industry has experienced tremendous growth. The hydraulic oils used are expensive and due to the close tolerances in hydraulic cylinders, high efficiency filters are required. The oil is changed due to build up of excessive water and solids and formation of oxidation by-products. In most applications, space is at a premium and consequently, the filters must face high velocities. Lubricating oils are changed for similar reasons. Approximately 1.2 billion gallons of used oil are generated in the U.S. alone. Considerable technical attention is being given to recycling lubricating and other oils. However, one must recognize that improved cartridge filtration can also help alleviate the problem by contributing to the longer use of the oil.

The de-ashing of liquefied coal products is another related application, in the sense that similar interfacial effects may be expected to play an important role. However, due to the high concentrations involved, typical end-of-line cartridge filters are impractical for this application.

In order to achieve better filtration products, it will be necessary to understand the role of interfacial phenomena in non-aqueous filtration. This paper reviews some of the work (over the last two decades) aimed at understanding these effects in the filtration of petroleum products. Basically, two areas are covered:
a) fibrous bed coalescence of emulsified water and, b) filtration of finely suspended solids. This is not meant to be a generalized review of work related to coalescence and filtration. The scope includes only the work, specifically related to the role of interfacial phenomena, for conditions relevent to end-of-line (cartridge) non-aqueous filtration. Technology, involving the active utilization of force fields (e.g. electrically enhanced filtration), is not within this scope, since these devices are often impractical and expensive for end-of-line applications.

FIBROUS BED COALESCENCE

A brief description of the process is in order. Three different regimes of the dispersed phase are assumed: (i) microdrops suspended in the oil (f) (ii) drops captured on fibers (S_2''). These may have undergone coalescence. (iii) capillary conducted coalesced phase (S_2') forming a network of connected channels. The process then involves:

a) Capture of the dispersed phase on fiber surfaces or on previously captured dispersed phase

b) Growth of the dispersed phase due to coalescence

c) Formation of large globules and ganglia and consequently, capillary conducted flow

d) Release and sedimentation of large drops at the exit section.

As the bed gets saturated, at constant influent concentration of the dispersed phase, (and in the absence of solid particulate matter) the average bed pressure drop increases to a pseudo equilibrium level. This is illustrated in Fig. 1. Note that the pressure drop does not reach steady state, but fluctuates around the mean shown in Fig. 1. The relative permeability of the continuous phase at saturation is defined as,

$$K_r = \frac{\Delta P_i}{\Delta P_e} \qquad (1)$$

Both the relative permeability at saturation and the

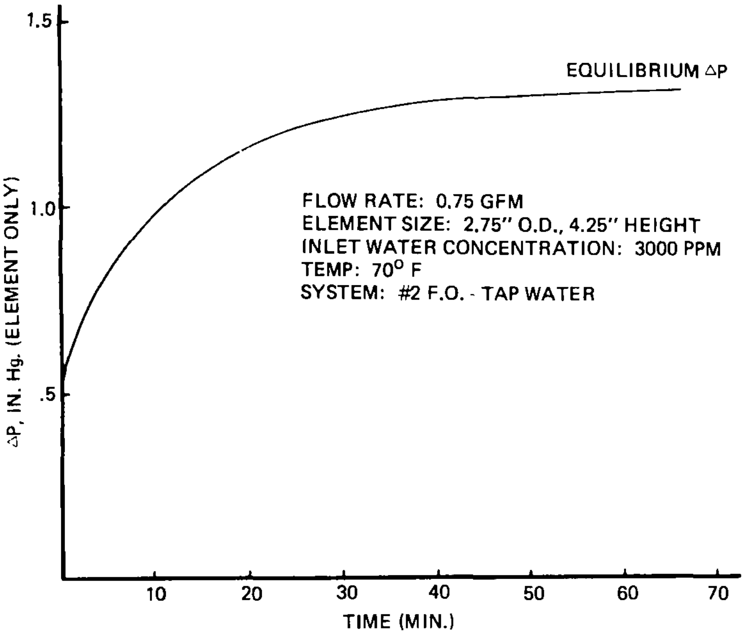


Figure 1

Typical increase in pressure drop due to coalescer bed saturation equilibrium pressure drop are important in determining the life of the coalescer elements.

A brief description of fibrous bed coalescence and design considerations are given by Jaisinghani (2). Reviews related to the general description of the coalescence process are available (3,4,5). Most of this work focuses on the macro description of the coalescence processes. Material balances are typically formulated, wherein the coalescence rate is not defined in terms of interfacial parameters, and usually is calculated after analysis of experimental results. Speilman and Goren (6), Spielman and Su (7) and Rosenfield and Wasan (8), have presented theoretical formulation for the process. Rosenfeld and Wasan (8) postulate the growth due to coalescence and release of coalesced globules due to hydrodynamic forces, while Spielman and Goren (6) and Spielman and Su (7) assume coalescence leading to capillary conducted flow of the dispersed phase.

Clearly, interfacial effects are expected to play an important role in the coalescence process. There has been considerable work related to drop-interface coalescence, emulsion stability and film thinning. For example, Wasan and co-workers (9,10) have illustrated the importance of interfacial shear and dilational viscosity related to oil-in-water emulsion stability. However, there have been few investigations regarding the effect of these and other interfacial properties on the performance of fibrous bed coalescers. The fundamental aspects of emulsion stability may not always have the expected impact on fibrous bed coalescers, since the coalescence process here is taking place under dynamic conditions of higher externally imposed stresses. A qualitative understanding of the importance of the interfacial effects is necessary, prior to incorporation into existing theory. As will be apparent from the work reviewed here, the current level of qualitative understanding is not adequate.

Wettability

The wettability of the fibers is expected to affect the dispersed phase saturation and distribution. Spielman and Goren (6) have shown that dispersed phase preferentially wetted beds have higher values of κ_r at saturation than continuous phase wetted beds. This is due to the smaller pores being occupied by the capillary conducted dispersed phase (S_2') leaving the larger pores open to the continuous phase. Jaisinghani et al. (11) have been able to modify the chemistry of the resin coatings to significantly improve the relative permeability via improved wettability. Resin coatings are essential for elimination of harmful filter media migration and for higher filter structural strength.

The resistance to flow of the continuous phase is also due to held globules (S_2''), in addition to the resistance due to space occupied by the coalesced capillary conducted phase and due to accumulation of this coalesced phase at the exit face of the bed. The wettability determines the form of the dispersed capillary conducted phase at the exit section of the bed. Beds preferentially wetted by the dispersed phase, have an adhering layer of coalesced phase at the exit section of the bed. The pressure loss due to this layer is the local capillary pressure just inside the exit section of the bed (7). The local capillary pressure is a function of the local pore size distribution, coalesced phase saturation (S_2') and wettability. Non-wetted (by dispersed phase) beds do not exhibit this additional resistance to flow.

Spielman and Su (7) used a deep bed of glass spheres and x-ray absorption to measure total oil fraction, S_2, as a function of bed depth (x). Further, by measuring the suspended dispersed phase concentration, f, along the bed and using material balance equations, they attempted to relate the coalescence rate of held globules, R, to the estimated values of S_2'' and S_2'. A typical distribution of S_2 and f is shown in Fig. 2. Similar distributions within thin fibrous beds were obtained by Bitten and Fochtman (12). The concentration, S_2, is highest at x=0. This led Spielman and Su (7) to modify the Spielman and Goren (6) model which only considered the f and S_2' regimes within the porous bed and thus predicted S_2 to be highest at x=L for preferentially wetted beds. They reasoned that the held globules (S_2'') accumulate at the influent section causing S_2 to be higher at this section (7).

At steady state the material balances give:

$$\frac{dn(ap)}{dx} = -\lambda(S_2)n(a_p) \qquad (2)$$

$$\frac{dq_2}{dx} = \varepsilon R \qquad (3)$$

Spielman and Su (7) reason that at steady state the coalescence rate, R, of the held globules must equal the rate of capture of suspended dispersed phase to give:

$$-q_1\frac{df}{dx} = \varepsilon R \qquad (4)$$

However, the following transformations due to coalescence and capture are viable (the rates are also indicated):

$$\begin{aligned} S_2'' &\xrightarrow{R} S_2' \\ f &\xrightarrow{R'} S_2' \\ f &\xrightarrow{R''} S_2'' \end{aligned} \qquad (5)$$

Spielman and Su (7) have, in effect, ignored the direct coalescence of suspended dispersed phase into the capil-

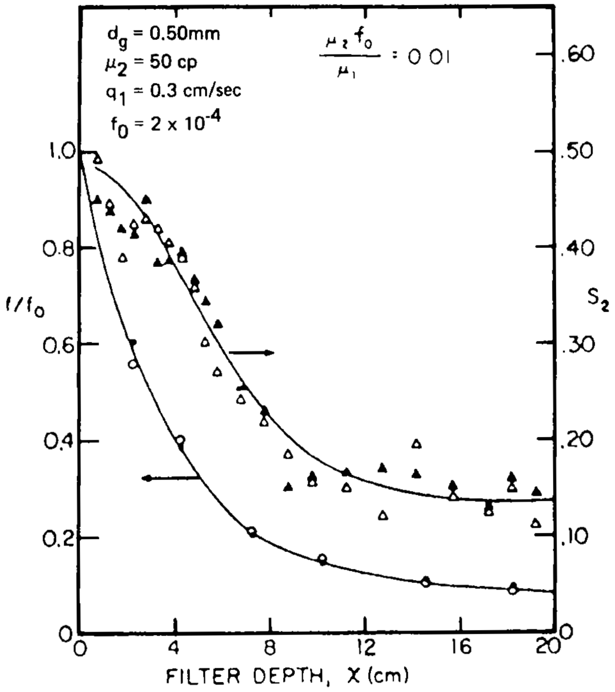


Figure 2

Typical results showing the total volume fraction of suspended oil (left ordinate) and total fraction saturation of held-up oil (right ordinate) as simultaneous functions of filter depth at steady state. The volume fraction of suspended oil is normalized with respect to the incoming volume fraction. Open and dark symbols respectively correspond to duplicated experiments under similar conditions. Reprinted with permission from Spielman and Su (7) . Copyright 1977 by the American Chemical Society.

lary conducted phase. Since S_2' can be as high as 0.2 - 0.3, this is not justified. Based on equation (5), equations (3) and (4) can be written as:

$$\frac{dq_2}{dx} = \varepsilon(R+R') \qquad (6)$$

$$-q_1\frac{df}{dx} = \varepsilon(R'+R'') \qquad (7)$$

If it is assumed that the held globules (S_2'') are not pushed out of the bed by hydrodynamic forces, prior to coalescence into the capillary conducted regime, then the left hand sides of equations (6) and (7) can be equated to give:

$$R+R' = R'+ R'' = \bar{R} \qquad (8)$$

and $$R=R''$$

The above assumption is not valid if the Rosenfeld and Wasan (8) model is valid. Equations (6) and (7) reduce to the Spielman and Su (7) equations (2) and (3), only if R' is neglected.

At any rate, Spielman and Su (7) further assumed that although the capillary conducted dispersed phase and continuous phase are flowing under different local pressures (the difference being local capillary pressure), the pressure gradients are the same. By using an overall mass balance

$$q_2 = q_1(fo-f) \qquad (9)$$

they arrive at the following relationship:

$$\frac{k_2(S_2')}{k_1(S_2)} = \frac{\mu_2 fo}{\mu_1}\left(1-\frac{f}{fo}\right) \qquad (10)$$

The only unknown is $k_2(S_2')$ since f_o is constant and k_1, f and S_2 are directly measured. Thus, by using prior knowledge of k_2 as a function of S_2' (two phase flow experiments) they were able to evaluate S_2'. Then by using equation (4) and experimental data for f with respect to x, they were able to estimate R. S_2'' was calculated by:

$$S_2 = S_2' + S_2'' \qquad (11)$$

Spielman and Su (7) were thus able to relate R to S_2''. They obtained a first order relationship, analogous to chemical reaction kinetics. R, however, also depends on S_2' (from the kinetics analogy) but they were not able to obtain a correlation of R and S_2' since under their experimental conditions S_2' did not vary significantly. The relationship between R and S_2'' reduced to:

$$R \approx 1\text{x}10^{-4}(s^{-1})\ S_2'' \qquad (12)$$

for fairly consistent values of S_2' ($\approx$0.16). This implies that the coalescing globules (S_2'') remain held in the bed for a few hours prior to coalescing into the capillary conducted phase. Fibrous bed coalescers, on the other hand, exhibit coalesced capillary conducted flow at the bed exit in less than half hour or so. This implies that the suspended drop-capillary conducted phase coalescence cannot be ignored. If equations (6) and (7) and an analogous (to Spielman and Su (7)), form of the average total rate, $\overline{R}$, are considered, equation (12) can be interpreted as:

$$\overline{R} = 1\text{x}10^{-4} \cdot S_2'' = k'(f)^r\ (S_2')^s(S_2'') \qquad (13)$$

On an ad-hoc basis, assuming r and s to be unity, k' can be evaluated, for the conditions used by Spielman and Su (7), to be of the order of 1 to 10^1 s^{-1}. The value of S_2' is assumed to be 0.16 and f varies from $2\text{x}10^{-4}$ to 10^{-5} within the bed. Thus, the average coalescence time is of the order of 1 to 10^{-1}s. The minimum residence time to achieve this reduction in f (at steady state) in the Spielman and Su (7) bed and in most realistic coalescer beds at steady state is of the order of 1 to 10^1 seconds for destabilized emulsions. Although inaccurate, this estimate of k' is an improvement over the result obtained by Spielman and Su (7).

The filter coefficient is calculated in a similar manner from the experimental data (7) using equation (2). The local value of λ at any position x along the bed is then related to the observed value of S_2. The results are shown in Fig. 3. The filter coefficients were observed to increase with increasing total dispersed phase concentration. For destabilized emulsions Spielman and Su (7) obtained the following correlation.

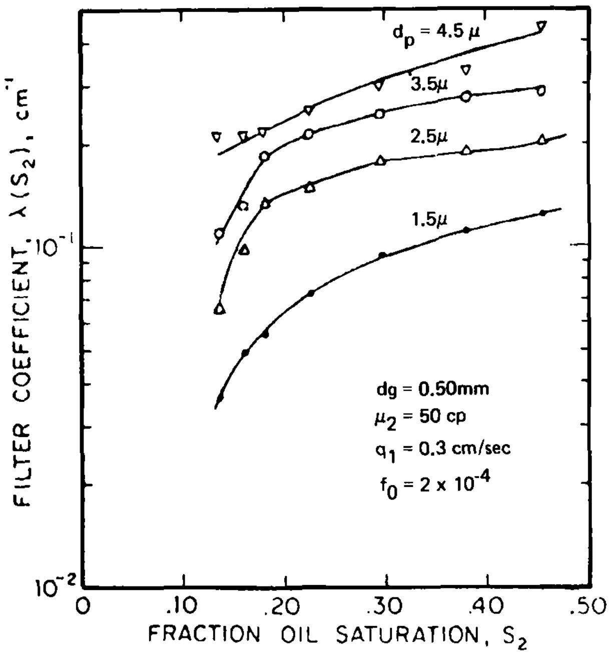


Figure 3

Typical results showing filter coefficients as a function of the fraction saturation of total held-up oil. Each curve corresponds to the microdrop diameter shown. Reprinted with permission from Spielman and Su (7). Copyright 1977 by the American Chemical Society.

$$\frac{dg^3\ \lambda(S_2c)}{d_p^2} = 62.4\ \left\{\frac{Q\ dg^2}{\mu_1 d_p^4 q_1}\right\}^{0.3} \qquad (14)$$

The dependence of the coalescence rate, R, (not withstanding the neglect of suspended drop-capillary conducted regime coalescence) filter coefficient, λ, and saturation relative permeability, κ_r, on the distribution of the dispersed phase regimes has been demonstrated. However, it is not possible to predict the concentration and distribution of these regimes from wettability data.

In a unique use of wettability, Davies et al. (13) have used mixed packings with high and low surface energy materials to enhance coalescence. The mechanisms are not very clear, but the difference in wettability is expected to cause increased flow of the film between drops caught at the intersection of the two different materials.

Interfacial Tension (IFT)

Earlier investigations (cf. Hazlett and Carhart (14)) concluded that the performance of jet fuel-water coalescers with additives depend upon the interfacial tension. However, their experimental results show many examples of good coalescer performance with low interfacial tension systems. Jaisinghani (15) conducted experiments using water-in-fuel emulsions (created by a 3500 rpm pump) equilibrated (aged) with common fuel oil additives (surfactants) and observed good coalescer performance at low interfacial tension. These results were analyzed in terms of interfacial properties by Jaisinghani and Verdegan (16). Their results (Fig. 4) show that coalescer performance cannot be explained by IFT alone. Each point in Fig. 4 represents the average coalescer performance for a particular oil-water-surfactant system. Some of the points are labeled, such that the same surfactant system can be identified in the following analysis (Figs. 5 and 6).

Drop Charge

The early work of Bitten, as reviewed by Fochtman et al. (17) has shown some evidence of captured water drops forming dendrite structures on single nylon fibers. Further, the electrical double - double layer of the water-in-oil system is expected to be predominantly in the oil phase. Spielman and Su (7) observed a loss in suspended drop removal for oil-in-water systems where

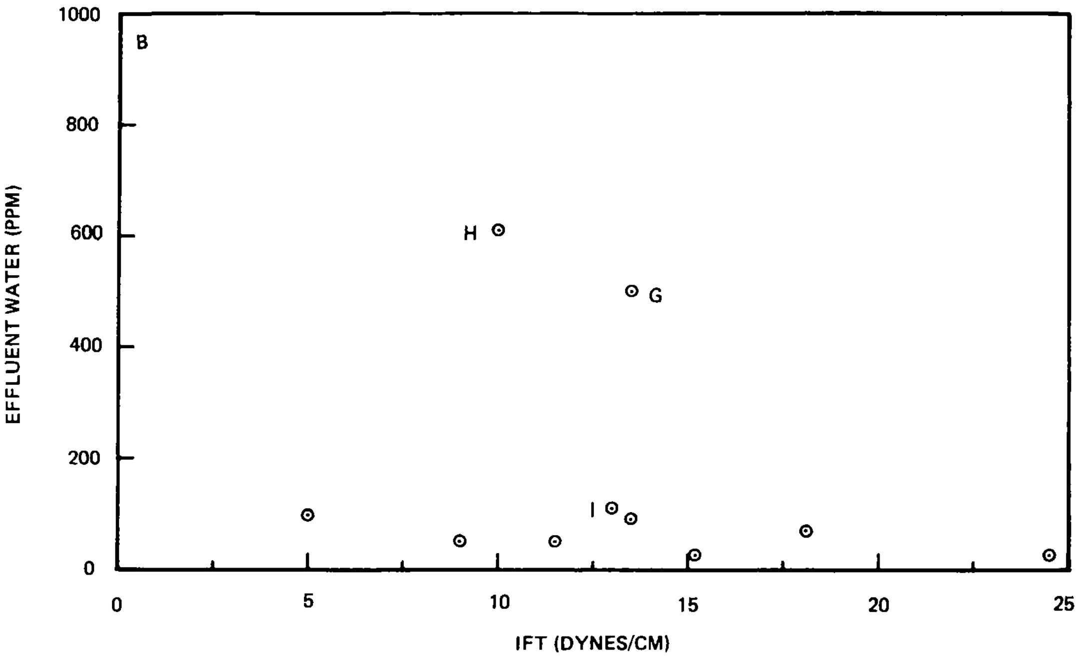


Figure 4 - Coalescer effluent concentration, (ppm undissolved water) versus interfacial tension, IFT (dynes/cm) System - #2 Fuel oil-water + fuel additives.

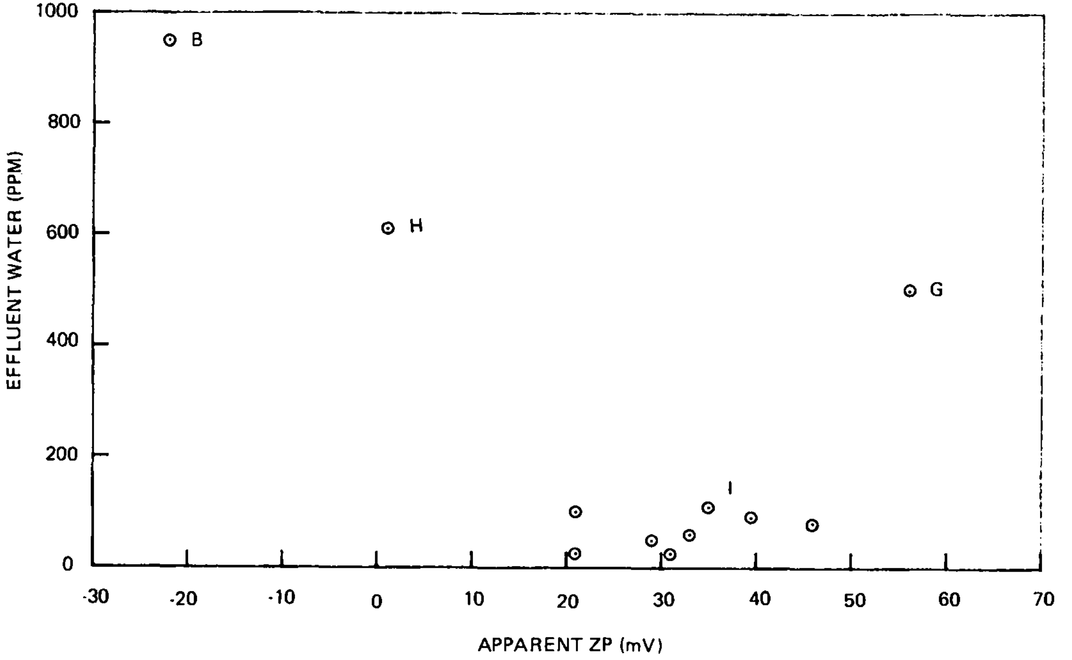
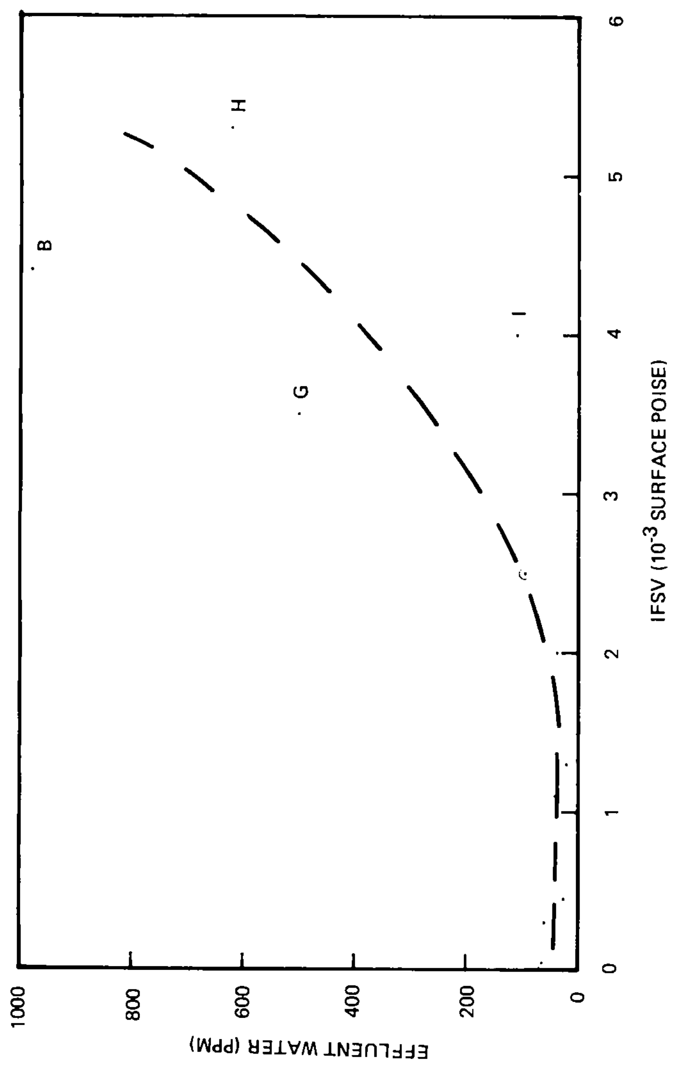


Figure 5 - Coalescer effluent concentration (ppm, undissolved water) versus apparent zeta potential, ZP (mV). System - #2 Fuel oil-water + fuel additives.



<u>Figure 6</u> - Coalescer effluent concentration (ppm undissolved water) versus interfacial shear viscosity, IFSV, ($x10^{-3}$ surface poise) System - #2 Fuel oil-water + fuel additives.

the double layer was not sufficiently supressed by acid. All this suggests, that strong charge effects are coming into play. Jaisinghani and Verdegan (16) investigated the effect of the drop-drop double layer interaction on the coalescence in fibrous beds. The electrophoretic mobility of water drops in oil with different fuel additives were measured by microelectrophoresis. The measuring technique met the criteria of measurement established by van der Minnie and Hermanie (18) for solids in ultra low conductivity fluids. However, it is highly probable that the introduction of emulsified water distorted the field. Hence, the observed mobilities were reported in terms of an apparent zeta potential (Fig.5). Jaisinghani and Verdegan (16) did not measure the apparent zeta potential of the fibrous structure. It was reasoned that the fiber would have a similar charge due to adsorption. Fig. 5 shows the effect of apparent zeta potential on coalescence for the same surfactant systems shown in Figs. 4 and 6. Fig. 5 suggests that there is possibly a zero offset in the zeta potential (perhaps due to a shift in the stationary plane caused by the introduction of water). If a constant zero offset can be assumed, then the expected relationship between zeta potential and coalescer performance is suggested by Fig. 5, viz. the best performance occurs at low drop charge while high (+ve or -ve) charge levels inhibit the coalescer. However, if there is no zero offset, then no reasonable relationship seems to exist between drop charge and coalescer performance. Clearly, a more rigorous study with fiber charge consideration is necessary for further understanding the role of double layer forces in fibrous bed coalescence.

Interfacial Shear Viscosity

Wasan and co-workers (9,10) have shown the importance of interfacial rheological parameters in the stability of oil-in-water emulsions, stabilized by relatively high concentrations of surfactants. Jaisinghani and Verdegan (16) evaluated the effect of interfacial shear viscosity, (of the fuel oil-water interface at equilibrium with the previously discussed additive/surfactant systems) on coalescer performance (Fig. 6). The interfacial shear viscosity was measured, using a viscous traction surface viscometer, similar to the one used by Wasan and Mohan (9). The results (Fig. 6) show good qualitative correlation even though the highest measured interfacial shear viscosities are relatively low when compared with the results of Wasan and coworkers (10). Additive G does not fit this qualitative dependence of coalescer performance probably due to its high surface charge (See Fig. 5).

These results (Figs. 4-6) show that the stability of emulsions flowing through fibrous beds is complicated and depends on more than one variable. It is not reasonable to estimate coalescer performance on the basis of IFT alone. The interfacial shear viscosity seems to be important, however, measurements of streaming potential during the capture phase of a coalescer (i.e. as the held dispersed phase concentration is increasing) and high confidence measurements of drop electrophoretic mobility are needed, in order to evaluate the drop-fiber double layer interaction. This presents significant experimental problems due to the presence of water. Before a quantitative description of the coalescence process can be developed, a thorough qualitative understanding of the role of interfacial forces is necessary.

NON-AQUEOUS FINE SOLIDS FILTRATION

Although petroleum oils have low dielectric constants and ultra low conductivities, particles suspended in the oils exhibit electrophorectic mobility. van der

Minnie and Hermanie (18,19) have shown that carbon particles in benzene with extremely low ionic concentration exhibit high levels of charge. Since then, there have been a number of investigations regarding the charge characteristics of particles in different non-aqueous systems. However, direct investigations regarding the impact of the charge on filtration are limited. Assuming the validity of the Gouy-Chapman model, the double layer thickness in these systems is usually of the order of a micrometer. This is due to the ultra low conductivities ($\approx 10^{-10}$ to 10^{-12} mho/cm). Hence, the double layer interaction is expected to play an important role in non-aqueous filtration.

Chowdhiah et al. (20) conducted filtration experiments with simultaneous measurements of streaming potential. This was the first investigation of the effect of double layer interaction in non-aqueous filtration. Fine (0.3 μm average size) carbon black was suspended in tetralin with ≈4500 ppm of Aerosol OT. The filter media was silica sand (81 μm size), of 1.5 cm and 0.9 cm bed depths. Fig. 7 shows a typical filter run; both streaming potential and effluent turbidity ratio are plotted against time. The coincidence of breakthrough, with filter media neutralization, is remarkably consistent for all the runs. The maximum value of specific deposit attained, prior to breakthrough was $4\times10^{-4}\mathrm{m}^3$ deposit/m^3 filter. Since, this value is too low for significant change in the filter morphology, the experimental evidence (Fig. 7) points to the strong effect of double layer interaction on filtration. Assuming charge neutralization due to particulate capture alone, they have used the Wnek et al. (21) charge balance approach in conjunction with material and rate balance equations of deep bed filtration to model the behaviour of the filter. The qualitative relationship between the influent con-

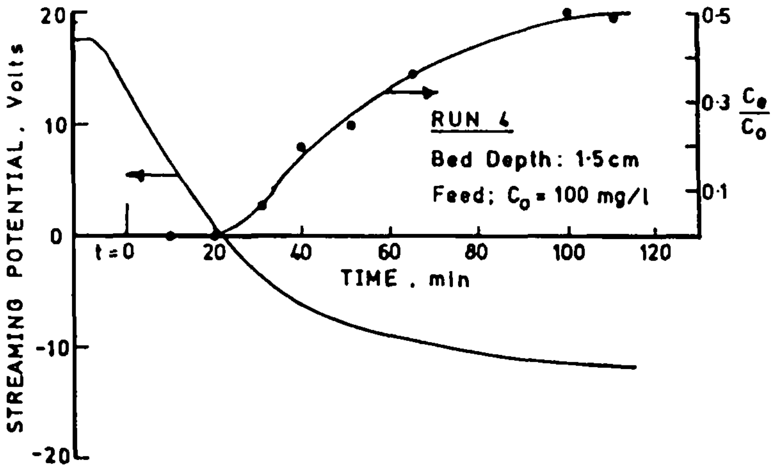


Figure 7

Filtrate turbidity and streaming potential curves for the filtration of carbon black from tetralin + 10 millimoles per liter Aerosol OT through a bed of sand. From Chowdhiah et al. (20). Used with permission of AIChE J.

centration and time for charge neutralization (evident in their experimental work) seems to justify this assumption. Using a similar approach but with conditions more relevent to non-aqueous fibrous cartridge filtration, Jaisinghani and Verdegan (22), however, reported rapid charge neutralization and reversal. This was due to adsorption of antistatic additive Shell ASA-3 (used instead of Aerosol OT) on the fibrous filter media in their study using hydraulic oil.

Jaisinghani and Verdegan (22) conducted a preliminary investigation of the role of electrokinetics in hydraulic oil filtration and the effect of 50 ppm of antistatic additive ASA-3. An important difference over the conditions used in the previous study (20), is that the conductivity, in this case ($\approx 10^{-11}$ mho/cm), was lower by one order of magnitude. Previous experience has shown that in the absence of ASA-3, the reproducibility of filter tests is poor. 50 ppm of ASA-3 seems enough to improve reproducibility. This level of ASA-3 was also enough to improve conductivity of the oil such that reasonable measurements of electrophoretic mobility of AC Fine Test Dust (ACFTD) could be made. These results are shown in Fig. 8. The charge, at each level of ASA-3 was distributed due to the heterogenous nature of ACFTD. The variation of ACFTD charge due to different batches of oil was observed. This variation was minimized by clay filtering the oil prior to addition of ASA-3. Apparently, as observed by van der Minnie and Hermanie (18,19) the presence of traces of multiple ionic species has a complex effect on the zeta potential. This would explain the problem of reproducibility of filtration tests.

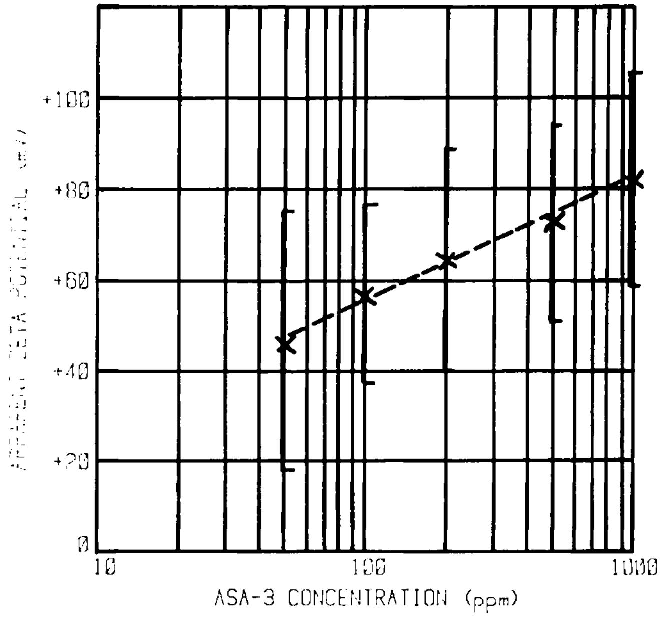


Figure 8

The effect of ASA-3 concentration on ACFTD apparent zeta potential.

In this study (22), glass fibers (0.8 μm) with and without a charge modifying coating were used as the filter medium. The filter media with an initial charge opposite to the ACFTD (i.e. negative) is referred to as media A, while the media with positive charge is referred to as media B. ACFTD was the contaminant in hydraulic oil. Although widely used, there is considerable debate regarding the mean size and shape factors of ACFTD. The number mean is expected to be between 1-3 μm.

Experiments were conducted with 0 and 50 ppm of ASA-3 as the ionic additive in the oil. Since small samples of fiber mats were used, there were significant deviations in the average (charge modifying) surface coating of the fibers, resulting in deviations of initial streaming potentials. This resulted in filter materials of varying initial streaming potential. However, all the physical properties such as fiber diameter and porosity were identical for these filter materials. This made it possible to qualitatively determine the effect of the double layer interaction from initial filter streaming potential and particle (ACFTD) zeta potential measurements.

Filtration performance measurements were made in terms of the filtration ratio at 5 μm:

$$\beta_5 = \frac{\text{No. of particle} > 5\ \mu\text{m, upstream}}{\text{No. of particle} > 5\ \mu\text{m, downstream}}$$

The filtration ratio at 5 μm was chosen since the optical particle counter accuracy below this limit is not reasonable. Figs. 9 and 10 show the results for hydraulic oil, with 0 ppm and 50 ppm of ASA-3 respectively. Each data point represents a different run. The data includes only initial measurements (made at 5 minutes). The results illustrate the effect of the double-layer interaction on filter performance. Keep-

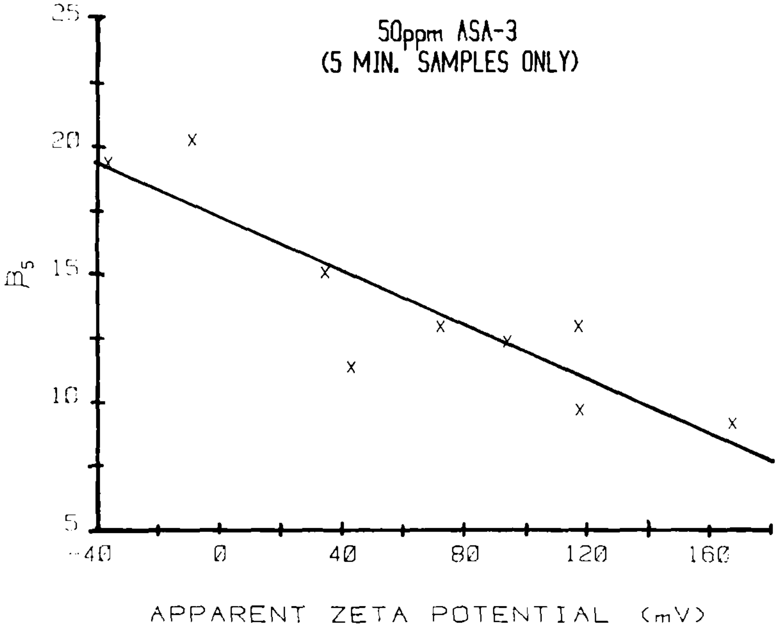


Figure 9 - Filtration ratio, β_5 versus apparent media zeta potential at 5 minutes. System - ACFTD suspended in Mil 5606 hydraulic oil containing 50 ppm ASA-3.

-ing in mind that the particles were positively charged (≈50mV) with the 50 ppm ASA-3 system, filter media having an initial negative charge or lower level of positive charge, (i.e. less repulsion) performed better initially than highly positively charged filter media (Fig. 9). With the 0 ppm ASA-3 system, all the filter media had negative charge levels (Fig. 10). Fig. 10 shows the same dependence of filtration ratio on the apparent zeta potential. This suggests that the ACFTD is slightly positively charged even with 0 ppm of ASA-3. This may be due to the presence of other trace impurities. It was not possible to confirm this by micro electrophoresis measurements due to the extremely low ($\approx 10^{-13}$ mho/cm) oil conductivity with 0 ppm of ASA-3.

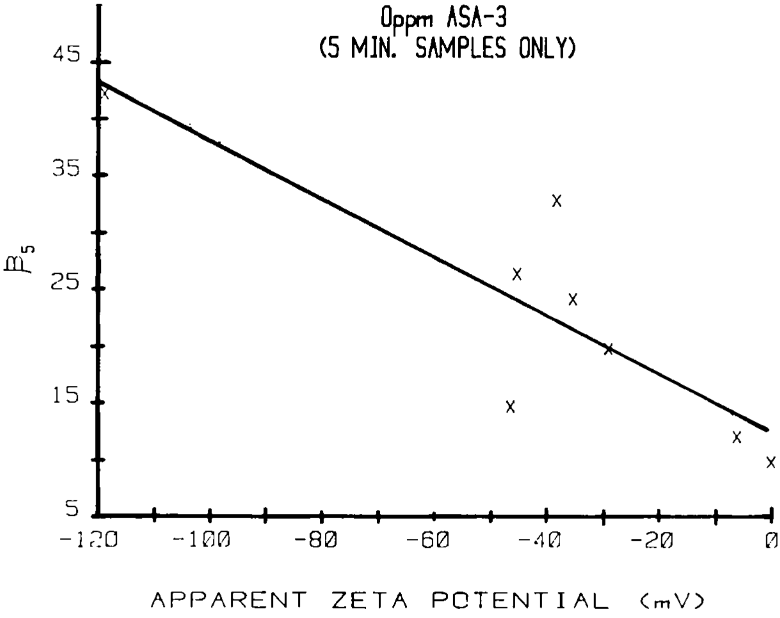


Figure 10 - Filtration ratio, β_5 versus apparent media zeta potential at 5 minutes. System - ACFTD suspended in Mil 5606 hydraulic oil containing 0 ppm ASA-3.

Since fine fibers and relatively coarse particles are used, straining is an important (although undesirable) mechanism in fibrous cartridge filtration. Hence, in this study (22), as the pressure drop increased, straining increased, such that the initial dependence of β_5 on the apparent zeta potential was masked. Also to be noted is the fact the β_5 decreased with time until the bed pressure drop increased over 100% of the initial, after which β_5 increased due to the straining mechanism. However, a steady curve for β_5 versus time (such as obtained by Chowdhiah et al. (20)) was not obtained in this study. This was probably due to the different conditions and filter media used in the two studies. Jaisinghani and Verdegan (22) were restricted to conditions used in a standard hydraulic filter test (23), since one of their goals was to analyze this test.

The results of Chowdhiah et al. (20) and Jaisinghani and Verdegan (22) illustrate the possibility of media surface charge manipulation to increase filter performance without increased restriction. A problem with the charge modifying coating used in the above study (22) is that the modified media (A) rapidly loses its original charge due to adsorption of the ionic additive. Although, charge reversal occurs for both media A and B, the resultant repulsive interaction was less for media A, for the duration of the filtration runs. For longer time periods, both media A and B ended up with similar repulsive charge levels. It should, however, be possible to develop surface coatings with lower adsorption potentials, resulting in improved filters.

CONCLUSIONS

It should now be clear that there has been an insufficient amount of work related to the role of interfacial phenomena in the filtration and separation of non-aqueous (petroleum product) systems. Clearly, more experimental work is needed to support further theoretical formulation. Specifically, attention is needed in the following areas related to coalescence:

1) Development of convenient methods for determination of wettability/capillary pressure and dispersed phase distribution inside thin beds.

2) Relate wettability to dispersed phase distribution inside fibrous beds.

3) Investigate the importance of interfacial dilational viscosity on coalescer performance.

4) Reliable methodology is needed to measure charge on water drops suspended in oil; also, the stream-

ing potential measurement difficulties, during the water drop capture phase of a clean fibrous bed coalescer, need to be resolved so that the role of double layer interaction can be better evaluated.

For solid, non-aqueous fibrous filtration, the areas needing attention are:

1) Development of a better understanding of the structure of the non-aqueous, ultra low conductivity system double layer.

2) Thus, the development of improved interpretation of electrophoresis and streaming potential experiments.

There is a need for further fundamental work related to non-aqueous solid particle and emulsion stability. This may then make it possible to define the filtration rate parameters in terms of interfacial properties.

SYMBOLS

a_p - microdrop radius, cm

C_e - effluent solids concentration (turbidity units)

C_o - influent solids concentration (turbidity units)

d_g - spherical collector diameter, cm.

d_p - particle or drop diameter, cm.

f - local volume fraction of dispersed phase

f_o - volume fraction of dispersed phase at inlet

k_1 - local permeability to continuous phase, cm^2

k_2 - local permeability to capillary conducted phase cm^2

k' - coalescence rate coefficient, s^{-1}

L - bed thickness, cm.

$n(a_p)$ - suspended drop number concentration distribution, number/cm^4

p_1 - local pressure in continuous phase, dyne/cm^2

p_2 - local pressure in capillary conducted phase, dyne/cm^2

P_c - local capillary pressure, dyne/cm^2

q_1 - continuous phase superficial velocity, cm s^{-1}

q_2 - capillary conducted phase superficial velocity, cm s^{-1}

Q - Hamaker constant, ergs

R - volume of held globules coalescing into capillary conducted phase per unit pore volume, per unit time, s^{-1}

R' - volume of suspended phase coalescing into capillary conducted phase per unit pore volume, per unit time, s^{-1}

R'' - volume of suspended phase coalescing into held globules per unit pore volume, per time unit, s^{-1}

$\overline{R}$ - $= R' + R''$ i.e. average total coalescence rate per pore volume, s^{-1}

r, s - emperical exponents

S_2' - fraction saturation of capillary conducted phase

S_2'' - fraction saturation of dispersed phase intermediate held globules

S_2 - $= S_2' + S_2''$ i.e. fraction saturation of total held dispersed phase, includes capillary conducted and held globules

S_{2c} - critical fraction saturation of dispersed phase

x - distance into bed from inlet face, cm

ΔP_e - pressure drop at equilibrium or saturation, dyne/cm

ΔP_i - initial, continuous phase only pressure drop, dyne/cm

β_5 - 5 μm filtration ratio, (equ. 13)

κ - relative permeability of continuous phase at saturation

λ - filter coefficient

μ_1 - continuous phase viscosity, g cm^{-1} s^{-1}

μ_2 - dispersed phase viscosity, g cm^{-1} s^{-1}

ε - Porosity

REFERENCES

1. M. F. Winkler, Marine Eng. Log, 88, (1983).

2. R. A. Jaisinghani, Handbook of Multi-Phase Systems; (Ed. G. Hetsroni), Hemisphere Pub. Co., N.Y. 1982

3. D. F. Sherony, R. C. Kintner and D. T. Wasan, Surf. and Coll. Sci., (Ed. E. Matijevic), Vol. 10, Plenum Press, New York, 1978.

4. W. M. Langdon and D. T. Wasan, Recent Developments in Separation Sci., 5, (1979).

5. L. A. Spielman, S. L. Goren, Flow Through Porous Media, ACS, Washington, D. C., 1970.

6. L. A. Spielman and S. L. Goren, Ind. and Eng. Chem. Fund. 11, 66, (1972).

7. L. A. Spielman and Y. P. Su, Ind. and Eng. Chem. Fund., 16, 262, (1977).

8. J. I. Rosenfeld and D. T. Wasan, Can. J. Chem. Eng., 52, 3, (1974).

9. D. T. Wasan and V. Mohan, in Improved Oil Recovery by Surfactants and Polymer Flooding, (eds. D. O. Shah and R. S. Schechter), Academic Press, New York, 1977.

10. V. Mohan, S. M. Shah, P. S. Patel and D. T. Wasan, paper at 83rd AIChE National meeting, Houston, March, 1977.

11. R. A. Jaisinghani, G. Sprenger, G. Deeley, C. Wilkie, and R. Roberts, proc. of Theory, Practice and Process Principles for Physical Separations, (ed.s M. P. Freeman and J. A. Fitzpatrick), Engineering Foundation, N.Y., 1981.

12. J. F. Bitten and E. G. Fochtman, J. Colloid Interface Sci. 37, 312, (1971).

13. G. A. Davies, G. V. Jeffreys, and M. Azfal, Brit. Chem. Eng. and Proc. Tech., 17, 709, (1972).

14. R. N. Hazlett and H. W. Carhart, Filtration and Separation, 9, 456, (1972).

15. R. A. Jaisinghani, Filtration and Separation, 14, 367, (1977).

16. R. A. Jaisinghani and B. M. Verdegan, presented at Filtration 80's, Filtration Society meeting, Minneapolis, November, 1979.

17. E. G. Fochtman, J. F. Bitten and R. H. Snow, proc. World Filtration Cong. III, Vol. II, 654, Downingtown, PA. September 13-17, (1982).

18. J. L. van der Minnie and P. H. J. Hermanie, J. of Colloid Sc., 7, 612, (1952).

19. J. L. van der Minnie and P. H. J. Hermanie, J. Colloid Sc., 8, 38, (1953).

20. P. Chowdhiah, D. T. Wasan and D. Gidaspow, AIChE J., 27, 975, (1981).

21. W. J. Wnek, D. Gidaspow and D. T. Wasan, Chem, Eng. Sci., 30, 10, (1975).

22. R. A. Jaisinghani and B. M. Verdegan, proc. World Filtration Congress, III, Vol. II, 618, Downington, PA. September 13-17, (1982).

23. American National Standards Instutute, Document No. ANSI B93.31, (1973).