

Factors in the Coalescence of Water in Fuel

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CONTENTS

Abstract	ii
Problem Status	ii
Authorization	ii
INTRODUCTION	1
THEORETICAL CONSIDERATIONS	2
Approach Mechanisms	2
Attachment	8
Release	10
EXPERIMENTAL DETAILS	11
Coalescer Material	13
Surfactants	14
Analysis for Water	14
EXPERIMENTAL RESULTS	15
Effect of Flow Velocity	15
Physical Characteristics of the Coalescer Bed	16
Surface Chemical Considerations	19
Examination of Filter/Separator Elements	21
DISCUSSION	22
CONCLUSIONS AND RECOMMENDATIONS	25
ACKNOWLEDGMENTS	25
REFERENCES	26

ABSTRACT

The removal of water from jet fuel is a necessity for the efficient operation of jet aircraft and the reduction of maintenance requirements. Experimental work has been performed to examine the important factors and forces in the coalescence phenomenon by which water is normally removed from jet fuel in field operations. The basic tool used in this study was the Water Separometer. The experimental work was supported by theoretical calculations. The interception process, rather than diffusion or inertial-impaction, is the primary mode of water-droplet approach to a fiber when a water-in-fuel emulsion is coalesced in a fibrous bed. The experimental evidence for the importance of small fibers in the coalescer material is supported by calculations for the interception process. The attachment step does not appear to be critical in the overall coalescence process. Surface-active materials function at the fuel/water interface rather than the fuel/solid interface. The marked deterioration of performance caused by surfactants in the fuel is thought to be related to phenomena occurring at the point of droplet release at the downstream face of the coalescer.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

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FACTORS IN THE COALESCENCE OF WATER IN FUEL

INTRODUCTION

Aircraft fuels are subject to contamination by a number of undesirable materials, such as corrosion products, microbiological debris, surface-active agents, gums and varnishes from oxidative degradation of the fuel, and water. Water is a critical contaminant, since corrosion and microbiological growth can be controlled by the removal of free water (1). In addition, the presence of free water may cause icing problems with low-temperature operations. The corrosion of aircraft fuel metering and flow-regulating mechanisms is the most significant problem with water contamination in Navy aircraft. This corrosion is due to the frequent occurrence of salt in the contaminating water.

The removal of water becomes more difficult as the fuel becomes heavier. Thus, jet fuels are more subject to contamination by water than aviation gasoline, and JP-5, because of its higher viscosity and density, retains free water more readily than JP-4 (2).

Water may occur in fuel in two forms: dissolved water and particulate water. Dissolved water amounts to 60 to 100 ppm for jet fuels at normal operating temperatures. Since the solubility of water in jet fuel decreases with temperature, the dissolved water becomes particulate water when the fuel is cooled. This phenomena has not resulted in icing difficulties with Navy jets of recent design because flight times are not long enough to cool the fuel to the critical temperature required for ice formation.

Particulate, or free, water is readily emulsified in fueling systems which use high-speed centrifugal pumps and are characterized by turbulent flow in fuel lines. A centrifugal pump readily produces a water-in-fuel emulsion in which 90% of the water droplets are less than 4.8μ in diameter and 100% are less than 8.6μ in diameter (3).

Water droplets of this size do not settle out of jet fuel if there is any agitation or sloshing in the storage tank or if thermal gradients are present. The drop size may be increased by passage of the emulsions through a fibrous bed. In this situation, small droplets are retained until growth occurs by coalescence. The larger drops are then swept from the fiber bed by dynamic forces and ideally are of such size that they can separate by gravitational forces. Fueling equipment employing this principle is known as a filter/separator. In addition to coalescing and separating emulsified water, this equipment serves as a filter for solid matter which is retained in the fibrous bed. A filter/separator typically consists of two stages. The first is a resin-bonded glass-fiber bed which retains solid matter and coalesces water drops. The second stage, a hydrophobic screen or paper, is included to strip water drops of an intermediate size which are too small to settle by gravity forces but too large to pass through the pores of this separator stage along with the continuous fuel phase (4).

A well-designed filter/separator can and does give excellent performance in all types of aircraft fueling systems, both on shore and at sea. The military services use filter/separators with fueling rates of 10 to 600 gal/min. The physical size of a particular installation is controlled by the fiber-bed-flow velocity, which has an upper limit of 1 to 2 ft/min. The performance of a filter/separator may be inadequate if the jet fuel contains surface-active materials (2). The presence of surfactants requires care on the part of the refiner, the transporter, and the user to insure that undesirable surfactants

are absent from the fuel. A consequence of the presence of additives is that certain ones, such as corrosion inhibitors and antioxidants, which might otherwise be useful in controlling certain fuel properties, must be selected carefully.

The coalescing capability of a filter/separator may deteriorate with time. The deterioration in performance may be gradual or sudden. It has not been possible to relate it to fuel quality or the amount of solid material retained in the fiber bed, nor has it been related to structural failure of the fiber bed, since recovery of coalescing ability has been observed (5).

It can be concluded that the complex events occurring in a filter/separator are not adequately understood. Further, the improvement of this type of equipment requires research into the mechanisms of coalescence. The work described in this report examines the factors and forces in coalescence in an effort to understand the physical and chemical phenomena involved and to determine the critical factors for coalescence. Continuing studies based on the work reported here should lead to improved design and operation of filter/separator units.

THEORETICAL CONSIDERATIONS

The process of coalescence in a fibrous bed may be divided into three main steps: (a) approach of a droplet to a fiber or to a droplet attached to a fiber, (b) attachment of a droplet to a fiber or to a droplet already attached to a fiber, and (c) release of an enlarged droplet from a fiber surface. Each of these major steps involves considerable complexity or alternate mechanisms. These mechanisms will be considered in the following sections.

Approach Mechanisms

A water droplet in a fuel emulsion must first arrive at a proper location before the subsequent steps of coalescence can occur. Three mechanisms of approach of a droplet can be envisioned: (a) interception, (b) inertial impaction, and (c) diffusion. All three of these mechanisms have been shown to be important in aerosol filtration, and the predominant mechanism varies with the flow velocity (6,7).

Superimposed on each of these approach mechanisms are the mechanisms of electrostatic and gravitational forces. Since water droplets in fuel and fibers in a flowing fuel have electrostatic charges, the sign and size of the respective charges would determine the amount of increase or decrease in the efficiency of the three primary approach mechanisms due to this type of phenomenon. Vinson has shown that gravitational effects are minor for small particles (8).

Interception — In laminar flow, a fluid passing a submerged cylinder, such as a glass fiber, will follow flow streamlines such as those depicted in Fig. 1a, where F is the cross section of a fiber. A water droplet w_1 will follow these flowlines. The droplet shown on streamline s_4 will be intercepted by the fiber when it reaches the position indicated as w_2 . A droplet of somewhat smaller size, w_3 , following streamline s_2 , which is equidistant with s_4 from the centerline, would pass the fiber without opportunity for interaction, even at closest approach, w_4 . Such a smaller droplet would be intercepted, however, if it were following a streamline closer to the centerline of the fiber.

In evaluating the interception mechanism, a simple relation proposed by Ranz (9) can be used:

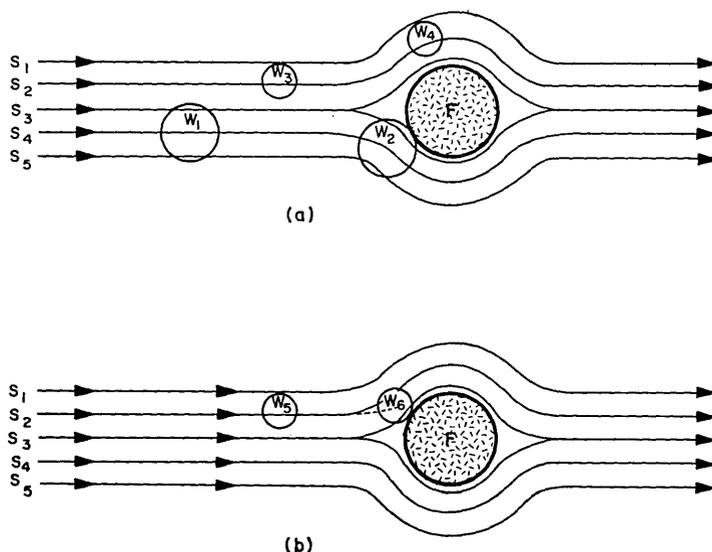


Fig. 1 - Flow patterns for interception and inertial impaction mechanisms

$$E = (1 + R) - \frac{1}{1 + R},$$

where E = efficiency of collection by a single isolated fiber, R = interception parameter = d_p/d_F , d_p = particle diameter, and d_F = fiber diameter. The effect of flow velocity is ignored in this formulation, however, and the equation developed by Langmuir is more widely used (10):

$$E = \frac{1}{2(2 - \ln N_R)} \left[2(1 + R) \ln(1 + R) - (1 + R) + \frac{1}{1 + R} \right],$$

where N_R = Reynolds number. The Reynolds number includes the velocity term and uses d_F as the characteristic dimension. The need for including the Reynolds number arises from the fact that the streamlines are influenced by the Reynolds number, being affected at a greater distance upstream from the fiber and displaced further from the fiber laterally as the Reynolds number (or velocity for a fixed particle diameter) decreases.

The effects of fiber and droplet size on the efficiency of a single, isolated fiber for interception of small water droplets in JP-5 fuel, based on the Langmuir equation, are shown in Fig. 2. The efficiency increases as the flow velocity increases but does not change very rapidly in the 0.01 to 0.1 ft/sec range, the velocity region of practical importance. The efficiency of interception varies greatly with fiber diameter, the smaller fibers being significantly more efficient. Thus, a 2- μ fiber is about 15 times more effective than a 10- μ fiber in removing 1- μ water drops from a jet-fuel stream of a width equal to that of the respective fiber diameters and flowing at 0.03 ft/sec. The efficiencies of the 1 and 2- μ fibers are appreciable, whereas that of the 10- μ fiber is quite low.

Inertial Impaction — A particle with a density different from that of a fluid with which it is flowing will deviate from the flow streamlines should the latter be diverted. A more dense particle will tend to move in a line less curved than that of the streamline. A possible path for a more dense particle is illustrated in Fig. 1b, where the dotted line indicates the departure from streamline S_2 . Particle W_5 , in deviating from the streamline, approaches close enough to the fiber to be captured when it reaches position W_6 . Thus,

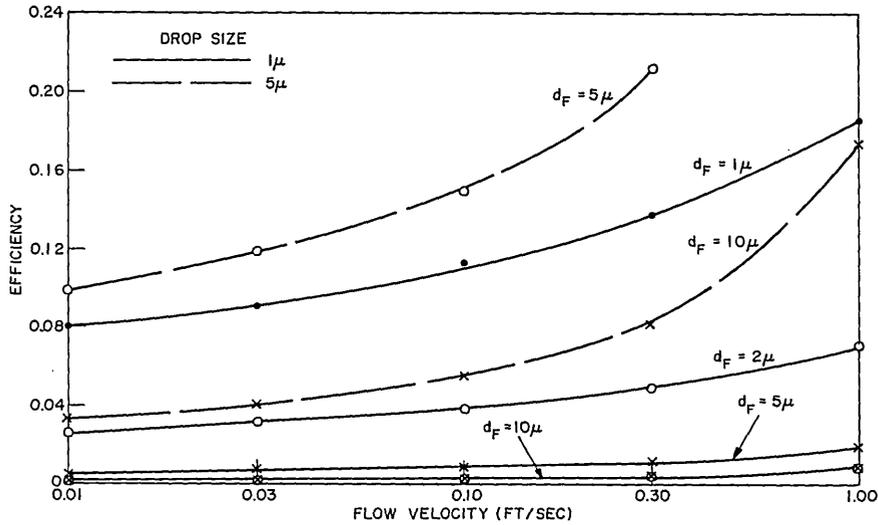


Fig. 2 - Efficiency for interception mechanisms; fuel density is 0.80 g/ml and fuel viscosity is 1.0 cp

the greater the density a particle has with respect to the continuous phase, the higher the probability that the particle will be captured. This approach mechanism has been called inertial impaction.

In aerosol filtration, inertial impaction is a significant mechanism for particle removal (6). Because of the low viscosity and density of air, inertial impaction is the most important mechanism at high-flow velocities. Since the density of jet fuel is close to that of water and the viscosity of a liquid is much higher than that of a gas, the significance of inertial impaction must be somewhat less for water-in-fuel emulsions than for aerosols. To evaluate the contribution of this mechanism to coalescence, the inertial parameter K of aerosol technology (11) was calculated for various conditions using the equation

$$K = \frac{(\rho_{H_2O} - \rho_F) V (d_p)^2}{9\eta d_F}$$

where ρ_{H_2O} = density of water, ρ_F = density of fuel, V = flow velocity of fuel, and η = viscosity of fuel. A density difference of 0.2 g/ml and a fuel viscosity of 1.0 cp were used for the calculations which are plotted in Fig. 3. The value of K increases with the velocity and with the water-drop size. The inertial parameter decreases, however, as the fiber diameter increases.

The application of the inertial parameter to efficiency calculations has been on an empirical basis. Landahl and Herrmann (12) used the formula

$$E = \frac{K^3}{K^3 + 1.54K^2 + 1.76}$$

to determine filtration efficiencies for aerosols at high Reynolds numbers (10 and above). This formula, which has supporting experimental work, was used to obtain the data plotted in Fig. 4. The efficiency of inertial impaction falls rapidly as K decreases, and it is evident that this mechanism is inefficient at most of the conditions shown on Fig. 3. The velocity must be quite high and the drop size large in order to attain a significant efficiency. The actual efficiencies in coalescence would probably be somewhat less than

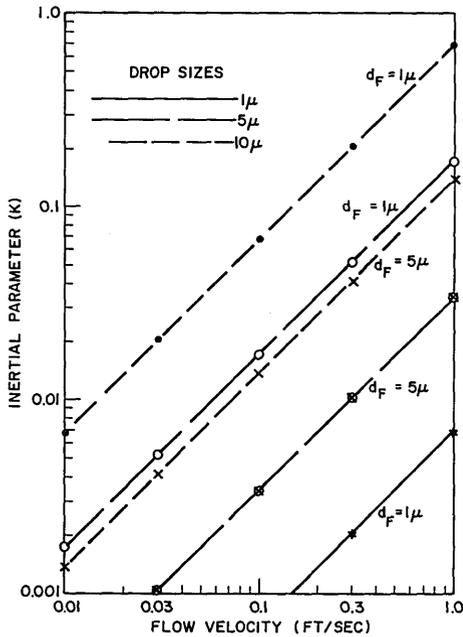


Fig. 3 - Inertial parameter as a function of flow velocity; fuel viscosity is 1.0 cp and density difference is 0.2 g/ml

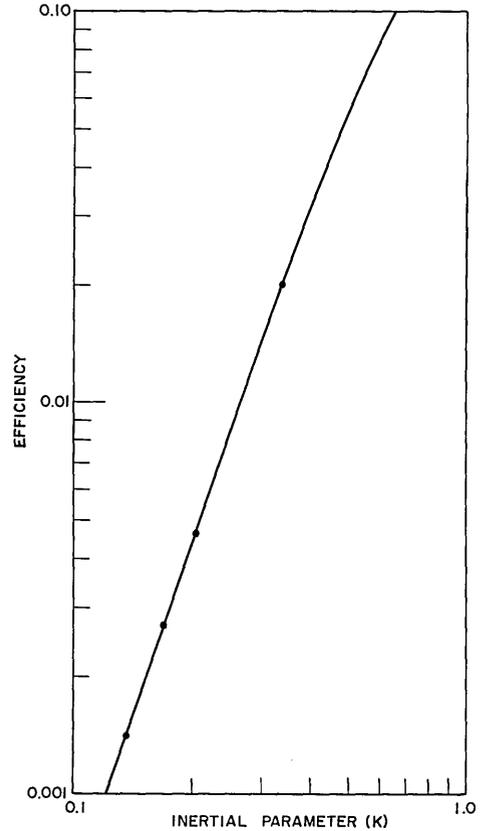


Fig. 4 - Efficiency as a function of the inertial parameter

those shown on Fig. 4, since the Reynolds number is usually less than 1 in coalescers. Although inertial phenomena have not been dealt with satisfactorily, Davies' (13) study has indicated a much lower efficiency for aerosol filtration at a N_R of 0.2 than a N_R of 10. If this effect holds true for liquid filtration, it can be concluded that inertial impaction contributes very little to the coalescence of the emulsions considered in this report.

Diffusion — A particle moving with a fluid will tend to depart from the flow streamline for reasons other than inertia. The most important of these is the random transverse motion due to diffusion. Capture of particles by the diffusion mechanism is important at lower flow velocities in aerosol filtration. The higher viscosity of liquids would lower the efficiency, while the generally lower flow velocities used in liquid filtration would raise the efficiency by this mechanism in water coalescence in a fuel. The viscosity of the fluid is incorporated in the following relation for the diffusion coefficient along with the temperature and the particle size:

$$D = \frac{kT}{3\pi\eta d_p}$$

where D = diffusion coefficient, k = Boltzman constant, and T = absolute temperature. By using a value of 20°C for the temperature and 1.0 cp for the fuel viscosity, the diffusion coefficient can be related to the water-droplet size as follows:

$$D = \frac{4.3 \times 10^{-13}}{d_p}$$

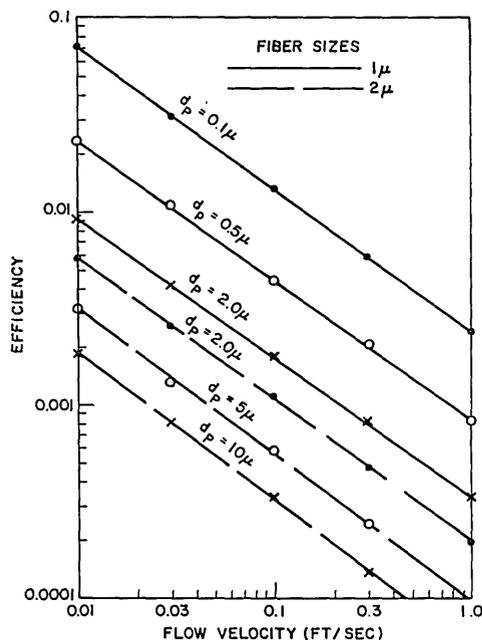


Fig. 5 - Efficiency for diffusion mechanism; fuel density is 0.8 g/ml and fuel viscosity is 1.0 cp

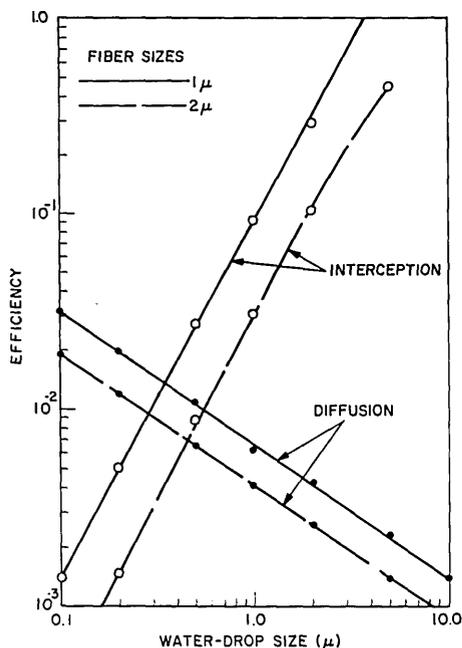


Fig. 6 - Comparison of efficiencies for interception and diffusion; flow velocity is 0.03 ft/sec

Langmuir (10) has related the efficiency of the diffusion mechanism for a single, isolated fiber to the diffusion coefficient of an aerosol particle at low flow velocities with the formula

$$E = 2.16 \left[\frac{1}{2(2 - \ln N_R)} \right]^{1/3} \left(\frac{D}{Vd_F} \right)^{2/3}$$

This equation was used to obtain the data in Fig. 5. It can be seen that the efficiency decreases with an increase in flow velocity, an increase in particle size, and an increase in fiber size. At a flow velocity of 0.03 ft/sec, which is typical of filter/separator flows, diffusion would be important only for droplets less than 1 μ in diameter and then only if the fiber diameter were less than 2 μ .

Combination of Approach Mechanisms — The previous discussion has indicated that an interception mechanism is the most important of the approach mechanisms examined. Inertial impaction is clearly insignificant, but diffusion may supplement direct interception as a primary mechanism for very small water droplets. The efficiency of the mechanisms as a function of drop diameter at a flow velocity of 0.03 ft/sec is shown in Fig. 6. At this flow velocity, interception predominates down to a drop diameter of about 0.4 μ . The higher efficiency of 1- μ vs 2- μ fibers is apparent in both mechanisms. This trend in efficiency continues for larger fibers. If the efficiencies of diffusion and interception are additive, the droplet size for minimum efficiency can be determined for different fiber diameters. These are listed in Table 1. At these small drop sizes, a 2- μ fiber is about 5 times more efficient than a 10- μ fiber. The relative efficiency of 2- μ vs 10- μ fibers is greater for larger drop sizes, since the contribution of diffusion decreases sharply as the drop size increases.

Efficiency of a Filter vs a Single Fiber — Extrapolation from a single-fiber efficiency to a filter-bed efficiency requires many assumptions. The flow pattern around a single fiber in a bed would be constrained compared to the isolated case. Adjacent fibers, as well as upstream fibers, would restrain the streamlines to a position closer to the fiber. Evaluation of this effect is difficult, but the efficiency of interception and diffusion mechanisms would both be increased, the former more than the latter. The packing fraction of the filter would influence this increase, since a streamline would be more con-

strained as the number of fibers per unit volume increased. Hence, the efficiency should be higher as the packing fraction increases. This effect has been observed by Bitten for some types of filter material (3).

Table 1
 Combined Efficiencies for Diffusion and Interception
 (Flow velocity of 0.03 ft/sec)

Fiber Diameter (μ)	Minimum Efficiency	Droplet Diameter for Min. Eff. (μ)
1	0.024	0.25
2	0.012	0.3
5	0.005	0.4
10	0.0025	0.6

An object, such as a cylindrical fiber, which is submerged in a flowing fluid causes disturbances of the flow pattern. At low Reynolds numbers this disturbance results only in a displacement of streamlines and laminar flow pertains. As the Reynolds number is increased, eddies occur on the downstream side of the object. Further increases result in flow of the eddies downstream and finally more severe turbulence. These phenomena are reported to develop with single, isolated cylinders at Reynolds numbers above 2; hence, they should not play a part at the flow velocities and fiber diameters used in a filter/separator. This may not be a realistic appraisal for a filter bed, however, since Kintner has observed turbulence in a fibrous bed (14). Zebel states that turbulence can augment the coagulation of aerosols, since particles of different sizes move at different velocities relative to each other and thus have opportunity to collide (15). In the field of water coalescence in a fuel, turbulence in a filter bed may have the opposite effect of emulsification. The degree of turbulence in a filter bed and effect of such turbulence on water drops in fuel need further investigation.

In lieu of acceptable methods of evaluating the efficiency of a filter bed, methods which would take into account the effect of adjacent fibers and turbulent conditions and the efficiencies for single, isolated fibers must be used to obtain a feel for the structural details of a filter bed. A completely ordered array of fibers must also be assumed in such calculations so that the distance between adjacent fibers in any direction is the same. The bed depths needed for an efficiency of 1 for glass fibers having diameters between 1 and 10 μ were calculated. Calculations were made using a glass with an absolute density of 2.5 g/cc and a fiber-bed density of 10 lb/cu ft. This gives a bed-packing fraction of 0.064. The bed depths were calculated in one instance for a water droplet of 1- μ diameter using only an interception mechanism. In a second case, the droplet diameter for minimum efficiency, which is shown in Table 1, was selected. For this situation, the efficiency is based on both interception and diffusion mechanisms. A flow velocity of 0.03 ft/sec was used throughout. The bed depths listed in Table 2 illustrate a remarkable dependence upon fiber size. A 10- μ fiber bed would need to be 400 times as thick as a 1- μ fiber bed for Case A and almost 100 times as thick for Case B.

The efficiency of a filter bed must be considered in conjunction with the pressure drop across the bed. Of importance for this discussion are the bed depth (b) and the fiber diameter (d_F). The filtration pressure is related to those two parameters as follows (16):

$$\Delta P = f \left(\frac{b}{d_F^2} \right).$$

Table 2
Minimum Bed Depth for Different Conditions

Fiber Diameter (μ)	Single-Fiber Efficiency		Minimum Bed Depth (cm)	
	Case A*	Case B [†]	Case A	Case B
10	0.0021	0.0025	6.0	5.0
5	0.0066	0.0050	0.96	1.28
2	0.031	0.012	0.081	0.210
1	0.091	0.024	0.014	0.052

*Case A -- Water-drop diameter, 1μ .

[†]Case B -- Water-drop diameter varies, see Table 1.

Using the data from Table 2 in this formula, the pressure drop for the minimum bed depth would be about the same for all four fiber sizes in Case B. The smaller fibers would afford a lower pressure drop for Case A, however. The $1\text{-}\mu$ fiber bed would develop about $1/4$ the pressure drop associated with the $10\text{-}\mu$ fiber bed.

Electrostatic Effects on the Approach Mechanisms -- Electrostatic charges are present on colloidal particles dispersed in a fluid. These charges are typical of water-in-fuel emulsions as well as other colloidal systems. This is shown by the fact that emulsified water greatly increases the charging current of a flowing fuel, particularly one passing through a fibrous filter. Surfactants also affect the charging current of water in fuel and can even reverse the polarity of the charge (3). The attraction or repulsion between a charged fiber and a charged drop must be considered as a secondary approach mechanism superimposed on the primary mechanisms previously discussed. Bitten (3) suggests that electrostatic phenomena are very significant in the coalescence of water. On the other hand, Reiman concluded that electrostatic charges did not participate in coalescence (17). Vinson used double-layer theory to examine electrostatic effects in liquid coalescence (8). His calculations indicated that the electrostatic influence was negligible for drops dispersed in hydrocarbons.

Attachment

Once a water drop in an emulsion has arrived at a fiber, the stage is set for further activity. The desired action is for attachment of the drop to the fiber and spreading of the drop on the fiber. Resisting this process is a film of fuel between the fiber and the drop. This film must thin to a certain minimum thickness before rupture occurs and attachment takes place. The rate of film drainage decreases as the film becomes thinner because of the drag associated with the two interfaces: the fuel/water interface and the fiber/fuel interface. Rupture times of seconds and even minutes have been observed in liquid-liquid coalescence (17). The rupture distance for large nitrogen bubbles in viscous oils is approximately 0.1μ (18). It has been well established (19) that the continuous phase can be trapped in a dimple as a liquid drop approaches a solid surface. The drop is deformed by the excess pressure developed by the film-drainage process. It would seem that an easily deformed drop might have a longer film-drainage time. The interfacial tension would affect the deformability of a drop, and it may be that some additives which degrade coalescence do so by lowering the interfacial tension and increasing the

deformability of a drop. Another possible effect of surfactants could be the change in interface viscosity. An additive locked in an interface should raise the viscosity tangential to the surface. An increased drag on the adjacent fluids should result, and the rate of film drainage be reduced. Surfactants can considerably reduce the rate of film drainage (18).

Film rupture of the thinned film is another important consideration in the attachment process. Mason states that the rupture time can be reduced by various means (18), some of which are effective by decreasing the film thickness at a localized spot. Undulations moving across a deformable interface, specks of solid debris in the interface, or sharp points or edges on a fiber are means of reducing the film thickness at a localized spot. Imposing an electric field such that a spark can penetrate the film and produce a bridge to a droplet also appears to enhance film rupture (18).

Weatherford concludes from his theoretical and experimental study that the film-drainage process is not controlling coalescence for low-viscosity liquids but that film rupture is the limiting step (20).

A fiber bed which has been exposed to an emulsion retains water attached to the fibers. Such attached water increases the effective fiber size. This increase affects the efficiency in a complex way, since the larger effective fiber would cause more displacement and disturbance of the flow patterns, thus reducing the efficiency, while the greater effective area for interception would increase the efficiency.

The attachment process for a small droplet approaching an attached drop is more complicated than the similar process for a droplet and a fiber. Both interfaces are deformable, and two interfacial films must be ruptured for coalescence. The discussion on film drainage and rupture presented should be applicable to this more complicated process also.

The experimental studies on film drainage and rupture phenomena have been restricted to relatively large drops. With small drops (less than 10μ) the volume of film which must drain is greatly reduced. In addition, the dimpling phenomenon may be less significant. On the other hand, the driving force for film drainage will be much less also. This subject of film drainage and rupture as related to small drops and coalescence is relatively unexplored, and its importance to coalescence is poorly understood. Imaginative research will be required to define for small drops the role of film drainage and rupture.

In order for attachment to be effective, the water drop must displace the fuel film from the fiber and, preferentially, wet the fiber. This process is encouraged as the surface energy of the fiber increases. A water droplet should readily displace fuel on hydrophilic surfaces — such high-energy ones as glass or metal. The displacement on a low-energy surface, such as polyethylene or Teflon, should be considerably less. This is confirmed by the measurement of contact angles of water on various surfaces in the presence of organic liquids (21). Typical contact angles reported by Beatty for a distilled-water-JP-5 system are 44° for glass, 89° for Nylon, 89° for cellulose acetate, 123° for phenolic resin, and 180° for Teflon (22,23). Shertzer and Lindenhofen give a contact angle of 50° for glass and 119° for phenolic resin for a water-RF-1* system (24).

The glass fibers in a filter/separator element are bonded together with a phenolic resin which gives an intermediate contact angle. It has been assumed that this afforded the desired wetting, sufficient to allow displacement of the fuel by water, but at the same

*RF-1 is a mixture of 15% toluene and 85% Bayol. The latter is a highly refined kerosene.

time being characterized by a modest fiber-water adhesion which permitted release of the coalesced water. A solid which gives a high contact angle with a water-fuel combination has been considered a poor coalescing material in the belief that water droplets would not displace fuel and attach to such a surface. Suggestions have been made that surfactants degrade coalescer performance by absorption on the fibers with a resulting increase in the contact angle and decrease in wettability.

Some recent studies do not support the suggestion that a surfactant absorbs at a bonded glass-fiber surface, raises the contact angle, and reduces the coalescing ability of a fiber. Single-fiber experiments with flowing water-in-fuel emulsions indicate that water droplets will attach and grow on all materials examined (3,23). Plastic fibers, even Teflon, which give high contact angles were effective in these coalescence studies. Furthermore, it was observed that corrosion inhibitors and other surfactants do not absorb on bonded glass fibers, although they do absorb on unbonded glass (22,24). Lindenhofen and Shertzer (24) interpret their work to show that a surfactant in a fuel is active at the fuel/water interface and not at the fuel/solid interface.

Release

Motion pictures taken by the Army Engineering Research and Development Laboratory revealed some of the phenomena occurring after initial coalescence. Brown and Estabrooke used a short section from a filter/separator element as a coalescer for this work. Installation of this section in a transparent plastic cell permitted photography of water-droplet passage through the fiber glass and droplet release at the outer surface of the coalescing media. The movement of the water drops was readily apparent when the water-in-fuel emulsion was made with water containing a soluble dye.

The color movies indicate that a water drop attached to a fiber will continue to grow until the force of the fuel flow overcomes the adhesive forces between the water and the fiber. In a fiber bed of reasonable packing density, the coalesced droplet size appears to be large enough so that it bridges to a fiber downstream and attaches before releasing from the first fiber. In fact, the movies show that the water does not move through the fiber bed as discrete droplets once attachment has occurred (25). Rather, threads of water snake through the coalescer. The thread size varies since the water readily deforms to fill the passageway through the coalescer. At the downstream face of the fiber bed, the water is released in individual drops.

Factors which affect the size of the droplets released are the flow velocity and the fiber size (23). Beatty has shown in single-fiber studies that detachment occurred more readily from small-diameter than from large-diameter fibers. A higher velocity removed smaller drops. The nature of the material had little effect on the detachment-flow velocity except for polyethylene filaments for which detachment was somewhat easier. Additives in the fuel usually encouraged detachment. At high concentrations (60 ppm) of powerful surfactants, Beatty found that droplets slid on the fibers and detached much more readily than drops in a fuel containing no additives.

The structural arrangement of a two-stage filter/separator is such that the fuel-flow velocity increases greatly as the fuel leaves the coalescer element, the point of water-drop detachment. Also the effluent fuel changes direction as it leaves the element. Whereas flow has been radially through the annulus of the element, it now becomes parallel to the length of the cylindrical element. Furthermore, the flow velocity increases along the length of the element, since the cross-sectional area available for flow does not change. Evaluation of the Reynolds number in the flow region exterior to the element indicates turbulent flow may be approached at some points. Combining this with the change in flow direction and the exterior roughness of the filter element, turbulence is probably occurring at some sites where water drops are released. Surfactants which

enhance emulsification are much more effective in such areas of turbulence, and coalesced drops may be broken up as they are released in such an environment.

A more favorable situation prevails in a single-stage filter/separator. Such a coalescer combines the coalescing and separating functions by surrounding the fiber-glass coalescer element with a fine-mesh screen. This shroud is normally given a hydrophobic coating to encourage the water-stripping action. This design affords a reduced flow velocity between the coalescer element and the surrounding shroud. In addition, the fuel does not change direction as it leaves the fiber-glass element. Furthermore, the water droplets at the point of release are not exposed to a turbulent environment.

Mason has observed drop rupture during coalescence of drops with a liquid surface (18). In this phenomenon, only part of the drop coalesces, and a daughter drop remains free of the bulk liquid. A similar behavior can be envisioned upon the release of a drop from a fiber. The drop is stretched by the fuel flow, and a neck or thread of water forms just prior to detachment. A small droplet is retained at the fiber, and the opportunity for fragmentation of the neck occurs. Formation of a thread of water and fragmentation to a series of small droplets is readily observed by gently rocking a fuel sample containing a small amount of water as a separate layer. Surfactants enhance this behavior. This type of phenomenon occurs with unattached droplets in a shear field. Taylor (26) and Rumscheidt and Mason (27) have studied the stretching and rupturing under these conditions. The latter authors suggest that capillary waves along an elongated water drop leads to rupture of drops into two or more smaller drops. The role of surfactants was not clearly defined by their work.

EXPERIMENTAL DETAILS

The previous discussion has dealt with a number of factors which may affect the efficiency of the coalescence process. These factors include structural and operational details of the coalescer bed, such as fiber size and material, flow velocity, packing density, and bed depth; emulsion properties, such as particle size, water content, and surfactant content; and fuel properties, such as density and viscosity. With the exception of the emulsion-particle size and the fuel properties, all of the factors listed have been varied to some extent.

The size of the water drops is not readily controlled. All methods of emulsion preparation give a range of particle sizes. Segregation into a narrow-size fraction might be feasible experimentally, but the routine determination of sizes in the micron range is extremely cumbersome. Therefore, an emulsion formed by feeding water into the inlet side of a centrifugal pump during circulation of fuel has been used in the experimental work described here. The size distribution of a pump-formed emulsion, which is typical of emulsions in the field, has been reported by Bitten (3).

The fuel properties chosen for these experiments were those which make coalescence more difficult. JP-5, the primary jet fuel used by the Navy, or closely related fuels were used, since these materials have higher viscosities and higher densities. The range in these properties, shown in Table 3, was limited since other factors were of greater interest.

The basic tool used in these experiments was the Water Separometer, which was designed by Krynitsky and Garrett (2) and further developed in cooperative studies in the Coordinating Research Council (28). This instrument was developed to rate jet fuels with respect to their coalescing properties and is used in the water separation specification test for purchase of jet fuels. In this use the Separometer is standardized with respect to configuration and operating procedures. The instrument prepares a 0.1% water-in-fuel emulsion, passes the emulsion through a selected coalescer bed of bonded fiber glass

Table 3
Properties of Fuels Used in Coalescence Studies

Fuel	Density at 25°C (g/ml)	Viscosity at 25°C (cp)
Bayol	0.777	2.63
RF-1	0.789	1.60
JP-5 (434)	0.810	1.72
JP-5 (435)	0.802	1.47

and a settling chamber, where coalesced water drops fall to the bottom, and determines the turbidity of the effluent water-fuel emulsion leaving the settling chamber by routing it through a turbidity analyzer. The light transmission in the turbidity analyzer at a prescribed time is taken as an indication of the water-separating performance of the fuel being tested. The light transmission is not directly related to the amount of water in the effluent fuel, since the amount of light scattered by an emulsion is a function of the particle size as well as the number of particles. A quantity of water dispersed as small droplets scatters light much more efficiently than when dispersed as large droplets. The relationship between scattering and particle size is not amenable to a formulation which would be useful for the current work. Even so, the turbidity is a useful indicator of coalescing action, although one cannot differentiate between two interpretations of a turbidity decrease: (a) all of the water drops have increased in size but the free-water content has not changed and (b) some of the water drops have not changed size, but the free-water content has decreased. Positions in between these two extremes are also possible. A concurrent analysis for water content is helpful in resolving this uncertainty.

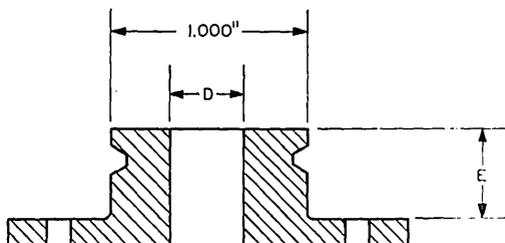
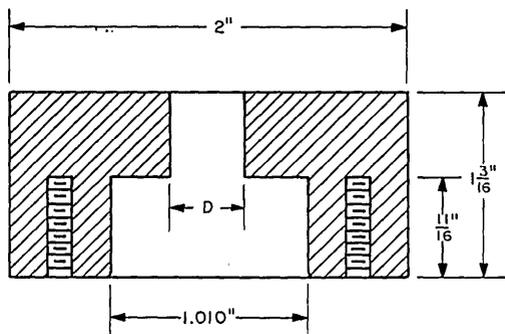


Fig. 7 - Coalescer cell

The Water Separometer is an excellent tool for coalescence studies. In addition to the versatility which permits adjustment of the many variables referred to above, the quantities of fuel and coalescer material required are limited, and all components of the apparatus are contained in a single unit which can be placed on a laboratory bench.

The flow velocity of the fuel through the coalescer was varied in two ways. The volumetric flow rate through the coalescer can be varied and was adjusted from 25 ml/min to 400 ml/min (for flow rates above 200 ml/min, the flowmeter cannot be used). The 150 ml/min rate for specification tests was used in a majority of the tests. The flow velocity was also altered by varying the area of the coalescer pad exposed to fuel flow. This was accomplished by fabricating coalescer cells with different cell openings (dimension D, Fig. 7). The four cells listed in Table 4 cover an area ratio of 30, and this allows an even

Table 4
Coalescer-Cell Studies

Cell	Cell Opening		Flow Velocity (ft/sec)	
	Diameter (in.)	Area (sq in.)	At 150 ml/min	At 37 ml/min
A*	0.140	0.0155	0.82	0.205
B	0.243	0.0464	0.27	0.068
C†	0.444	0.155	0.082	0.020
D	0.770	0.464	0.027	0.0068

*Standard cell for modified Water Separometer.

†Standard cell for original Water Separometer.

greater velocity ratio when combined with the different volumetric flow rates. When the cell opening is altered to effect a change in velocity through the coalescer cell, the velocity in the settling chamber remains the same. However, the velocity through the settling chamber is affected when the coalescer-cell velocity is adjusted by changing the volumetric flow rate. The flow velocity in the settling chamber varies linearly with the flow rate and at a flow rate of 150 ml/min., this value is 0.017 ft/sec. The velocity in the settling chamber determines the size particle which will collect in the sump. A 4-fold velocity increase would decrease the maximum size of particles retained in the sump by a factor of two.

The coalescer bed depth was varied by adjusting the effective length of dimension E of the coalescer cell (Fig. 7). One or more 1/16-in. spacers were used to reduce this dimension from the standard dimension of 5/8 in., thereby increasing the bed depth from the standard 1/16 in.

Coalescer Material

Glass fibers were used throughout these studies. Fibers with average diameters varying from 0.4 to 11 μ were investigated. The fibers down to 0.75- μ diameter were available with a phenolic bonding. Unbonded fibers were available in the 0.4 to 11 μ range or could be prepared by removal of the bonding agent with a 1-hr heat treatment at 450°C.

In view of the importance of fiber dimensions it was felt that valid comparisons of different surfaces must take these fiber dimensions into consideration. This was accomplished by modifying the surface of a coalescer pad containing the desired fiber diameter. By this means, coalescer pads which differed only in a surface coating could be compared. The bonded fiber glass afforded a medium-energy surface, and the unbonded material gave a high-energy surface. A low-energy surface was attained by treating the unbonded glass, such that a hydrocarbon moiety controls the properties of the surface. Two chemical methods and one physical method were used to accomplish this result. The hydrophilic hydroxyl sites were esterified by refluxing with anhydrous n-octyl alcohol (29) or complexed by treatment with a dilute chromium stearate solution (Quilon) (30). The physical method involved dipping the fiber glass in a boiling xylene solution of polyethylene followed by evaporation of the xylene at 100°C. A concentration of 0.3 to 0.5% was suitable for this last procedure.

The effectiveness of these three treatments was determined by observing the behavior of a coalescer pad in a two-phase system, Bayol over distilled water. Unbonded glass, when placed in the Bayol layer, readily penetrates the interface, and water displaces the Bayol. An organic coating alters this behavior, and the coalescer pad will not move through the interface without additional force. Even then the Bayol is not displaced without vigorous agitation and the water adsorbed can be easily removed by re-exposure to Bayol. This behavior is typical of the phenolic-bonded fiber glass, as well as the coatings produced for a low-energy surface. The coating prepared by treatment with octanol appeared to be the most resistant to displacement of Bayol by water.

Coalescer pads were also cut from fiber-glass elements designed for use in military filter/separators. Both new and used elements were tested. These elements consist of several layers of fiber glass, graded with respect to fiber diameters, which may vary between 2 and 9 μ . The finest fibers were at an intermediate position in the element. These layers were used separately, with each other, or with other coalescing material. They were also treated in various ways to remove bonding or contaminants.

Surfactants

The presence of surface-active agents can have a dramatic effect on the coalescibility of fuels. An understanding of the influence of these materials is the key to a major advance in the understanding of fiber-bed coalescence. The surfactant of major interest in this work was sodium petroleum sulfonate. Two major reasons for this choice were that sulfonates can be contaminants from refinery processes, and they degrade coalescence at a very low concentration in fuel—less than 0.5 ppm (wt/vol). Other surfactants were used in some absorption studies with bonded-glass-fiber coalescers. These included natural anionic surfactants (sodium petroleum naphthenates), a typical cationic surfactant (cetyl trimethylammonium bromide), and a typical nonionic surfactant (Triton X-100). These surfactants, which are listed in Table 5, were dissolved in toluene, where possible, and added to the desired fuel shortly before an experiment. One-gal glass bottles were used to mix samples. Since the solubility of the cationic material in fuel was very low, this surfactant was dissolved in the water used to make the emulsion. The concentration was based on the quantity of fuel used.

Table 5
Surfactants Used in Coalescer Studies

Code	Name	Type	Mol. Wt.
A	Sodium petroleum sulfonate	Anionic	400
B	Sodium petroleum sulfonate	Anionic	420
C	Sodium petroleum naphthenate	Anionic	220
D	Sodium petroleum naphthenate	Anionic	330
E	Triton X-100	Nonionic	620
F	Cetyl trimethylammonium bromide	Cationic	364

Analysis for Water

In addition to a continuous monitoring of percent transmission (% T) of the effluent fuel stream leaving the settling chamber, in some experiments the water content was determined. Batch samples were collected for the water analysis. Two methods were used. One method, a determination with Karl Fischer reagent, must be corrected for water dissolved in the fuel. This method is not very accurate for water contents less than 25 ppm because of a relatively large correction factor. The other, which might be

called the dye-centrifuge method, determines only free water and was developed for the present study. In the latter method, a water-soluble dye (Acid Fuchsin Red has been used successfully) is added to the water used in the preparation of the water-in-fuel emulsion. The effluent fuel sample collected after passing through the Water Separator is treated with a known amount of distilled water. The sample is then alternately shaken and centrifuged to separate the colored water. An aliquot of this centrifuged water is diluted 1:1 with isopropyl alcohol, and the intensity of the dye determined in a spectrophotometer. The amount of free water in the fuel sample can then be related to the dye concentration in the diluted sample. The light transmission of a water-in-fuel emulsion is not significantly altered by the presence of the dye in the water. Water contents determined by the two methods, Karl Fischer titration and dye-centrifuge technique, were comparable.

EXPERIMENTAL RESULTS

Effect of Flow Velocity

The flow velocity through the coalescer material was varied over a wide range. The % T of the turbidity cell was taken at comparable total fuel flows for each flow velocity. The effect of flow velocity on % T, which is shown for three different fuels in Fig. 8, is rather slight. Additional data, which are not plotted, indicate only a slight velocity effect for other conditions also. A 30-fold decrease in the flow velocity raises the % T of RF-1 with 1.0 ppm of additive less than 10 points, although this same velocity change causes a larger response with 0.5 ppm of additive. The flow velocity for RF-1 + 0.5 ppm of sodium petroleum sulfonate was altered both by using the four coalescer cells described in Table 4 and by adjusting the flow rate. The data which were obtained were interconsistent and are plotted together in Fig. 8.

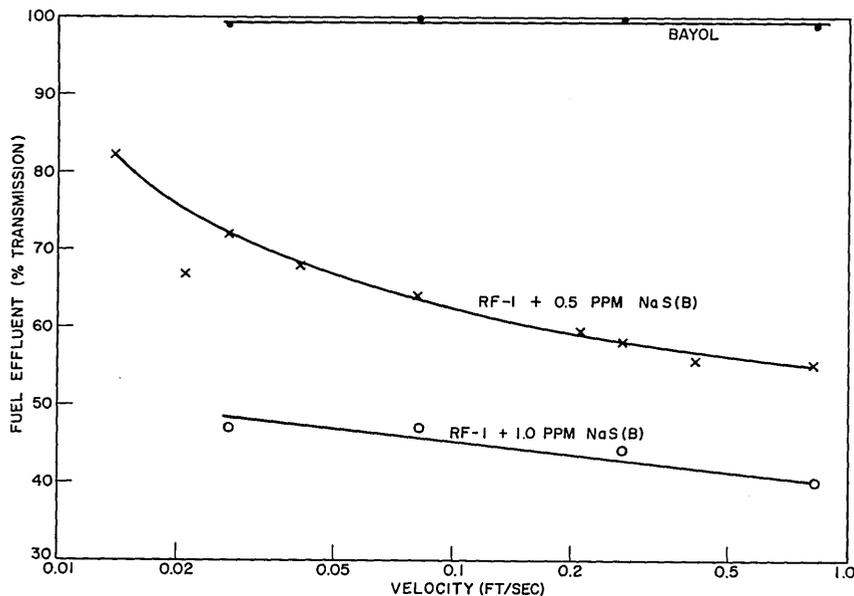


Fig. 8 - Effect of flow velocity on % T; cell gap is 1/16 in. and coalescer bed consists of one bonded pad with 1- μ -diameter fibers and one bonded pad with 4.6- μ -diameter fibers

Figure 8 also illustrates the remarkable effect of surfactant on the % T in coalescence experiments. As can be seen, a doubling of the surfactant level influences this coalescence phenomena more than a 30-fold change in velocity.

A comparison of Fig. 2 with Fig. 8 indicates a flat response for both single-fiber interception efficiency and % T with respect to flow velocity. Although the slopes are opposite for the two criteria, the effect of velocity in each case is slight. The apparent upturn in % T at lower velocities might be explained by the increasing efficiency of the diffusion mechanism at lower velocities. The slope is less pronounced than that expected for a diffusion-controlled process, however (Fig. 5). Other phenomena downstream from the point of initial droplet approach to a fiber are influenced by velocity, and such effects would be superimposed on the approach mechanisms.

An indication of the complicated nature of coalescence is obtained when a water analysis is made in addition to the % T. For Bayol fuel the water content of the effluent from the Water Separometer increased with flow velocity, although the data in Table 6 indicate that % T does not change with velocity. When an additive is present in the fuel, the opposite behavior is observed. The water content in the effluent for flow velocities used is about 500 ppm for an additive containing fuel to which 1000 ppm of water was added, while the % T changes as shown in Fig. 8.

Table 6
Effect of Flow Velocity on Coalescence Using Bayol
(Coalescer bed consisting of one 1.0- μ fiber pad and
one 4.6- μ fiber pad with a cell gap of 1/16 in.)

Flow Velocity (ft/sec)	Bonded Fibers		Unbonded Fibers	
	% T	H ₂ O Content (ppm)	% T	H ₂ O Content (ppm)
0.028	99	1	100	10
0.083	100	0	100	1
0.28	100	8	99	1
0.83	99	34	—	—

Physical Characteristics of the Coalescer Bed

The amount of fibrous material, the fiber sizes, and the arrangement of different components of a bed have a significant effect on coalescence. The mass of filter needed for efficient coalescence is shown in Fig. 9. The data were obtained with bonded-fiber-glass beds in which the amount of 4.6- μ -diameter fibers was held constant, and the amount of 1.0- μ -diameter fibers was varied. The smaller fiber preceded the coarse fiber in all of the beds. The amount of filter material is indicated by a pressure differential for airflow through the beds. The data indicate that efficiency is not raised by increasing the mass of fiber glass beyond a certain amount. This is the case both for a good fuel, which gives a high reading of % T, and for a fuel with additive. The sharp contrast between fuels of different quality is quite obvious.

The influence of fiber diameter, as well as amount of coalescer material, is shown in Fig. 10. These results were obtained with a constant amount of 4.6- μ bonded fiber glass preceded by varying amounts of smaller-diameter unbonded fiber glass. As before,

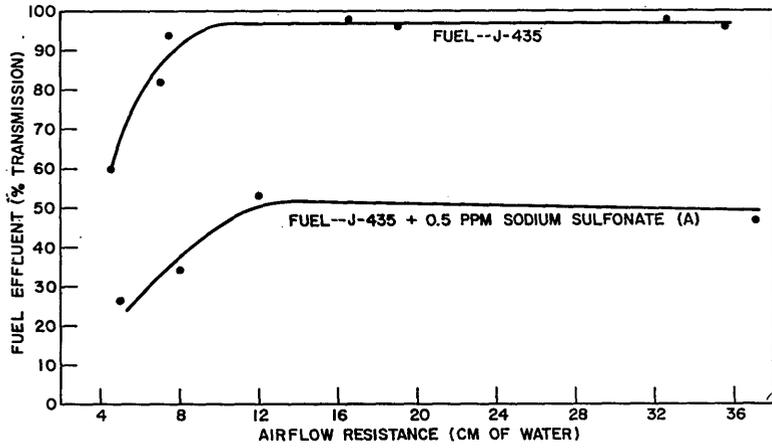


Fig. 9 - Effect of amount of coalescer material on % T; coalescer bed consists of bonded fiber glass, varying quantity of 1- μ -diameter fibers and a constant quantity of 4.6- μ fibers; cell gap is 1/16 in. and fuel velocity is 0.82 ft/sec

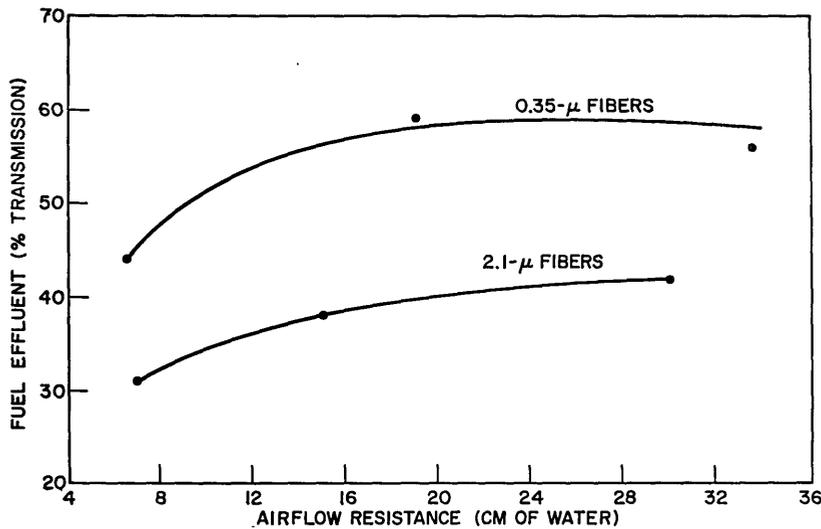


Fig. 10 - Effect of glass-fiber diameter on % T; fuel consists of J-435 and 0.5 ppm sodium sulfonate (A); fuel velocity is 0.82 ft/sec and cell gap is 1/16 in.; coalescer bed consists of a varying quantity of small-diameter-unbonded fibers and a constant quantity of 4.6- μ -bonded fibers

the flat response of % T to quantity of fiber glass is noteworthy. In addition, the greater efficiency of small-diameter fibers is apparent. The data for 1.0- μ -diameter fibers shown for this same fuel as the lower curve in Fig. 9 would fall between the 0.35 and 2.1 μ fibers. The 1.0- μ -pad data are for bonded fibers, but the data still fall in the same order. Attempts were made to obtain comparable data for the 4.6- μ -diameter-bonded material alone, but an airflow resistance beyond 10 cm of water could not be

attained without tearing the pads at the high-packing densities required. The % T values were in the low 20's, but no general trend could be established. The data generally support the pattern established for the smaller fibers. The efficiency with the larger fibers may still be increasing as bed resistance increases, and they might approach the level attained by the small fibers if sufficient material was added. The efficiency of the small fibers is significantly greater with respect to the larger fibers than that expected from the calculations presented earlier. These calculations, made on the basis of single, isolated fibers, did not take fiber interaction into account. This interaction should favor the bed composed of small fibers, since fiber spacings are less with these fibers and flow patterns would be more restricted.

The % T for coalescer beds composed of two or more pads with different fiber diameters are depicted as bar graphs in Fig. 11. The necessity for including more than one fiber size is clearly evident. A small fiber (0.75 and 1.0 μ) or a coarser fiber (2.8 and 4.6 μ) are both inefficient by themselves. Combinations of a small and large size greatly improve the efficiency. Thus, a 0.75 or 1.0 μ pad with a 2.8- μ pad is efficient, and a pad made from either of the small fibers is efficient when combined with a 4.6- μ fiber pad. A gradation of fiber sizes does not further enhance the efficiency. A bed consisting of a 0.75- μ pad plus a 4.6- μ pad is slightly better than a graded bed containing pads of each of the fiber sizes used in Fig. 11.

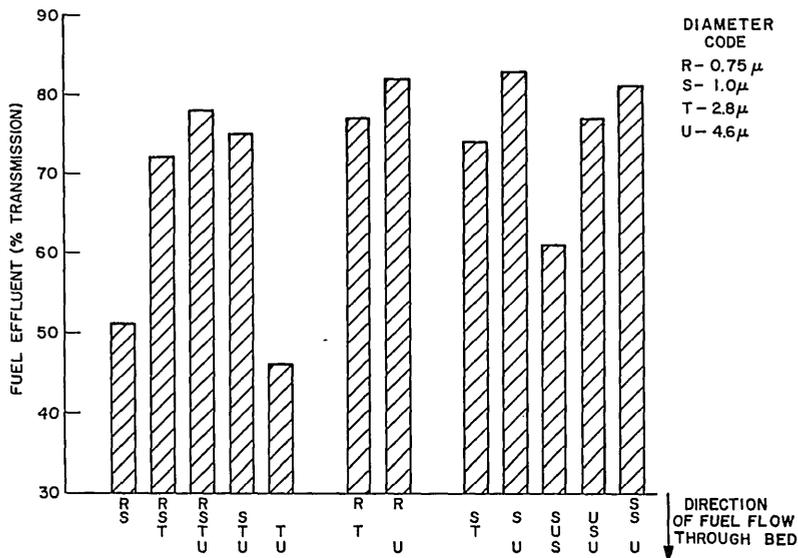


Fig. 11 - % T for coalescence with combinations of bonded fiber-glass diameters; fuel consists of RF-1 and 0.5 ppm sodium sulfonate (B); cell gap is 1/8 in. and fuel velocity is 0.82 ft/sec

The order of the fiber sizes is quite important. The performance of a bed made from 1.0 and 4.6 μ fibers deteriorates if a small fiber pad is added to the downstream side of the bed (1.0-4.6 combination vs 1.0-4.6-1.0 combination), but there is no change if the same pad is added to the upstream side (1.0-4.6 vs 1.0-1.0-4.6). Addition of a coarse pad on the upstream side is not detrimental either (4.6-1.0-4.6 combination). It thus appears that the downstream fiber size has a marked control on coalescence. The interception, attachment, and growth of droplets can occur in efficient processes but may be nullified if droplet release is inadequate. There appears to be an optimum fiber size for release, since it was observed under conditions different from those in Fig. 11 that

the 1.0-4.6 combination % T was decreased from 62 to 46 by the addition of an 11- μ pad to the downstream side.

Surface Chemical Considerations

The behavior of different surfaces with respect to coalescence was examined. The important physical characteristics were kept constant by modifying the surfaces of fiber-glass samples in several different ways. Surface effects for a particular fiber size with a variety of surface treatments could then be compared. In Table 7 comparison is made between 1.0- μ bonded-fiber-glass pads which have been heated for 1 hr at various temperatures. In each case the 1.0- μ pad was followed in the coalescer bed by a bonded 4.6- μ fiber pad. Most of the bonding material is removed at 300°C, and all is burned off at 400°C. The behavior in a two-phase fuel-water system is consistent with this fact. A fiber pad heated at 200°C, as well as an unheated pad, prefers the fuel layer, whereas fuel is readily displaced by water with pads heated at 300°C and above.

Table 7
Effect of Heat Treatment on Coalescence Using J434 Plus 0.5 ppm Sodium Sulfonate (A) (Flow velocity of 0.82 ft/sec, coalescer consisting of 1.0- μ and 4.6- μ fiber pads, and cell gap of 1/16 in.)

Temperature (°C)	Wettability	% T
No heating	Hydrophobic	42
200	Hydrophobic	42
300	Hydrophilic	46
400	Hydrophilic	40
500	Hydrophilic	42
600	Hydrophilic	31

The only significant difference with the observed % T in coalescence experiments was found for the pad heated to 600°C. Since this pad fused slightly at this temperature, the changes in fiber physical characteristics, rather than surface properties, are probably responsible for the poorer performance.

Comparisons were next made with modifications of the 1.0- μ fiber surface, the 4.6- μ fiber surface, or both. In each case the larger size fiber was used with and preceded by the smaller fiber pad in the coalescer bed. Three surfaces were compared: (a) fiber glass with phenolic bonding, (b) unbonded fiber glass prepared by heating bonded fiber glass at 450°C for 1 hr, and (c) Quilon-treated surface prepared by treating unbonded fiber glass with a chromium stearate complexing reagent. The comparisons are listed in Table 8 for a high-quality fuel and the same fuel to which a surfactant was added. All combinations performed well with RF-1. With the additive fuel, the unbonded samples gave % T readings which were slightly higher than the bonded fiber glass. The hydrophobic fibers were similar to the bonded samples. The comparable behavior of bonded and unbonded fibers with a good fuel is also indicated when the water content of the effluent is determined at different flow velocities (Table 6).

The 1.0- μ fiber pads were treated in other ways and then combined with the bonded 4.6- μ material in coalescence experiments. Two additional treatments gave hydrophobic surfaces similar to the Quilon reagent. These treatments were esterification of the hydroxyl sites on the glass and coating the fibers with polyethylene by dipping in a dilute solution of this polymer in boiling xylene. The % T readings with pads treated in either way were very close to those for bonded fibers. Partial degradation of the phenolic-bonding material by treatment with acids, bases, or oxidizing agents also failed to alter the coalescing behavior of 1.0- μ material.

Table 8
Variation of Coalescer Surface
(Flow velocity of 0.82 ft/sec and cell gap of 1/16 in.)

1.0- μ Fibers*	4.6- μ Fibers*	% T	
		RF-1	RF-1-B†
B	B	99	63, 59, 55
U	B	100	67, 66
B	U	100	66, 61
U	U	99	67, 74, 70
Q	B	99, 98, 97	56, 55, 56
B	Q	98	64
Q	Q	95	57

*B — fiber-glass bonded.

U — fiber-glass unbonded (hydrophilic).

Q — fiber-glass unbonded and treated with Quilon (hydrophobic).

†RF-1-B — RF-1 + 0.5 ppm sodium petroleum sulfonate (B).

The absorption of surfactants on fiber glass was examined as regards the effect of these materials on fiber-surface characteristics. An emulsion made with a poor quality fuel or a fuel containing an additive was passed through bonded fiber-glass coalescers. After 5.5 l of the poor fuel had passed through, a good fuel was used with the same coalescers. The % T for the two different samples was observed and is presented in Table 9. Included among the poor samples are a specification jet fuel which became contaminated in handling and one which was artificially aged by exposure to sunlight. Good jet fuel was also contaminated with Navy Special Fuel Oil, a material which is a potential contaminant for jet fuel in the field because of faulty fuel handling. Other additives investigated covered the three major types of surfactants — anionic, cationic, and nonionic. None of the poor fuels contaminated the fiber-glass coalescers such that coalescing performance was greatly deteriorated. In fact only in the case of fuel J-417 is there an indication of any degradation, and this degradation is slight.

Table 9
Effect of Contaminants on Coalescence
(Flow velocity of 0.82 ft/sec, cell gap of 1/16 in., and coalescer bed consisting of 1.0- μ and 4.6- μ fiber pads)

Poor Fuel*	Additive Concentration (ppm)	% T	
		Poor Fuel	J-434 Follow-Up
J-417	—	22	80
J-434 + C	10	34	89
J-434 + D	20	20	87
J-434 + A	2	17	89
J-434 + E	20	34	87
J-434 + F	10	10	87
J-434 + Navy Special	50	54	85
J-434†	—	72	94
J-434	—	—	88, 90, 93

*See Table 5 for description of additives.

†Aged by exposure to sunlight.

Poor fuels were also passed through coalescer pads without the addition of emulsifying water. Fuel J-434 was again used as a follow-up fuel and gave % T values of 87, 85, and 95 in three separate experiments when the pretreatment fuel contained additive A. There is another indication that additive A is not absorbed from the fuel by passage through the separometer. When a sample passed through a coalescer without water is rerun through a fresh coalescer with water addition, the % T is about the same as that for an experiment with an identical sample run in the normal manner. A monolayer of additive absorbed on the fiber glass would not reduce the additive concentration a great amount, but a measurable change in the % T should have resulted if monolayer coverage had occurred.

Absorption studies were also undertaken with unbonded fiber glass and additive B. Experiments similar to those above were carried out, both with and without water addition during the pretreatment step. Unbonded fiber-glass pads were also soaked up to 48 hr as a pretreatment step in 0.25% solutions of additive B in toluene or Bayol. None of these procedures degraded the coalescing performance of a followup fuel sample.

Unbonded fiber pads were also presoaked in distilled water and 50% aqueous glycerine solution prior to coalescence experiments. The latter is of interest because it is a component of an anti-icing additive used in the military services. Neither of these liquids altered the coalescing behavior.

The results given above on fiber surfaces and surfactant absorption studies indicate that the surface chemistry of the fiber is not critical. Rather the effects of surfactants on coalescence must be assigned to the water/fuel interface, as Lindenhofen and Shertzer have proposed (24).

Examination of Filter/Separator Elements

Fiber-glass elements from filter/separators in military service were dismantled, fiber sizes of the various layers were examined with a microscope, and coalescer pads were cut from the elements. The elements appeared to have four distinct fiber-glass layers, although the Kingsville element may have had only three, since the data in Table 10 for the middle layers indicate the fiber sizes are quite similar. It is noteworthy that this element was hydrophilic, being different in behavior from the other elements in this respect. Element K was saturated with liquid, which could be removed by washing with water or alcohol. It is apparent that the liquid is glycerine, which had contaminated the entire JP-4 jet-fuel handling system at Kingsville during difficulties in 1963 (31).

The coalescing ability of 1-in.-diameter pads cut from the layer of an element with the smallest diameter fibers was tested in the Water Separometer. Data for the four elements with two different fuels are shown in Table 11. The Kingsville element again seems to be different, since its performance is distinctly poorer with both fuels. Treatments were undertaken to remove possible contaminants in this used element to evaluate the possibility that the glycerine or other foreign material was responsible for the poor performance. This explanation is only partially valid in view of the results presented in Table 11.

The poor performance of the pad cut from element K is primarily due to the absence of small fibers. The addition of 1.0- μ fibers ahead of an element-K pad in a coalescer bed raised the % T for fuel with additive from 53 to 63, the latter value approaching that for the other elements.

The Aeronautical Engine Laboratory has run full-scale flow tests of filter/separator elements obtained from Miramar and Kingsville Naval Air Stations (32). These used elements had comparable service history to those examined at NRL. The water content of

Table 10
Filter/Separator Elements

Code	Source	Where Used	Wettability	Layer	Fiber Size (μ)
M-1	AEL *	Miramar (1964)	Hydrophobic	1	8
				2	4
				3	2
				4	5
M-2	Miramar†	Miramar (1966)	Hydrophobic	1	—
				2	—
				3	—
				4	—
K	AEL	Kingsville‡ (1964)	Hydrophilic	1	8
				2	4
				3	3.5
				4	5
U	AEL	New element - never in service	Hydrophobic	1	7
				2	4
				3	2
				4	5

*AEL - Aeronautical Engine Laboratory, Philadelphia, Pa.

†Miramar - Miramar Naval Air Station, California.

‡Kingsville - Kingsville Naval Air Station, Texas.

effluent fuel samples from these similar coalescer elements is shown in Table 12. The AEL test data are for a good fuel containing 0.1% emulsified water, the same basis used for the NRL data on % T for effluent fuel in the Water Separometer.

DISCUSSION

The experimental work presented in this report focuses our attention upon four salient features of this coalescence study, namely: (a) the importance of fiber sizes in the coalescer bed, (b) the strong effect of surfactants on coalescence, (c) the minor influence of the flow velocity on the % T readings, and (d) the flat response of the % T to the quantity of coalescer material once a critical amount has been exceeded.

The fact that the % T for a poor fuel reached a plateau similar in shape to that for a good fuel as the amount of coalescer material increased shows that the efficiency of the approach step can reach unity for both types of fuel by proper bed design. Further, since the only effect of surfactant on the approach mechanism would be through a change of particle size of the water drops, the droplet size in the emulsion must not be greatly affected by sodium petroleum sulfonate in the fuel.

The slight effect of flow velocity on % T supports the viewpoint that the interception process is the primary approach mechanism for water in fuel emulsions. Theoretical calculations agree with this finding, while both theory and experiment point to an increasing efficiency of the diffusion process at low flow velocities and for particles less than 1μ in size.

Table 11
Coalescing Ability of Pads from Filter/Separator Elements
(Flow velocity of 0.82 ft/sec, cell gap of 1/8 in., and filter/separator
pad followed by 4.6- μ -diameter fiber pad)

Treatment	Fuel -- RF-1				Fuel -- RF-1-B*			
	M-1	M-2	K	U	M-1	M-2	K	U
None	90	89	70	98	71	65	48	67
	97	92				66	56	74
							58	
							43	
One hour heating at 120°C	95	—	82	—	70	—	55	—
	99	—	81	—	70	—	47	—
200°C	98						38	
	95	96	75	98	72	—	47	70
480°C	98				71		42	70
							38	
Extraction with Hydrochloric acid	94	—	—	—	69	—	41	—
	99	—	—	—	75	—	45	—
Ethyl alcohol							47	
							48	
Trisolvent†	99	—	—	—	74	—	40	—
							41	
H ₂ O then acetone	98	—	—	—	67	—	41	—
	97	—	—	—	70	—	—	—

*RF-1-B -- RF-1 + 0.5 part per million sodium petroleum sulfonate (B) before.

†Trisolvent -- Equal amounts of benzene, acetone, and isopropyl alcohol.

Table 12
Water Content in Effluent Fuel

Element	Water Content (ppm)*	% T†
M-1	7	90, 97
M-2	4	89, 92
K	>30	70
U	0 to 5	98

*AEL data, full element.

†NRL data, 1-in.-diameter pad cut from the element layer containing smallest diameter fibers + 4.6- μ fiber pad; fuel -- RF-1.

The greater efficiency of small fibers in the coalescer bed is a result of the flow patterns associated with different fiber sizes. A small fiber causes less disturbance of the flow streamlines and, thus, displaces these streamlines away from the fiber to a lesser amount. Effective approach of a drop to the fiber is therefore enhanced by the smaller fiber. The data are not sufficient to differentiate between the interception, the inertial impaction, and the diffusion processes of water-droplet approach. However, the marked influence of fiber size would qualitatively support the interception mechanism, since the calculations presented in Figs. 2, 3, and 5 show that the response of this mechanism to fiber size is greater than that of the other two processes.

An additional piece of evidence which bears on the approach problem is the relationship of the water content to the % T reading for fuel samples containing sodium sulfonate. The % T of such a fuel leaving a good coalescer is much higher than that of the entering fuel and may even be above 90% if the additive concentration is low. The water content of the effluent fuel does not change accordingly, and all of the incoming water may be retained in the effluent from the settling chamber. This is interpreted to mean that approach has been accomplished successfully, coalescence of all small drops has occurred, but drop growth beyond a certain size is limited by the additive. Alternately the drop size may be reduced during the release process but still be much larger than the incoming drop size. Visually it has been observed that effluent samples which have a high % T and a high water content have little or no haze, and any haze which is present quickly settles to the bottom of a container. The loss in light transmission for such samples is thus due to scattering by relatively large coalesced drops which are not massive enough to settle in the settling chamber, rather than scattering by small droplets from the entering emulsion which have passed through the coalescer bed without any interaction.

It has been reasoned that the interception mechanism is the significant approach step for coalescence and that an efficiency of unity for approach can be attained even for an additive-containing fuel. The site of additive action must therefore be assigned to the attachment or release processes. The former process is a time-dependent one, since the drainage of a fuel film from between an approaching water drop and a fiber requires a finite time. If this were the crucial step, the flow velocity should have a significant effect on overall coalescence efficiency, that efficiency increasing as the velocity is reduced. The experimental results indicated that this was not the case. The other arguments presented in favor of an efficient approach mechanism — namely, the flat response of % T to the amount of coalescer material and the observance of high % T readings in conjunction with high water contents — also support an efficient attachment mechanism.

Valid reasons have been presented which suggest that the surfactant in a fuel does not alter the approach or attachment steps of coalescence such that either of these steps becomes controlling. Let us look at the final step, the release of the water droplet. In his observations of droplet detachment (23), Beatty found that the droplets oscillated prior to release. A small residual water drop remained attached to the filament after release, and detachment occurred much more readily in fuel containing the more powerful surfactants. Events subsequent to release occurred rapidly and were not observed. Others have examined the action of a shear field on free droplets (26,27). Dispersed droplets elongate in a shear field and may even become long thin threads. Rupture to small droplets occurs readily under these conditions due to capillary waves on the surface of the dispersed thread. A mathematical treatment of this phenomenon has been made, but it is not readily applied when surfactants are present in the emulsion.

The interfacial properties which are important in emulsion stability are not well defined (33a), but interfacial tension does not predominate. Interfacial film viscosity and plasticity are considered to be involved, but these parameters have not been measured accurately for emulsion systems (33b). The mechanics of emulsion formation should also depend on these properties, but experimental work bearing on this area is not available, and in general the important aspects of emulsion formation are not as well understood as those of emulsion stability.

Thus, the postulation of re-emulsification of coalesced water as it is released from a filter bed must be considered a poorly defined speculation.

Passage of relatively large water drops, about 2-mm diameter, through a coalescer bed gave interesting results. Individual droplets passed through almost intact, even through a bed composed of 1- μ fibers, in which case the pore sizes are quite small, about 1/200 the size of the drop. Some rupturing of the drop occurred, however, since free water in small droplets was detected. The amount of free water was greater when

small fiber sizes were present in the bed. A more significant effect was that due to sodium petroleum sulfonate in the fuel. The effluent fuel with 2 ppm of additive had a visually detectable haze, although the time for equilibration of the additive with the water/fuel interface was only a few seconds. This haze, which settled very slowly with time, amounted to 18 ppm of free water. It is evident, therefore, that water coalesced from an emulsion by movement through fiber glass will not necessarily stay as enlarged droplets but may be ruptured to sizes which are too small to settle from the moving fuel stream.

The following picture of coalescence in a fiber bed emerges from this study. Water droplets in a fuel emulsion approach the fibers and reach a fiber primarily by the interception mechanism. Hydrodynamic factors — fiber size, particle size, differential density, and fuel viscosity — control the efficiency of this mechanism, but beds can and have been designed which afford an efficiency of unity. The drops attach to a fiber and grow by further droplet interception to a larger size. The extent of growth is determined by the balance between the adhesive forces of the water/fiber interface and the flow forces of the fuel. The fiber-to-fiber distance is small compared to the coalesced droplet size, and the droplet is attached simultaneously to several fibers as it threads through the fibers. At the downstream side of the fiber bed the droplets are released as discrete drops. The type and concentration of surfactant, as well as the fiber size at the point of release, are important influences on the size of the released water drops and largely determine the amount of water left in the fuel after passage through a coalescer.

CONCLUSIONS AND RECOMMENDATIONS

This report presents theoretical and experimental information which shows that the interception process is the predominant mechanism for approach of a water drop to a fiber from a flowing fuel emulsion. The interception theory explains the reason for the importance of small fibers in a fiber bed. The attachment process does not appear to be a critical one for this type of coalescence. The release of water from the downstream face of a fiber bed is an important phenomenon which has not been adequately considered. Although theoretical and experimental validations are weak, surfactants are thought to interfere with coalescence during the release process.

Future experimental work should examine the droplet growth and movement through a fiber bed and the mechanism of droplet release from a fiber bed. The effect of surfactants on these phenomena should be determined, and the primary site and mode of surfactant action investigated. Coalescence studies need to be made in which both the amount of water and the particle size of the droplets are measured simultaneously in the fuel stream leaving a coalescer bed. Both of these measurements should be made in-line if suitable instruments are available, but analysis of batch samples may be the only feasible system in lieu of acceptable in-line procedures.

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13. ABSTRACT <p>The removal of water from jet fuel is a necessity for the efficient operation of jet aircraft and the reduction of maintenance requirements. Experimental work has been performed to examine the important factors and forces in the coalescence phenomenon by which water is normally removed from jet fuel in field operations. The basic tool used in this study was the Water Separometer. The experimental work was supported by theoretical calculations. The interception process, rather than diffusion or inertial-impaction, is the primary mode of water-droplet approach to a fiber when a water-in-fuel emulsion is coalesced in a fibrous bed. The experimental evidence for the importance of small fibers in the coalescer material is supported by calculations for the interception process. The attachment step does not appear to be critical in the overall coalescence process. Surface-active materials function at the fuel/water interface rather than the fuel/solid interface. The marked deterioration of performance caused by surfactants in the fuel is thought to be related to phenomena occurring at the point of droplet release at the downstream face of the coalescer.</p>			

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