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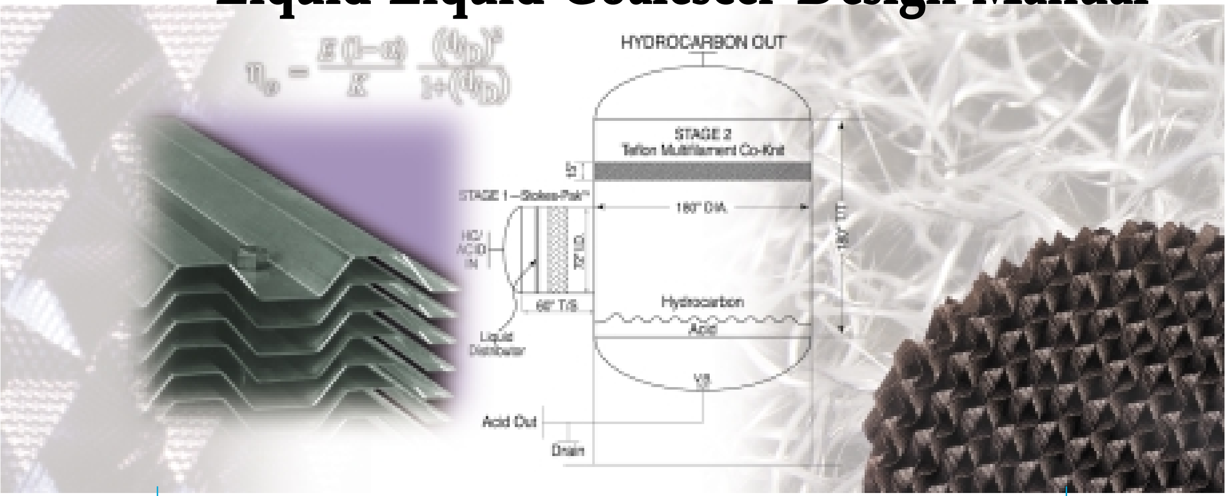

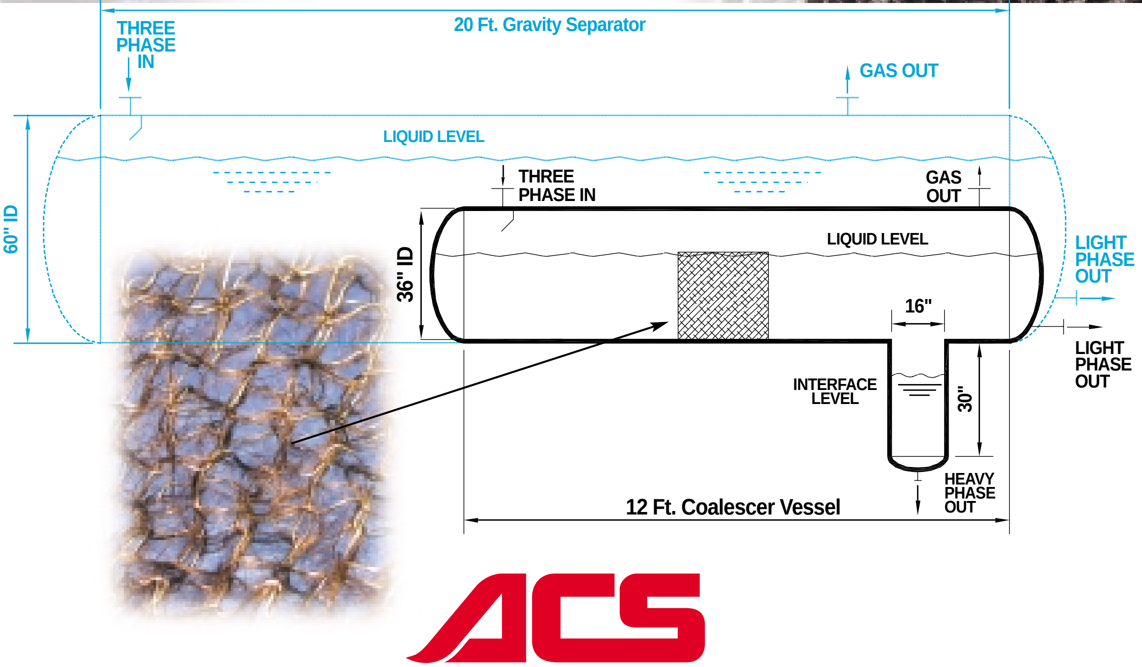

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SEPARATIONS & MASS-TRANSFER PRODUCTS

ACS Industries, LP • Houston, Texas • USA

800-231-0077

14211 Industry Road • Houston, TX 77053 • **TEL:** 713-434-0934 • **FAX:** 713-433-6201
eMail: separations@acsind.com • ***Visit our web site*** www.acsseparations.com

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LIQUID-LIQUID COALESCER DESIGN MANUAL

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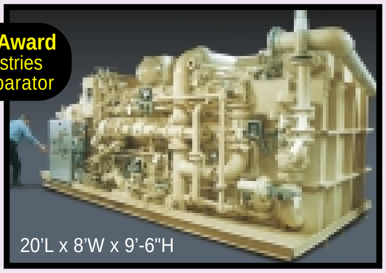
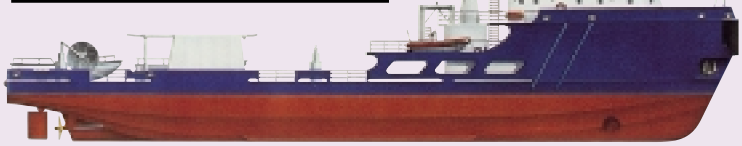
ACS Oil / Water Separators utilize patented* technology to separate oily waste water. Applications include oil spill clean up for marine, power plants, refineries, vehicle terminals, and countless others. The separated water is purified for direct sewer or ocean discharge. The oil is captured and recycled.

*US Patent Nos. 5,023,002 & 5,246,592

1992 Vaaler Award
for ACS Industries
Oil-Water Separator





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TEL: 800-231-0077 • **FAX:** 713-433-6201 • **WEB:** www.acsseparations.com • **EMAIL:** acsseparations@acsind.com

Introduction

Whether engineering a new coalescer vessel, or debottlenecking an existing separator, full knowledge and understanding of the basic principles involved are required. Often overlooked are the capabilities of properly selected and designed internals for the enhancement of simple gravity separation. This *Liquid-Liquid Coalescer Design Manual* describes the use of various media and methods employed for decades to increase plant productivity. Typical applications include:

- **Removal of Bottlenecks in existing Decanters and Three Phase Separators.**
- **Reduction in New Vessel Sizes – Up to five times relative to gravity settling alone.**
- **Improvements in Product Purity – Carry-over entrainment reduced to 1 ppm and less.**
- **Compliance with Environmental Regulations – Cost effective solutions to wastewater treatment and oil spill cleanups.**

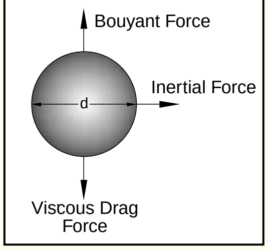
When two liquids are immiscible, or non-soluble in one another, they can form either an *emulsion* or a *colloidal suspension*. In either of these mixtures, the *dispersed* liquid forms droplets in the *continuous* phase. In a suspension, the droplets are less than one micron in diameter and the liquids cannot readily be separated with the technologies described here. Fortunately, in the chemical and hydrocarbon process industries droplet sizes are typically greater than this and/or the purities required can be achieved without addressing the ultra-light colloidal component of the stream.

Stokes Settling – Using Gravity

Traditionally, gravity separators were used to handle emulsions before the use of coalescing media became commonplace. In this equipment, differences in densities of the two liquids cause droplets to rise or fall by their buoyancy. The greater the difference in densities, the easier the separation becomes. Rising (or falling) droplets are slowed by frictional forces from viscous effects of the opposing liquid. When the stream is not flowing and the opposing forces of buoyancy and viscous drag balance (Figure 1), the droplet has achieved its *Terminal Settling Velocity*. This vertical velocity is constant because there are no net forces acting upon the droplet. This mechanism of separating liquids by gravity is called *Stokes Settling* after the nineteenth century English researcher Sir George Stokes.

FIGURE 1

Forces on a light droplet dispersed in a heavy liquid



The equation he developed for the terminal settling velocity is still used today:

$$v_t = 1.78 \times 10^{-6} (\Delta S.G.) (d)^2 / \mu \qquad (1)$$

v_t = **Terminal Settling Velocity, ft/s**

d = **Droplet Diameter, microns**

$\Delta S.G.$ = **Specific Gravity Difference between the Continuous and Dispersed Phases**

μ = **Continuous Phase Viscosity, centipoise**

The size of a gravity decanter is derived from 1) the terminal settling velocity of a *minimum* sized droplet and 2) the inertial force imparted to the droplet due to the velocity of the emulsion through the vessel. At these conditions, all droplets larger than a minimum will be removed at a quicker rate and hence need not be considered. The minimum sized droplet must be estimated if empirical data is not available. Typically the minimum droplet size is estimated to be between 75 to 300µm. For example, API Publication 421 uses minimum sized droplets of 150µm for oil/water systems in refineries. Note that in Stokes Settling the vessel must be sized to ensure *laminar* or streamline flow; *turbulent* flow causes remixing. An example of this sizing method in a decanter is contained in Case Study 2, see page 12.

In order to settle fine droplets and ensure laminar flow, large vessels and long residence times are required. It may take five, ten, and or even thirty minutes to make a separation, depending on the physical properties of the stream. With the capacity intensification forced on modern refineries and chemical plants and achieved with advanced mass transfer internals, catalysts, and heat exchanger designs, operators find that their separators only have half or a third of the time originally anticipated. This results in hazy, off spec products or intermediates that cause problems in downstream equipment.

With Coalescer Media and Internals, unit performance can be restored. Typical applications include:

- **Upgrading 3-Phase Separators and Decanters**
- **Removing haze from finished products such as diesel and jet fuel**
- **Oil/Water Separators**
- **Solvent recovery from liquid/liquid extraction towers**

Basic Design Concepts

The Emulsion

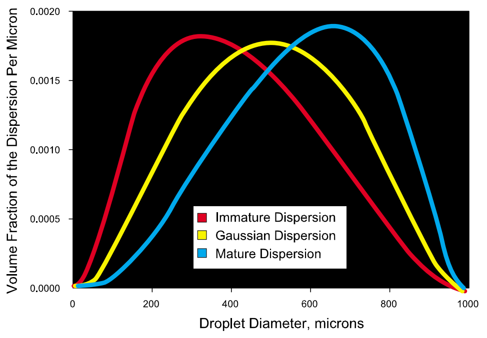
In selecting and designing a coalescer, it is important to understand and characterize the emulsion that has to be treated. The finer the droplets dispersed in an emulsion, the more stable it is, because the buoyancy force diminishes in magnitude as the diameter decreases. The manner in which the mixture is created effects the droplet size distribution. For instance, centrifugal pumps shear liquid droplets much more severely than progressive cavity, thereby creating finer droplets. It is also important for the designer to know how much time has elapsed since the mixing/shearing occurred. This is because as time goes on, smaller droplets aggregate (or coalesce) and larger droplets are more likely to have joined a separate layer so that they are no longer considered to be entrained.

An important tool to quantify an emulsion is the *Droplet Size Distribution Curve* generated by plotting the droplet diameters against the volume or mass fraction at that differential diameter. As stated above, the shape of the distribution is affected by the manner in which the emulsion was formed, and its age. Consider a stream with a fine emulsion (or immature dispersion) as in Figure 2. Overtime, the peak of the volume fraction curve shifts to greater droplet diameters – until there are more large droplets than fines.

Another key characteristic of an emulsion and the distribution that describes it is the existence of a Maximum Droplet Diameter (1000µm in Figure 2). The maximum stable droplet size that an emulsion will develop in a given situation depends on the mechanism of their creation, the amount of energy imparted to the mixture, and the interfacial tension between the phases. Droplets larger than the maximum quickly leave the dispersed phase to form a separate liquid layer and therefore need not be considered part of the emulsion.

FIGURE 2

VOLUME FRACTION FREQUENCY DISTRIBUTIONS FOR DISPERSIONS OF VARIOUS MATURITIES



Generating distributions can be done by collecting and plotting empirical data. Alternately, Mugele and Evans (see General References) showed they have a reliable method for modeling this data as a function of standard deviations that requires only knowledge of the maximum droplet diameter and two different values of the mean. In the typical interconnecting piping between a condenser and a two or three phase separator; from a centrifugal pump and a distillation column feed coalescer; etc., a dispersion develops to where the Sauter (volume/ area) mean is roughly 0.3 and the mass (volume/ diameter) mean is roughly 0.4 of the maximum diameter, respectively.

A coalescer is often needed, though, for mature distributions (when the mean will be larger than a Gaussian 0.5 of the maximum diameter). Examples are the dispersion of produced water in crude oil that has traveled for weeks in a tanker and the water that has settled in a product storage tank over several days. Therefore, with minimal data, an experienced designer can have an accurate idea of the dispersion that a coalescer must treat.

When the average droplet is greater than roughly 1/2 millimeter (500 microns), an open gravity settler is appropriate. Table 1 shows some typical sources that can generate dispersions that require the use of liquid-liquid coalescers. Also given are some characteristics of the emulsions that are created.

Source	Stability	Droplet Size Range
Flash Drum Emulsions with >5 % Dispersed Phase, Static Mixers	Weak	100-1000 microns
Flash Drum Emulsions with <5 % Dispersed Phase, Impellor Mixers, Extraction Columns	Moderate	50-400 microns
Centrifugal Pump Discharges, Caustic Wash Drums, Low Interfacial Tension Emulsions	Strong	10-200 microns
Haze from Condensing in Bulk Liquid Phases, Surfactants Giving Emulsions With Very Low Interfacial Tensions	Very Strong	0.1-25 microns

Table 1

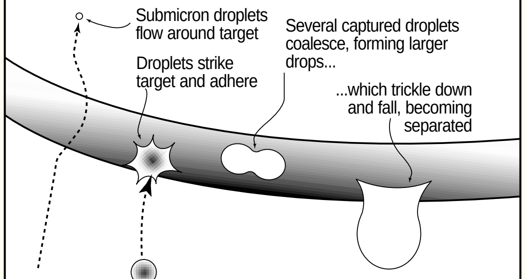
Basic Design Concepts

Operating Principles of a Coalescer

Liquid-Liquid Coalescers are used to accelerate the merging of many droplets to form a lesser number of droplets, but with a greater diameter. This increases the buoyant forces in the Stokes Law equation. Settling of the larger droplets downstream of the coalescer element then requires considerably less residence time. Coalescers exhibit a three-step method of operation as depicted in Figure 3.

FIGURE 3

THREE STEPS IN COALESCING



1) Collection of Individual Droplets
2) Combining of Several Small Droplets into Larger Ones
3) Rise/Fall of the Enlarged Droplets by Gravity

Step 1 – Droplet Capture

The first step of coalescing is to collect entrained droplets primarily either by Intra-Media Stokes Settling or Direct Interception. Figure 4 gives the useful zones of separation for various mechanisms. Elements that depend on Intra-Media Stokes Settling confine the distance a droplet can rise or fall between parallel plates or crimps of packing sheets (Figure 5). This is compared to simple gravity separators in which the traveling distance is equal to the entire height of the pool of liquid present in the separator. This effect is also seen in knitted wire mesh, but their high void fractions mean the surface is very discontinuous.

FIGURE 4

ZONES WHERE DIFFERENT COALESCING MECHANISMS APPLY

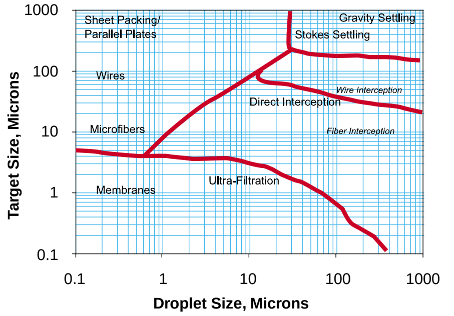
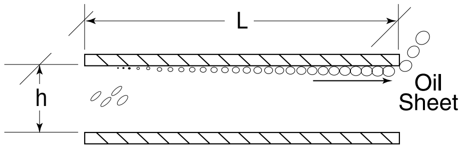


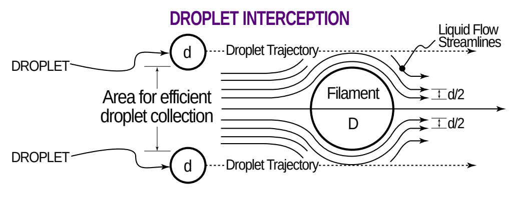
FIGURE 5

OIL DROPLETS RISING TO A COLLECTION SURFACE



Meshes, co-knits of wire and yarns; and wire and glass wools all depend primarily on Direct Interception where a multiplicity of fine wires or filaments collect fine droplets as they travel in the laminar flow streamlines around them (Figure 6). As can be see in Figure 4, in general they can capture smaller droplets than those that depend on enhanced Stokes Settling. A general rule with Direct Interception is that the size of the target should be close to the average sized droplet in the dispersion. Finer coalescing media allow for the

FIGURE 6



separation of finer or more stable emulsions (Table 2). Note that fine media will also capture or filter fine solid particulates from the process stream. Therefore, unless the emulsion is very clean, an upstream duplex strainer or filter is needed to protect a high efficiency coalescer.

Media	Source	Max Droplet Diameter, µ	Flow Range gpm/ft^2
Corrugated Sheets	Separators with Coarse Emulsions & Static Mixers	40-1000	15-75 (35-180 $m^3/hr/m^2$)
Wire Mesh, Wire Wool	Overhead Drums, Extraction Columns, Distillation Tower Feeds, Impeller Mixers	20-300	7.5-45 (20-110 $m^3/hr/m^2$)
Co-Knits of Wire & Polymer	Steam Stripper Bottoms, Caustic Wash Drums, High Pressure Drop Mixing Valves	10-200	7.5-45 (20-110 $m^3/hr/m^2$)
Glass Mat, Co-Knits of Wire & Fiberglass	Haze from Cooling in Bulk Liquid Phase, Surfactants Giving Emulsions with Very Low Interfacial Tension	1-25	7.5-45 (20-110 $m^3/hr/m^2$)

Media	Hydro/Oleophilic	Porosity	Target Size	Fouling/Cost
Metal/Plastic Corrugated Sheets	H/O	98-99%	3/8" - 1" Spacing/Crimps	Low/Low
Wire/Plastic Mesh Wire Wool	H/O H	95-99%	.002" - .011"	
Wire/Polymer Co-Knits	O	94-98%	21-35 micron	
Wire/FG Co-Knits, Glass Mat	H	92-96%	8 - 10 micron	High/High

Table 2

Step 2 – Droplet Coalescence

The second step is to combine, aggregate, or *coalesce* captured droplets. Increasing the tendency for droplets to adhere to a medium, increases the probability that subsequent droplets will have the opportunity to strike and coalesce with those that already have been retained. Whether a coalescer medium is hydrophilic (likes water) or oleophilic (likes oil) depends on the solid/liquid interfacial tension between it and the dispersed phase. In general an organic dispersed phase 'wets' organic (that is plastic or polymeric) media, as there is a relatively strong attraction between the two, while an aqueous dispersed phase preferably 'wets' inorganic media, such as metals or glass. This aids in the coalescence step as the droplets adhere to the media longer. Also assisting coalescing is the density of media: lower porosities yield more sites available for coalescing. In the case of yarns and wools, capillary forces are also important for retaining droplets.

Once several droplets are collected on a plate, wire, or fiber, they will tend to combine in order to minimize their interfacial energy. Predicting how rapidly this will occur without pilot testing is very difficult to do. Judgments of the proper volume, and therefore residence time, in the coalescers are guided by experience and the following properties:

Coalescing Media:

- **Media/Dispersed Phase Interfacial Tension**
- **Porosity**
- **Capillarity**

Liquid Phases:

- **Continuous/Dispersed Interfacial Tension**
- **Continuous/Dispersed Density Difference**
- **Continuous Phase Viscosity**
- **Superficial Velocity**

Coalescers work better in laminar flow for several reasons. First, as mentioned above, droplets will stay in the streamlines around a wire or fiber target. Second, high fluid velocities overcome surface tension forces and strip droplets out of the coalescer medium. This results in re-entrainment in co-current flow and prevents droplets from rising/sinking in counter-current flow. Lastly, slower velocities result in greater residence time in the media and therefore more time for droplet-to-target impact, droplet-to-droplet collisions, and Intra-Media Stokes Settling.

The guidelines in Table 2 are used for selecting the proper coalescer for a given source based on the media's Droplet Collection ability. Also given are typical flow ranges for each type of coalescer media.

Step 3 – Stokes Settling With Coalesced Droplets
The third step is the Stokes Settling of the coalesced droplets downstream of the medium. The degree of separation primarily depends upon the geometry of the vessel and its ability to take advantage of the large coalesced droplets that were created through steps one and two as described above.

Basis for Sizing and Selection

A preliminary procedure for determining how difficult it is to separate two immiscible liquids involves the performance of a simple field test. A representative sample of the emulsion is taken from a process pipeline or vessel. It is either put in a graduated cylinder in the lab or, if it is under pressure, in a clear flow-through sample tube with isolation valves. The time required to observe a clean break between phases is noted. If the continuous phase has a viscosity less than 3 centipoise, then Stokes Law says the following:

Separation Time	Emulsion Stability	Droplet Size, Microns
< 1 minute	**Very Weak**	**>500**
< 10 minutes	**Weak**	**100-500**
Hours	**Moderate**	**40-100**
Days	**Strong**	**1-40**
Weeks	**Very Strong**	**<1 (Colloidal)**

Fortunately, the experienced designer with knowledge of the application, equipment, and physical properties can often estimate the strength of the emulsion and determine which medium will be successful. A more definitive approach, and one that is often needed to provide a process warranty, is the use of an on-site pilot unit.

Liquid-liquid coalescer performance is often rated in parts per million of dispersed phase allowable in the continuous phase effluent. Even trace amounts of contaminants such as emulsifiers and chemical stabilizers can have dramatic effects on results at these levels. In a pilot program, several alternate media are provided to the customer so that their performance can be documented on the actual process stream, thereby taking into account the effects of any particulates or surfactants present. ACS has several of these available, both as hand-held batch testers and continuous units ºgle, double, or triple coalescer stages (Figure 7). This allows a coalescer system to be developed that is optimized for its removal efficiency, on-stream time, and cost effectiveness.

FIGURE 7

For liquid-liquid coalescers, as with any process equipment, successful sizing and selection is always a combination of empirical observation/experience and analytical modeling. Of the three steps in coalescing – droplet capture, combining of the collected droplets, and gravity separation of the enlarged droplets – the first and the last can be modeled with good accuracy and repeatability. The modeling of the middle and the actual coalescing step is a complex function of surface tension and viscous effects, droplet momentum, and the dynamics of the sizes of the droplets in the dispersion. This has been done successfully in porous media, but is beyond the scope of this brochure.

Droplet capture, the first step in liquid-liquid coalescing, is the most important. The next two sections describe the formulas used for the collection mechanisms of Intra-Media Stokes Settling and Direct Interception.

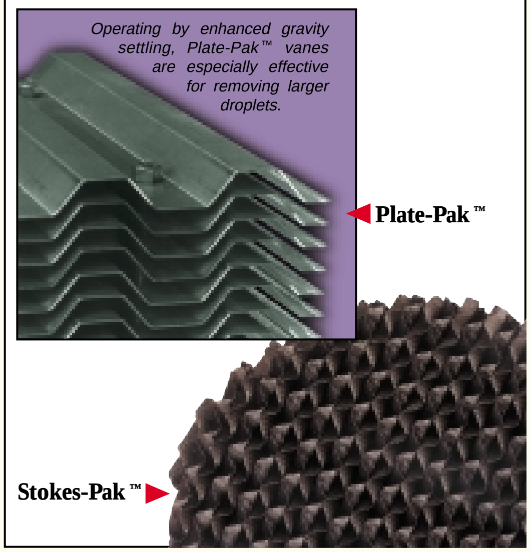
Intra-Media Stokes Settling

In a horizontal 3-phase separator, in order for efficient separation to take place, droplets of some minimum size which exist in both the gas and the liquid phases must be captured within the equipment. When coalescing media is installed in the lower segment of the vessel, the furthest a droplet has to travel is from plate to plate or sheet to sheet, rather than down from the liquid level to interface level and/or up from the vessel wall to the interface level (depending whether the dispersed phase is heavier or lighter than the continuous phase).

ACS offers a number of Corrugated Plate Interceptors (CPI) to enhance coalescence, such as Plate-Pak™ and STOKES-PAK™ crimped sheet packing (Figure 8).

FIGURE 8

COALESCING MEDIA THAT DEPENDS ON STOKES SETTLING



Operating by enhanced gravity settling, Plate-Pak™ vanes are especially effective for removing larger droplets.

They make more efficient use of a vessel volume than a straight PPI (Parallel Plate Interceptor) since more metal is used and the specific surface area is greater. It can be shown from Equation 1 for V_t that the volume of media necessary to remove virtually all droplets equal to a minimum, typically 30-60 microns, is given by:

$$V_C = \frac{(C_1)\ Q\ h\ \mu}{(\Delta S.G.)\ d^2} \qquad (2)$$

Where

V_C = Coalescer volume, cubic feet

C_1 = 164 for Plate-Pak w/horizontal sheets
219 for STOKES-PAK w/horizontal sheets
312 for STOKES-PAK w/vertical sheets

Q = Liquid/liquid emulsion flow, US GPM

h = Corrugated plate spacing or structured packing crimp height, inches

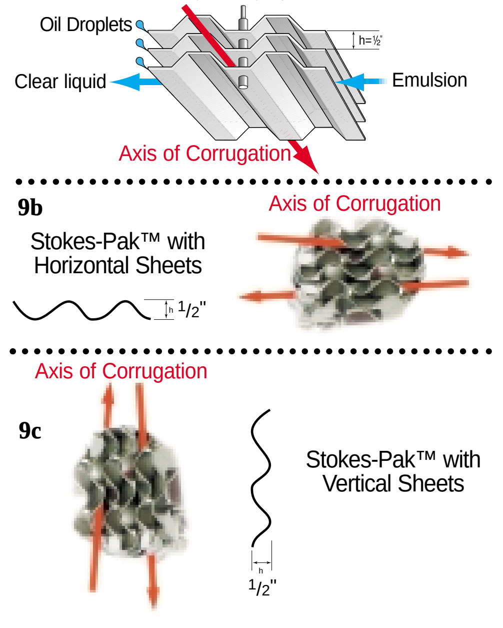
d = Minimum droplet diameter, microns

μ = Continuous phase viscosity, centipoise

Plate-Pak is the most efficient CPI and thus has the smallest C_1. The reason for this is that the height, h, a droplet must traverse before hitting a solid surface is minimized in this construction (see Figure 9 a-c).

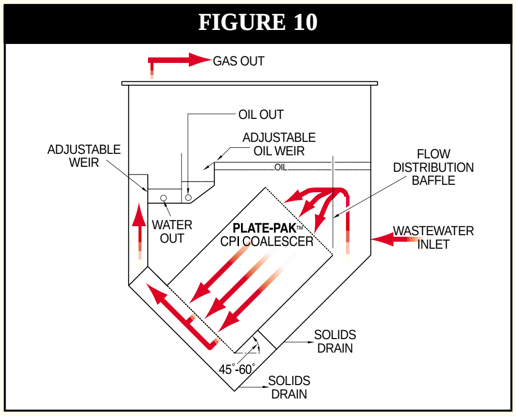
FIGURE 9

DISTANCE BETWEEN PLATES IN VARIOUS STOKES-PAK COALESCERS



In order to decrease solid retention the axis of the corrugations of Plate-Pak should be parallel to the flow. However, vessel geometry often necessitates that the corrugations be perpendicular to the flow, especially in round vessels. Due to its light, self-supporting structure and ease of installation, the overall project cost is normally less for STOKES-PAK than Plate-Pak when they both have sheets in the horizontal. STOKES-PAK with vertical sheets, on the other hand, retains fewer solids than the horizontal sheet version and so is often required in fouling situations. In this case, there is some loss in coalescer efficiency due to the longer distance a droplet could travel (see Figure 9 b and c). The entire CPI unit can also be put on a 45˚ to 60˚ angle in order to retard fouling. However, this requires much more support structure and an additional 40 to 100% of coalescer volume since droplet trajectory is lengthened (Figure 10).

FIGURE 10



Equation 2 incorporates empirical factors that increase the coalescer design volume over the theoretical in order to compensate for the effects of bypass and back mixing. With knowledge of the cross-sectional area of a fully flooded coalescer vessel or the lower segment available in a horizontal 3-phase separator, the required depth can easily be calculated from Vc. ACS Plate-Pak and Stokes-Pak both come in units which are 8" (203 mm) deep as a standard, but custom depths are also available.

Once the final coalescer length is selected the minimum droplet size that can be collected at 99.9% efficiency can be found by trial-and-error substitution of the terminal settling velocity from Equation 1 into Equation 3 below

$$\eta_s = (v_t/h)/\ (v_s/L) = .999 \qquad \textbf{(3)}$$

where

η_s = Fractional Collection Efficiency by Stokes Settling
v_s = Superficial Velocity
L = Element Length
v_t/h = Droplet Rise Time
v_s/L = Droplet Residence Time

In horizontal flow when this length is over four elements, ~32" (813 mm), the coalescer is usually split in two or more beds with intermediate spacers or spacer rings. Also, cross-flow designs are often used in this situation to allow for more frequent removal of the collected dispersed phase.

Direct Interception

Direct Interception occurs when a droplet follows a streamline around a target but collides with it because the approach distance is less than half its diameter, d/2 (Figure 6). The formulas for Direct Interception in mesh, co-knits, wire and glass wools are given below. Given first is a formula for the collection of a droplet on a single target. Following that is a formula which, based on this factor, calculates the depth of the coalescer element necessary to achieve a desired overall collection efficiency at a selected minimum droplet size.

$$\eta_D = \frac{E\,(1-\alpha)}{K}\;\frac{\left(d/D\right)^2}{1+\left(d/D\right)} \qquad \textbf{(4)}$$

η_D =Collection Efficiency of a Single Target by Direct Interception

E =Effective Length Multiplier

α =Volume Fraction of Fibers or Wires

d =Droplet Diameter, inches

K =Kuwabara's Hydrodynamic Factor
$-0.5 \ln \alpha - 0.25\, \alpha^2 + \alpha - 0.75$

The formulas for Direct Interception have no velocity term in them, but to allow coalescence to take place designs are normally done for the middle of the flow ranges given in Table 2. K, the Kuwabara Hydrodynamic Factor, above is a correction to the collection efficiency term that assumes a laminar/viscous flow field. The effective length multiplier, E, is an empirical factor that takes into account the uneven distribution of curved and crinkled targets in a wool medium and/or the shielding effects of the loops of knitted mesh and twists of adjacent filaments in a strand of yarn. The idealized layout of fiber targets where E=1 in a coalescer is shown in Figure 11, while what actually exists in a co-knit is shown in Figure 12. The finer the filament or wire the more the nesting/shielding effect and the lower the value of E.

FIGURE 11

INTERCEPTOR LAYOUT IN AN IDEAL COALESCER

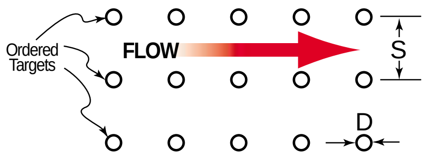
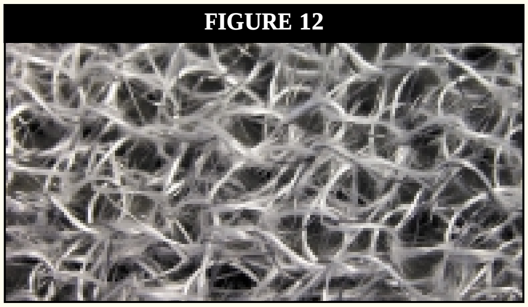


FIGURE 12



CO-KNIT MESH COALESCER THAT DEPENDS ON DIRECT INTERCEPTION

As with CPI coalescers, sizing of a liquid-liquid coalescer that operates primarily on Direct Interception also correlates well to an Overall Collection Efficiency of 99.9% of a minimum droplet size. Once this droplet size, empirically found to be approximately half the target diameter, is substituted into Equation 4, the length, L, required for a clean break can be predicted as follows.

$$L = \frac{\pi D\,(1-\alpha)\ln\,(1-\Sigma)}{-4\,\eta_D\alpha} \qquad \textbf{(5)}$$

Σ = Overall Collection Efficiency by Direct Interception
L = Element length required for removal of all droplets $\geq$ a minimum size at a Σ = .999, inches

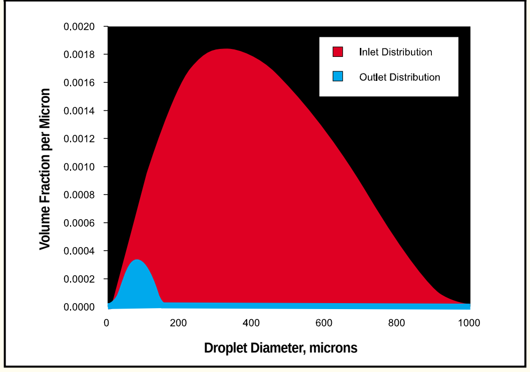
As can be seen in Figure 4, there are two broad categories of Interceptor-Pak™Coalescers that depend in Direct Interception, those that are made with fine wires and those that are made with fine fibers. The factors to be used in the formulas above for these media, the appropriate minimum droplet size to use; and the applications where they have found success are given in Table 3. In wire-yarn co-knits the wire occupies as much as a third of the volume fraction as the yarn, but exhibits only a few percent of the surface area. Therefore, for the sake of conservatism, the constants given in the table do not take into account either factor.

Application	Min. Droplet Diameter microns	Coalescer	D microns/in.	α	E
Wastewater Sheen	4.5	Fiberglass Mat Fiberglass Co-Knit Interceptor-Pak™	8.9/0.00035	0.037 0.027	.04 .02
Caustic Wash Drums	11.0	Teflon Co-Knit Interceptor-Pak™	21/0.00083	0.019	.07
Impeller Mixers	12.5	Polyester Co-Knit Interceptor-Pak™	24/0.00095	0.021	.07
Mixing Valves	22.0	Wire Wool Interceptor-Pak™	50/.002	0.028	.40
Extraction Columns	79.0	Knitted Mesh Interceptor-Pak™	152/.006	0.014	.60

Table 3

The equations for droplet collection above can also be used to derive the dispersed phase's concentration in the effluent stream. First, a measured distribution or the curve estimated with Mugele's droplet size distribution equations is broken up into a large number of discrete diameter ranges. The fractional collection efficiency is then calculated at the mid-point of the range using either equation 3 or 5 (rewritten to be explicit in Σ) thereby deriving the volume of dispersed phase that penetrates at that diameter. The effluent curve is then plotted. The area under both curves is found with the influent normalized to 1 (Figure 13). With knowledge of the influent dispersed phase concentration, the effluent level is found by multiplying by the ratio of these areas.

FIGURE 13



Gravity Separation Downstream of a Coalescer Element

Successful gravity separation downstream of a coalescer element depends primarily on vessel geometry. Various schemes are used with horizontal vessels depending on whether there is a significant amount of gas present as with Three-Phase Separators (Fig. 14A) and/or the volume percent of the dispersed phase. The formation of a wedge between a coalescer and a sharp interface level as seen in Fig. 14B is well documented. A boot is desirable when the amount of dispersed phase is <15% v/v (Fig. 14C) where the control of the interface level is linear with the volume of dispersed phase discharged. A dispersed phase velocity of 10 inches (254 mm)/minute is desirable to allow disengagement of the continuous phase, while keeping the boot diameter <40% of the diameter of the horizontal portion to minimize the necessity for weld pads. The most common applications for coalescers in vertical flow are extraction/liquid-liquid absorption towers (Fig. 14D) and entrainment knockout installations (Fig. 14E) where the available plot plans in the plant are at a premium. The coalescer is located downstream of the interface so that entrained continuous phase is removed from the dispersed. Lieberman (see General References) recommends that the liquid loading in a vertical wash tower be limited to at most 1.6 ft/min of the dispersed phase. With the installation of a coalescer this can safely be increased to 2 ft/min (15 gpm/ft^2) thereby decreasing the cross-sectional area of the column by 20 to 40%.

In pressure vessels with full diameter coalescers such as those shown in Figures 14B and 14C, it is important economically to keep the L/D ratio in the range of 3 to 5. It is typical and desirable that coalesced droplets emerge from media that operates either on Intra-Media Stokes Settling or Direct Interception at a size of from 500 to 1,000 microns. The vessel length necessary for inlet distribution devices upstream of the media (such as sparger pipes, ‘picket fences’, and perforated plates used to assure uniform flow through the media as in Figures 14B and 14C) and the depth of the typical coalescer element itself with supports is typically 1 to 1.5 D. In order to keep the vessel’s aspect ratio in the economical range, assuming an average 750-micron droplet emerging from the coalescer, the axial velocity of the two liquid phases should be limited to:

$$U_{Max} = \frac{0.78\,|\Delta\rho|}{\mu} \qquad (6)$$

Where

U_{Max} =Emulsion velocity, feet/minute

$|\Delta\rho|$ =Absolute value of the difference between the densities of the continuous and dispersed phase, pounds/cubic feet

μ =Continuous phase viscosity, centipoise

The successful design of a liquid-liquid coalescer starts with knowledge of the source of the emulsion and the stream’s physical properties. It has been shown that a combination of empirical experience and analytical modeling of available coalescing media based on removal of 99.9% of a minimum droplet size can then be used to predict allowable entrainment concentrations in the effluent stream. Once the coalescer is properly located in an existing or new vessel a project that has a high rate of return is achieved that gives many years of reliable service.

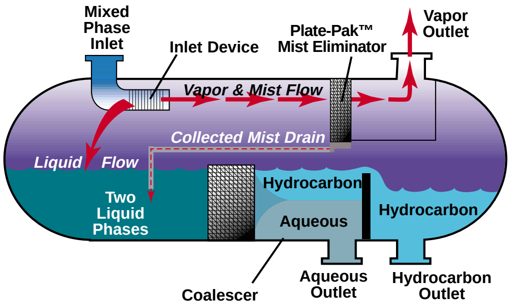
COALESCER
Configurations

Vertical Coalescers ►

Horizontal Coalescers ▼

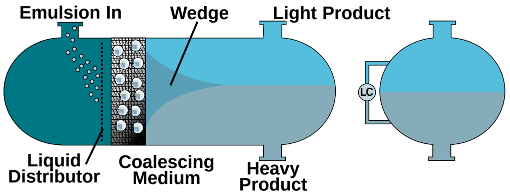
FIGIRE 14 A

3-Phase Horizontal Coalescer Vessel



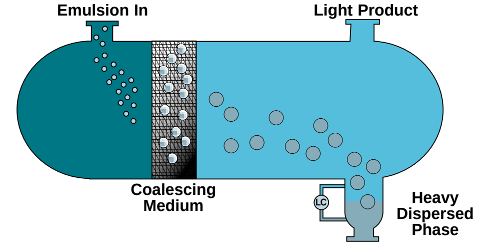
FIGIRE 14 B

2-Phase Horizontal Coalescer Vessel



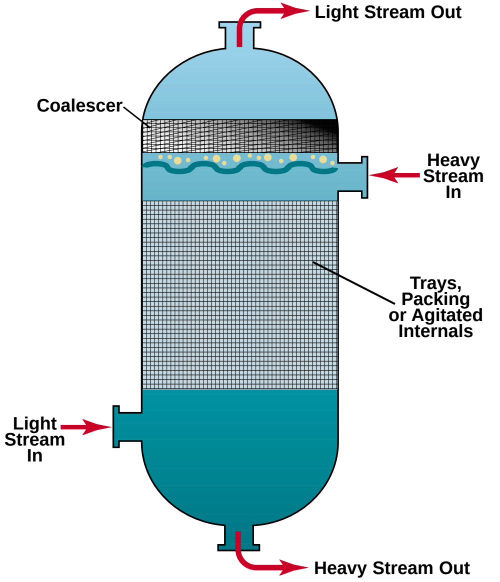
FIGIRE 14 C

2-Phase Horizontal Coalescer Vessel with Boot



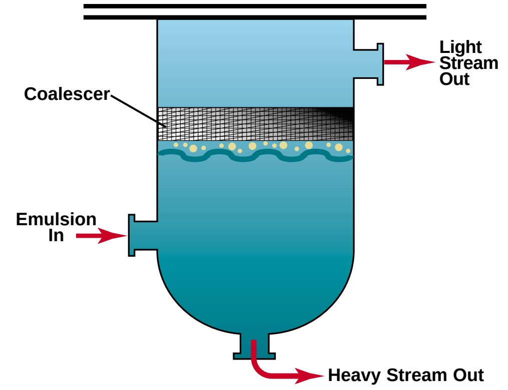
FIGIRE 14 D

Vertical Extraction Column with Coalescer



FIGIRE 14 E

Vertical Decanter with Coalescer



CASE STUDY #1

Oil-Water Separators — Environmental Response

The Oil-Water Separators (OWS) developed by ACS to handle accidental offshore spills have three stages of coalescing, one using Stokes Settling and two using Direct Interception. It can, therefore, serve as an example of how to apply all the equations for droplet coalescing given above. After the Exxon-Valdez incident the US government was looking to set up a quick response system with ship-board equipment to skim potential large spills of crude oil that on the frigid ocean waters congeals to a viscosity of up to 50,000 centistokes, separate out all contaminants on board, and return the sea water with less than the EPA mandated 10 ppm hydrocarbons present. The Marine Spill Response Corporation (MSRC) was set-up for this purpose with 16 locations in all major US ports including Puerto Rico, Hawaii, and Guam. ACS engineers quickly developed, tested, and proved to MSRC the viability of the 525-gpm OWS system shown in Figure 15 below, two of which were installed on each quick-response vessel. ACS was awarded the prestigious Vaaler Award and two US patents (Nos. 5,023,002 and 5,246,592) in developing the coalescers for this application.

Typical conditions are – removing 25 gpm of oil with a specific gravity of 0.85, and a viscosity of 12,000 centistokes from 500 gpm of water with 3% salinity, a specific gravity of 1.02, and a viscosity of 1 centistoke. The overall dimensions of the OWS for the MSRC are 8' square by 25' long at a full of water weight of 25,000 lbs.

CPI media, such as ACS Plate-Pak™ which in this case had 3/4" plate spacing to accommodate the highly viscous oil, is known to be able to remove 99+% of all droplets down to about 100 microns.
Putting these factors into equation 2 yields –

$$V_C = \frac{164\,(525)\,0.75(1.02)}{0.17\,(100^2)}$$

$$= 38.0 \text{ cubic feet}$$

The Plate-Pak was designed for 25gpm/ft^2, requiring 21 square feet (installed at 7 feet wide X 3 feet high to accommodate the design shown in Figure 15 and the shipping dimensions given above). Therefore, the required depth is 38.0 cubic feet/21 square feet, or 1.81 feet. This was rounded up to two feet for safety.

In order to meet stringent EPA regulations for discharging wastewater overboard, two stages of ACS Interceptor-Pak™ Co-Knit coalescing media were used. Their efficiency was maintained despite the presence of the highly viscous oil by cleaning both of them with diesel oil which was injected at an amount equal to only 0.5% by weight of the amount of oil anticipated to be collected. This media works on Direct Interception so equations 4 and 5 are used. Media properties are given in Table 3. First Kuwabara's Hydrodynamic Factor is calculated as follows.

$$K = -0.5 \ln .027 - 0.25(.027)^2 + (.027) - 0.75$$

$$= 1.083$$

According to Table 3 fiberglass co-knit can remove 99.9% of all droplets 4.5 microns and larger. Therefore

$$\eta_D = \frac{0.02\,(1-.027)(4.5/8.9)^2}{1.083\,(1+(4.5/8.9))}$$

$$= 0.00305$$

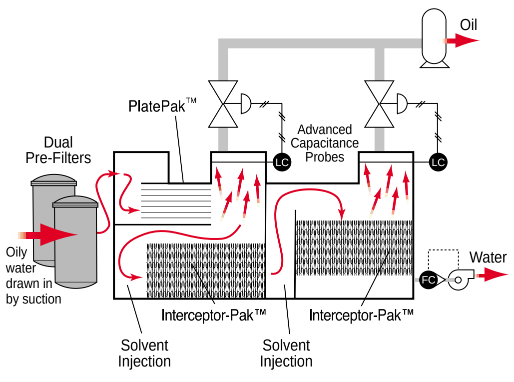
$$L = \frac{\pi\,(.00035")\,(1-.027)\ln(1-.999)}{-4(0.00305)\,0.027}$$

$$= 22.4"$$

For safety each stage was supplied with a 24" thick fiberglass co-knit element.

FIGURE 15

ADVANCED OIL/WATER SEPARATOR



CASE STUDY #2

Coalescers in Gas Plants

A major South American engineering company was designing a 100 MMSCFD natural gas plant that used ethylene glycol (EG) for dehydration and for inhibiting hydrate formation. There is a horizontal Three Phase Cold Separator with a boot in this process that does mist elimination in the free board above a large liquid hold-up section that extends the length of the vessel. The latter volume is used to recover the glycol that has become emulsified as fine droplets in the NGL's (natural gas liquids) and the dispersed hydrocarbons that have stabilized in the EG. Since the glycol continually re-circulates in the system, fine NGL droplets tend to build up in the inventory causing an emulsification of both liquid phases. The EG droplets are thought to be as small as 30 microns in the organic phase, so 30-minute hold-up times for gravity separation are not uncommon in the industry. ACS was asked if a coalescer could be provided to significantly reduce the resultant vessel size.

The process conditions for the coalescer sizing was for it to handle 37.5 gpm of NGL's that had a density of 31 lbs/ft3 and a viscosity of 0.11 cp; and 7.5 gpm of 75% ethylene glycol that had a density of 51.1 lbs/ft3 and a viscosity of 7.2 cp. A quick design for a gravity separator can be done with equation 2 if the maximum height that a 30-micron glycol droplet would have to fall from the liquid level to the boot at the bottom of the vessel is used as if it was the CPI coalescer's h. In this case 42" was assumed for a 60" ID vessel. Thus

$$V = \frac{162(45)\,42\,(.11)}{(.818-.496)30^2}$$

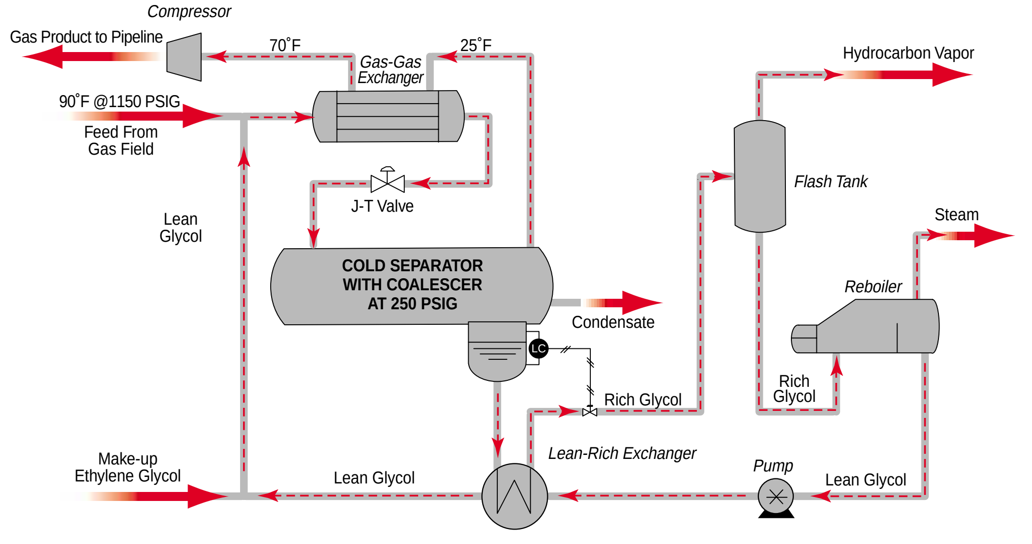
$$= 215 \text{ cubic feet}$$

This means with gravity alone a 5' dia. x 20' tangent to tangent vessel would be required. In order to improve control and to allow for disengagement at 10"/min., a 16" dia. x 30" tall boot was specified. ACS recommended and supplied a 24" thick mesh coalescer of a co-knit of fiberglass yarn and stainless steel wire. The liquid loading sizing criteria required the installation of a 24" high segment in a 36" ID vessel. This vessel was 12' tangent to tangent with the same 16" diameter X 30" tall boot. Thus, as compared to a conventional gravity separator, the use of an engineered coalescer was successful in reducing the vessel volume by a factor of 4.5.

An illustration of this is shown on the cover of this bulletin.

FIGURE 16

GAS PLANT WITH JOULES-THOMPSON DEW POINT CONTROL



CASE STUDY #3

Coalescers in Alkylation Units

A refinery was using a 15-psi mix valve to acid wash the reactor products of their H_2SO_4 alkylation unit. This is done to extract both acidic and neutral ester side products that readily polymerize, reduce acid strength, and cause foaming. A vertical two-stage coalescer drum with a horizontal boot (Figure 17) follows immediately in order to make a clean break between the two immiscible phases and lower the free acid concentration in the hydrocarbon to less than 15 ppm. The first coalescer stage in the horizontal section, used to remove the bulk of the acid, is a vertical Stokes-Pak™ element, which is preceded by a 20% open perforated plate liquid distributor. The second stage is a horizontal ACS Interceptor-Pak™ with Teflon® Multi-Filament Co-Knit. The inlet section of the large diameter vertical section removes the fine acid droplets and allows them to drain counter-current to the ascending continuous hydrocarbon stream.

Process conditions were 2480 GPM of alkylate that had a specific gravity of 0.59 and a viscosity of 0.21 cp was mixed with 110 GPM of acid (2/1 ratio of recycle to fresh) that had a specific gravity of 1.85 and a viscosity of 25 cp. The mix valve is reported to create an average droplet size of approximately 400 microns for the washing, but also generates a significant amount of fine droplets. Stokes-Pak™ with horizontal sheets and 1/2" crimps was chosen to remove 99+% of all droplets down to about 35 microns. The volume of coalescer required was estimated with equation 2:

$$V_C = \frac{219 * 2590 * 0.5 * .21}{(1.85-.59)\ 35^2} = 38.6 \text{ cubic feet}$$

Thus a 16" thickness of Alloy 20 Stokes-Pak was used in the 78" ID X 5’ long horizontal boot.

As mentioned above, counter-current flow in the vertical portion of the tower necessitates liquid loads on the coalescer below 15 gpm/ft^2 (2 ft/min). This required a 15’ diameter vertical section. The Teflon Multi-Filament Co-Knit Coalescer was chosen due to corrosive conditions and the tight residual acid specification. Experience has shown that a 15-ppm spec requires removing essentially all droplets down to 15 microns. A Kuwabara hydrodynamic factor for this media of 1.251 is found using the data from Table 3. The collection efficiency of a single Teflon fiber is found when this factor and the data above are plugged into equation 4 as follows

$$\eta_D = \frac{0.07\ (1-.019)\ (15/21)^2}{1.251\ (1+(15/21))} = 0.0163$$

Putting this value in equation 6 gives

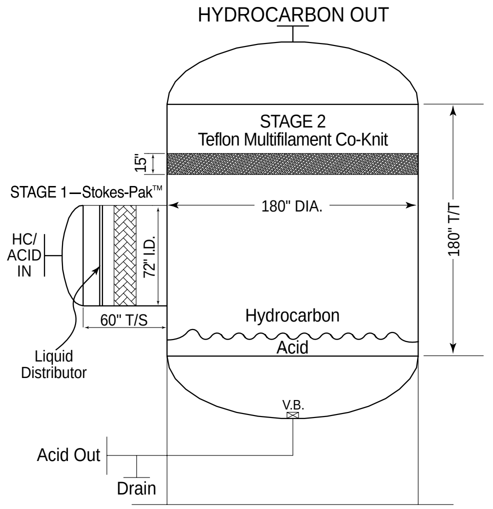
$$L = \frac{\pi\ (.00083")\ (1-.019) \ln (1-.999)}{-4(0.0163)\ 0.019}$$

$$= 14.3"$$

Thus a 15" depth of a 15’ diameter Alloy 20/Teflon Multi-Filament Interceptor-Pak Coalescer was chosen for the second stage element.

FIGURE 17

COALESCER IN ALKYLATION UNITS



Case Study #4

Oil-Water Separator on a Production Platform

Produced water enters an oil and gas production platform along with the organics and forms a distinct separate phase after several let downs in pressure through First, Second, and even Third Stage Separators; FWKO (Free Water Knock Out) Treaters, Test Separators, etc. According to the governing regulations for the Gulf of Mexico all water must be treated to remove oils down to <25 mg/l before it can be discharged overboard. Plot plan area is at a premium on a platform. This often necessitates a vertical 'Oil Skimmer Vessel' and, even though a significant amount of fine sand comes in with the process stream, it must still be high efficiency. In many cases these are also four phase separators as a small amount of residual gas needs to be handled as well.

ACS worked with a Gulf Coast fabricator to both design the pressure vessel shown in Figure 18 and then supply the internals. Here 10,000 BWPD (barrels of water per day) of salt water are handled in an 8' diameter X 15' seam-to-seam vessel with a cone bottom. The inlet nozzle extends into a tee immediately inside the vessel. One arm extends vertically above the liquid level where gasses can be discharge. It was determined that the amount of gas is so small that the use of a mist eliminator was not necessary. Simultaneously the contaminated water jets down toward the cone via the opposite arm. A vertical baffle retains the water in a low velocity zone at the bottom of the vessel where the flow is sufficiently slow for the sand to drop out. Lastly, at the top of the vessel there is an overflow weir that collects the oil which flows by gravity off all the coalescers and then flows through the oil outlet nozzle under pressure to a suitable, atmospheric holding tank.

The water is then forced through two stages of coalescing media. The first is 24" depth of vertical Plate-Pak™ with its plates also in the vertical. When the spacing in this media at 1/2" there is no line-of-sight and the oil droplets in the stream are forced to hit 33 baffles in series. Very fine ones could still float up 42" before striking the roof of the housing, but are collected at the oil/water interface. At an effective width of 92" the liquid load is ~11gpm/ft2. Nonetheless, this is the less efficient orientation, but also the least susceptible to fouling.

The second stage is in vertical down flow. First there is a liquid distributor made from 10% perforated plate. This is needed in order to take full advantage of the entire volume of coalescing media. The element is 22" depth of co-knit of stainless steel wire and fiberglass yarn that has 2" of a fiberglass mat below it. The latter media has the same size target collectors at 8.9 microns as the yarn material. Besides being denser at an α of 0.037, its needled, non-woven construction exposes much more surface area so that it has been found to have an E of 0.04. The additional high efficiency polishing of the effluent water stream obtained with the mat is allowable at this point since it is well protected from particles of sand by the co-knit mesh above.

It is difficult to tell exactly which media did the most to achieve the effluent produced water's compliance with the <25 mg/l level as is regularly confirmed by an EPA approved lab. However, the following calculations show that the fiberglass mat is up to three times more efficient than fiberglass yarn in coalescing oil droplets from water. The Case Study on page 11 showed that 22.4" of co-knit were required to remove 99.9% of all droplets $\geq$ 4.5 microns.

Similarly, the Kuwabara Factor for fiberglass mat is

$$K = -0.5 \ln .037 - 0.25(.037)^2 + (.037) - 0.75$$

$$= 0.935$$

Equation 4 is then used to calculate the collection efficiency of a single target by Direct Interception as follows:

$$\eta_D = \frac{0.04\,(1-.037)\,(4.5/8.9)2}{0.935\,(1+(4.5/8.9)}$$

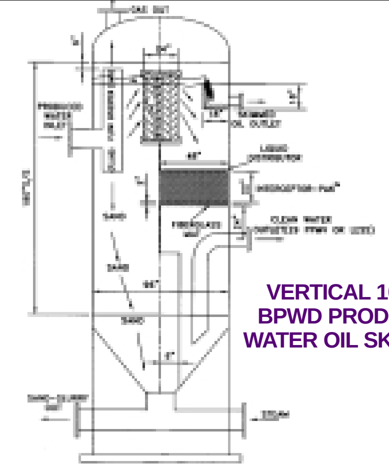
$$= .00699$$

Finally, by Equation 5 the required element length for fiberglass mat is only

$$L = \frac{\pi\,(0.00035)\,(1-.037)\,\ln\,(1-.999)}{-4\,(.00699)\,.037}$$

$$= 7.1"$$

FIGURE 18



VERTICAL 10,000 BPWD PRODUCED WATER OIL SKIMMER

Case Study # 5

Upgrading a Three Phase Separator

A major refiner in the Central US was reluctant to put any internals in a critical Three Phase Separator, the Naphtha Stripper Overhead Drum of the FCC Unit. However, slugs of water entraining in the hydrocarbon phase's outlet were continually causing cycling of its transfer pump which was a high head centrifugal. Water must be injected upstream of an air cooled condenser to dissolve ammonium sulfide. The rate of injection had recently been raised 20% due to an increase in salt forming components in a new slate of crudes. Nonetheless, any solution had to be able to operate over a 30 month turn-around cycle. Another problem was that their engineers did not want to weld to the vessel's shell since the sour water service required stress relieving.

The three phase inlet consisted of 3900 BPD of naphtha that at operating conditions had a specific gravity of 0.82 and a viscosity of 1.6 cp, 1200 BPD of foul water that had a specific gravity of 0.99 and a viscosity of .55 cp, and 2.2 MMSCFD of Off Gas at 0.1136 lbs/ft^3. ACS engineers worked around the constraints of an existing 60" ID X 15' T/T separator with a 24" diameter X 36" tall boot that was now undersized (see Figure 19). Calculations of the gas velocity of 1.8 ft/s showed that the Normal Liquid Level (NLL) had to be left at 39" to allow for mist droplets to fall out in the vessel. However, the velocity of water in the boot was 20"/minute, double that allowable for oil disengagement (see page 9). Because of this ACS recommended that the oil/water interface be relocated to the main horizontal section of the vessel and that the naphtha outlet's internal standpipe with vortex breakers on a tee be raised from 6" to 24". This also helped to prevent water droplets coming off the top of the downstream coalescer face from entraining into the HC outlet nozzle.

A Stokes Law analysis of the separator while it was cycling showed that mean and maximum aqueous droplet sizes were 105 and 350 microns, respectively, as they entered with the naphtha. In order to achieve the specification of <1/2% water in the naphtha at normal flow and <1% at 120% of design, a Stokes-Pak® Coalescer segment that extends to a 39" height and has horizontal sheets with 1/2" crimps needs to be 48" deep. Due to the low pressure drop of this media a liquid distributor of 10% open perforated plate was held 6" away with integral trusses. In order not to weld to the vessel expansion rings of 1-1/2" angle were installed upstream of the distributor and downstream of the coalescer. These rings incorporate jack bolts at several splits in the hoops which forced the ring up against the inside of the vessel wall.

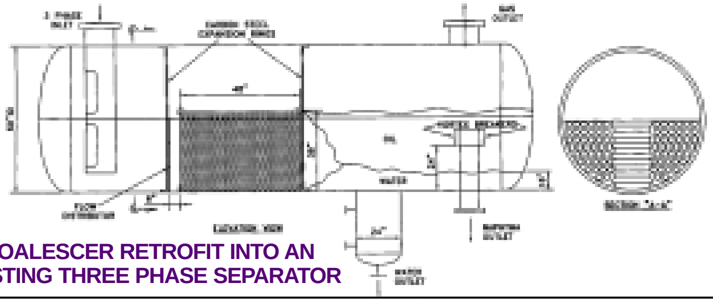
In order to achieve the < 1% outlet spec above at 120% of design flow, 99.9% of all droplets > 60 microns must be removed. Equation 3 shows

$$V_C = \frac{219\ (178.5)\ .5\ (1.6)}{0.17(60)2}$$

$$= \mathbf{51.1\ cubic\ feet}$$

The 39" high segment of 60" ID is equal to 13.5 square feet. Thus 45" of depth is required. This was rounded up to the 48" used. After installation the cycling problem stopped, outlet specs were achieved, and the Stokes-Pak made it to the next turn-around without significant fouling.

FIGURE 19



COALESCER RETROFIT INTO AN EXISTING THREE PHASE SEPARATOR

APPROXIMATE RANGES OF APPLICATION FOR VARIOUS COALESCING MEDIA

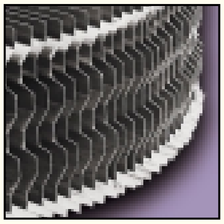
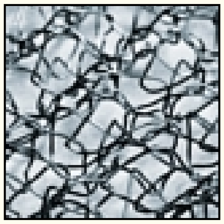
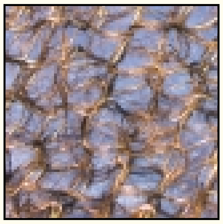
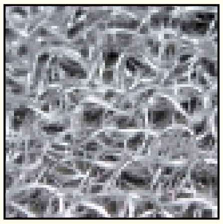
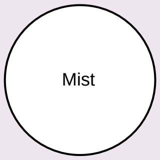
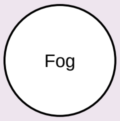
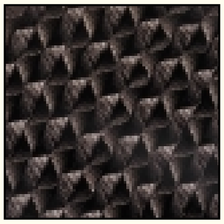
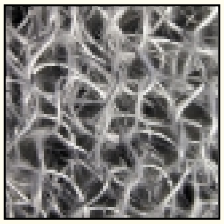
			

Plate-Pak™ Coalescer	**Wire Mesh Interceptor-Pak™**	**Teflon® Fiber Interceptor-Pak™**	**Fiberglass Interceptor-Pak™**
125 micron	**75 micron**	**15 micron**	**7.5 micron**
			
Three-Phase Separators	**Extraction Columns**	**Mix Valves**	**Condensation in Pipelines**
Static Mixers	**Two-Phase Pump Discharges**	**Caustic Wash Drums**	**Anti-Foam Surfactant**
Stokes-Pak™	**Wire Wool Interceptor-Pak™**	**Polyester Fiber Interceptor-Pak™**	**Fiberglass Mat Interceptor-Pak™**
			

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