

KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	 www.klmtechgroup.com	Page : 1 of 49
		Rev: 01
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TABLE OF CONTENT

INTRODUCTION	4
Scope	4
General Design Consideration	5
DEFINITIONS	23
NOMENCLATURE	25
THEORY OF THE DESIGN	
Liquid-Liquid Coalescer Design	27
A. Stokes Settling	27
B. Direct Interception	31
Liquid-Gas Coalescer Design	33
A. Gravity Settling	34
B. Media Velocity	37

KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 2 of 49
		Rev: 01
		Oct 2012

C. Annular Velocity	37
APPLICATION	
Example 1: Liquid-Gas Horizontal Coalescer Design	42
Example 2: Liquid-Gas Vertical Coalescer Design	44
Example 3: Liquid-Liquid Coalescer Design	46
REFERENCES	48
CALCULATION SPREADSHEET	
Liquid-Gas Horizontal Coalescer Design.xls	49
Liquid-Gas Vertical Coalescer Design.xls	50
Liquid-Liquid Coalescer Design.xls	51
LIST OF TABLE	
Table 1. Coalescing media	12
Table 2. Coalescing media and their applications	13
Table 3: Typical sources and characteristics that can generate dispersion	30
Table 4: Type of coalesce with their coefficient	32
LIST OF FIGURE	
Figure 1: Vertical coalesce	6
Figure 2: Horizontal coalesce	7
Figure 3: Three steps coalescing	9

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 3 of 49
		Rev: 01
		Oct 2012

Figure 4: Zones where different coalescing mechanisms apply	10
Figure 5: Coalescing in the medium	14
Figure 6: Horizontal liquid–liquid coalescer configuration	17
Figure 7: Vertical liquid–liquid coalescer configuration	18
Figure 8: High efficiency liquid-gas coalesce	22
Figure 9: Forces on a light droplet dispersed in a heavy liquid	28
Figure 10: Mechanism in liquid-gas coalesce	34
Figure 11: Forces on Liquid Droplet in Gas Stream	35
Figure 12: Drag coefficient of rigid sphere	36
Figure 13: Effect of surface treatment on annular velocity (a) surface treated and (b) untreated	40

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 4 of 49
		Rev: 01
		Oct 2012

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INTRODUCTION

Scope

This guideline covers the basic elements of coalescer design in sufficient detail to allow an engineer to design a coalescer with the suitable size including diameter, length media velocity, and terminal settling velocity.

For 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.

The design of coalescer may be influenced by factors, including process requirements, economics and safety. In this guideline there are tables that assist in making these factored calculations from the various reference sources. Include in this guideline is a calculation spreadsheet for the engineering design. All the important parameters use in the guideline are explained in the definition section which helps understand the meaning of the parameters or the terms used.

The theory section explains source, type of coalesces and its characteristic of droplet, treated and untreated coalescer and how to calculate sizing and selecting the coalescer. The application of the coalescer theory with an example will help the engineer understand the coalescer and the ready to perform the actual design of the coalescer.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 5 of 49
		Rev: 01
		Oct 2012

General Design Consideration

The biggest development in recent years is the widespread recognition that the actual performance of a separator may fall far short of the theoretical performance due to the actual flow patterns within the vessel being far from the ideal. It has, however been helped by two visualization techniques computational fluid dynamics (CFD) and physical modeling, which vividly show what can go wrong and how to correct it.

The following factors must be determined before beginning separator design.

1. Gas and liquids flow rates (minimum, average, and peak).
2. Operating and design pressures and temperatures.
3. Surging or slugging tendencies of the feed streams.
4. Physical properties of the fluids, such as density, viscosity, and compressibility.
5. Designed degree of separation

The most important areas to ensure a separator performs to design are as follow.

1. Correct inlet nozzle sizing and a good inlet device (momentum breaker).
2. Primary fluid distribution—distribution plates to translate the reduced but still high velocities from the inlet device into quiescent flows in a liquid–liquid separator body, or distribution plates either side of a vane pack (downstream is best as upstream ones shatter droplets unnecessarily) or other gas demister.
3. Intermediate fluid distribution when necessary.
4. Exit devices: vortex breakers and anti-liquid–pickup details.

Coalescer is a mechanical process vessel with wettable, high-surface area packing on which liquid droplets consolidate for gravity separation from a second phase (for example gas or immiscible liquid), where small particles of one liquid phase must be separated or removed from a large quantity of another liquid phase. The coalescers might be designed vertically or horizontally.

The vertical design is used to separate water from hydrocarbons when the interfacial tension is greater than 3 dyne/cm. The separation stage is achieved using hydrophobic separator cartridges that provide an effective barrier to aqueous coalesced drops, but

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 6 of 49
		Rev: 01
		Oct 2012

allow hydrocarbon to pass through them. The separator cartridges can be stacked below the coalescers for the most efficient utilization of the separator medium. This configuration only applies to the separation of water or aqueous contaminants from hydrocarbons.

After leaving the coalescing stage, the large aqueous coalesced drops and hydrocarbon then flow axially in a downward direction and the flow direction is from the outside of the separator to the inside. The large coalesced drops are repelled by the separators and are collected in the bottom sump. The purified hydrocarbon passes through the separators and exits at the bottom of the housing. The aqueous phase in the collection sump can be drained manually on a periodic basis or equipped with an automatic level control and drain system.

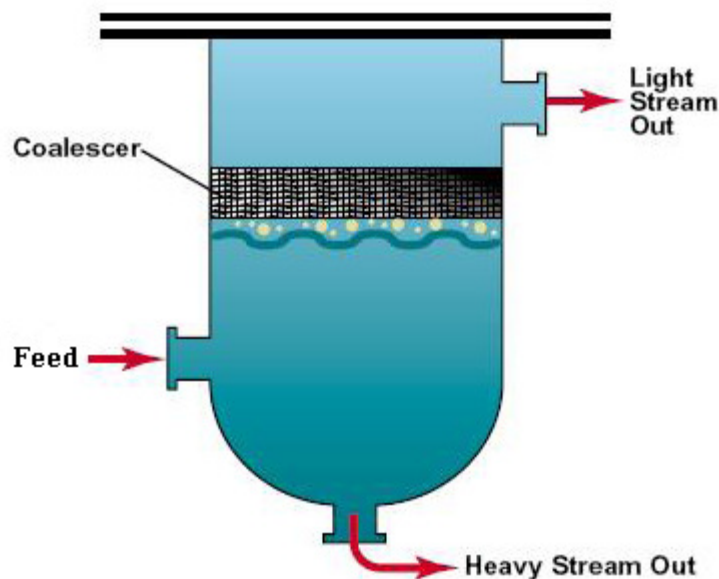


Figure 1: Vertical coalescer

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 7 of 49
		Rev: 01
		Oct 2012

In the horizontal configuration, a settling zone achieves separation by gravity. This configuration is used when the interfacial tension is less than 3 dyne/cm or for the separation of oil from the water phase. The coalescer housing contains a settling zone that relies on the difference in densities between the coalesced droplets and the bulk fluid. This configuration can be used for both hydrocarbon from water and water from hydrocarbon separation, but the location of the collection sump and outlet nozzle will need to be reversed. For the case of removal of hydrocarbon from water, a collection sump is located at the top of the housing and the purified water leaves at the bottom outlet nozzle. The sump can be drained manually on a periodic basis or equipped with an automatic level control and drain system.

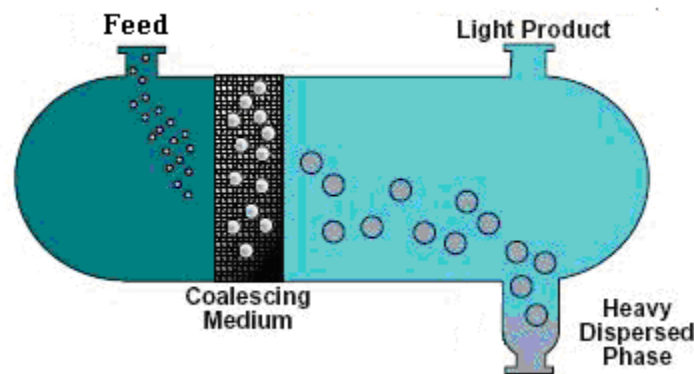


Figure 2. Horizontal coalescer

Liquid-liquid coalescer

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

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 8 of 49
		Rev: 01
		Oct 2012

sizes are typically greater than this and/or the purities required can be achieved without addressing the ultra-light colloidal component of the stream.

Liquid-liquid separations may require the use of special equipment when the drop sizes are small, typically in the range of 1 to 50 μm in size. These fluid systems are classified as stable emulsions, and often conventional bulk separators with mist pads or plate-type internals will not be effective. High-efficiency liquid-liquid coalescers have been developed to break these emulsions and provide improved separation.

Liquid-Liquid coalescers are used to accelerate the merging of many droplets to form a lesser number of droplets, but with a greater diameter. Settling of the larger droplets downstream of the coalescer element then requires considerably less residence time. There are three-step methods of coalescing separation: collection of individual droplets; combining of several small droplets into larger ones; and rise (or fall) of the enlarged droplets by gravity

Coalescers are typically manufactured as either pads or cartridge filters that have been designed especially to take small droplets in an emulsion and grow them into large drops that are separated more easily. This process is accelerated over natural coalescing by the fibers present in coalesce media that force the contact of small droplets, thereby promoting the coalescing process. The pore gradient of coalescer medium is constructed so that the inlet medium has fine pore sizes that increase in size with the flow direction.

Liquid-liquid coalescer are constructed from polymer and fluoro polymer materials that have been optimized to separate the most difficult emulsions with interfacial tensions as low as 0.5 dyne/cm. This coalescer can be used with a broad range of applications. It can process aggressive chemicals and handle demanding operating conditions while providing the highest level of performance.

Operating principles of a liquid-liquid 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 coalesce element then requires considerably less residence time. Coalescers exhibit a three-step method of operation as depicted in Figure 3.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 9 of 49
		Rev: 01
		Oct 2012

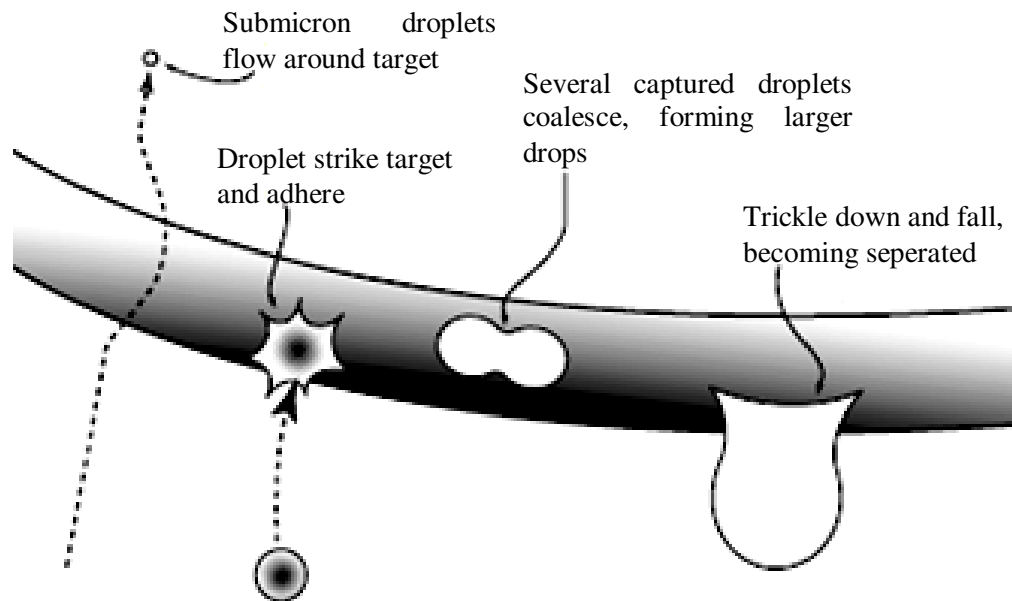


Figure 3: Three steps coalescing

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. Solids can increase the stability of an emulsion and removing solids can make coalescing easier. Generally, this step can be achieved by a separate cartridge filter system or by a regenerable backwash filter system for high levels of solids. In addition, the filtration stage protects the coalescer and increases service life. This step also initiates the coalescence of the hydrocarbon droplets, thereby enhancing the separation capabilities of the system.

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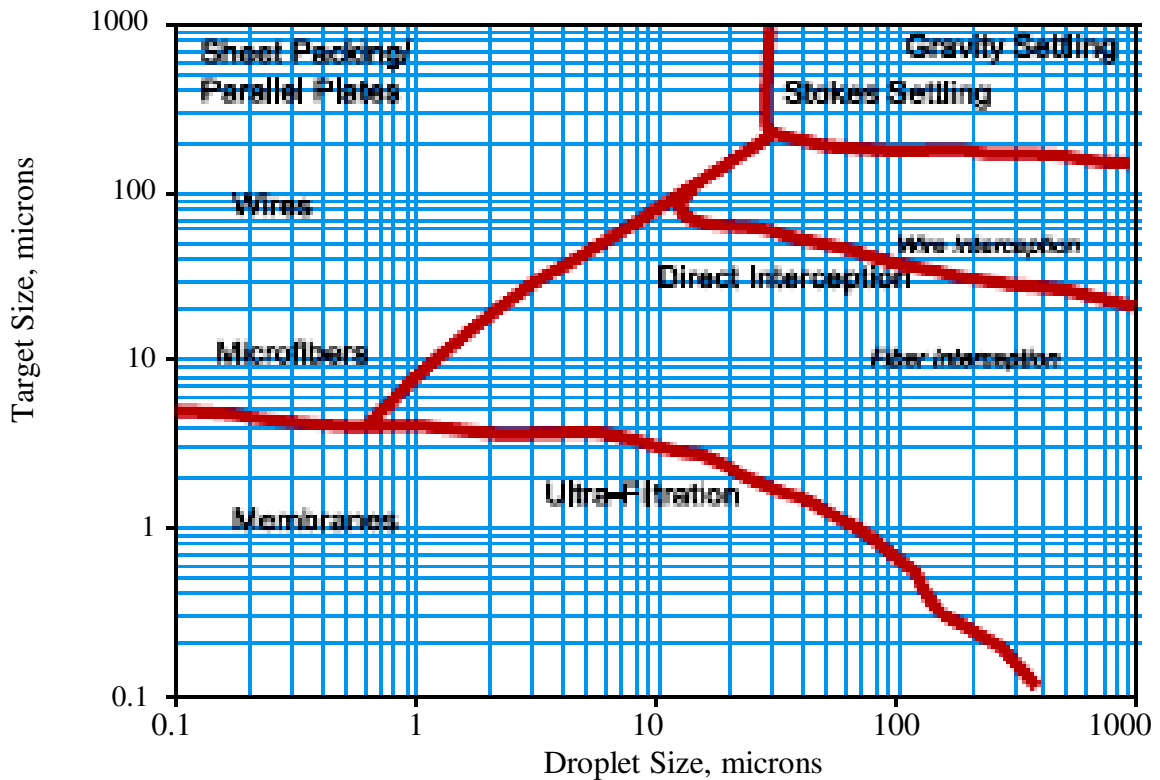


Figure 4: Zones where different coalescing mechanisms apply

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 separation of finer or more stable emulsions (Table 1). 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.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 11 of 49
		Rev: 01
		Oct 2012

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

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:

1. Media/Dispersed Phase Interfacial Tension
2. Porosity
3. Capillarity

Liquid Phases:

1. Continuous/Dispersed Interfacial Tension
2. Continuous/Dispersed Density Difference
3. Continuous Phase Viscosity
4. Superficial Velocity

Different coalescing materials have been found suitable for different applications. Commercially, fiberglass seems to be the most popular medium due to its availability and low cost. Table 1 below shows different coalescing medias with their different surface properties, cost and fouling properties. In addition to the numerous coalescing media, Table 2 presents some coalescing media and their industrial applications with regard to the nature of emulsions they separate (emulsion source), flowrate and maximum droplet diameter.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 12 of 49
		Rev: 01
		Oct 2012

Coalescers work better in laminar flow for several reasons.

1. Droplets will stay in the streamlines around a wire or fiber target.
2. High fluid velocities overcome surface tension forces and strip droplets out of the coalescer medium. This results in reentrainment in co-current flow and prevents droplets from rising/sinking in counter-current flow.
3. 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 coalescence mechanism can be described by the following steps.

1. Droplet adsorption to fiber
2. Translation of droplets to fiber intersections by bulk flow
3. Coalescence of two droplets to form one larger droplet
4. Repeated coalescence of small droplets into larger droplets at fiber intersections
5. Release of droplets from fiber intersections due to increased drag on adsorbed droplets caused by bulk flow
6. Repeat of steps 1–5 with progressively larger droplet sizes and more open media porosity

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 13 of 49
		Rev: 01
		Oct 2012

Table 1. Coalescing media


Media	Surface Characteristic	Porosity	Size	Fouling/Cost
Metal/plastic corrugated sheets	hydrophilicity, oleophilicity	98-99%	9,5-25,4 mm Spacing/Crimps	Low/Low  High/High
Wire/plastic mesh	hydrophilicity, oleophilicity	95-99%	0,05-0,279 mm	
Wire wool	hydrophilicity	95-99%	0,05-0,279 mm	
Wire/polymer co-knits	oleophilicity	94-98%	21-35 µm	
Wire/fiberglass co-knits, glass mat	hydrophilicity	92-96%	9-10 µm	

Table 2. Coalescing media and their applications

Media	Source	Max. Droplet Diameter (µm)	Flow Range (gpm/ft ²)
Corrugated sheets	Separators with coarse emulsions and static mixers.	40-1000	15-75 (35-180 m ³ /hr/m ²)
Wire mesh, wire wool	Extraction columns, Distillation tower feeds, impeller mixers.	20-300	7,5-45 (35-180 m ³ /hr/m ²)
Co-knits of wire and polymer	Steam stripper bottoms, Caustic wash drums, High pressure drop mixing valves.	10-200	7,5-45 (35-180 m ³ /hr/m ²)
Glass mat, co-knits of wire and fiberglass	Haze from cooling in bulk liquid phase, Surfactants giving, Emulsions with very low interfacial tension.	1-25	7,5-45 (35-180 m ³ /hr/m ²)

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 14 of 49
		Rev: 01
		Oct 2012

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.

The successful design of a liquid-liquid coalescer starts with knowledge of the source of the emulsion and the stream's physical properties.

1. Typically the minimum droplet size is estimated to be between 75 to 300µm.
2. Large vessels and long residence times are required to settle fine droplets and ensure laminar flow
3. When the average droplet is greater than roughly 1/2 millimeter (500 microns), an open gravity settler is appropriate.
4. Successful gravity separation downstream of a coalesce element depends primarily on vessel geometry.
5. A boot is desirable when the amount of dispersed phase is <15% v/v where the control of the interface level is linear with the volume of dispersed phase discharged.
6. 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.
7. The most common applications for coalescers in vertical flow are extraction/liquid-liquid absorption towers and entrainment knockout installations where the available plot plans in the plant are at a premium
8. The coalescer is located downstream of the interface so that entrained continuous phase is removed from the dispersed.
9. Some recommendations that the liquid loading in a vertical wash tower be limited to at most 1.6 ft/min of the dispersed phase.
10. With the installation of a coalesce this can safely be increased to 2 ft/min (15 gpm/ft²) thereby decreasing the cross-sectional area of the column by 20 to 40%.
11. It is important economically to keep the L/D ratio in the range of 3 to 5.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 15 of 49
		Rev: 01
		Oct 2012

12. 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.

13. 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 and the depth of the typical coalescer element itself with supports is typically 1 to 1.5 D.

There are some benefits from modern coalescer technology:

1. Reduce size and cost of new liquid-liquid separators
2. Improve product purity in existing installations
3. Debottleneck existing reflux drums
4. Reduce downstream corrosion caused by corrosive liquid carryover
5. Reduce losses of glycol, amine and other valuable chemicals
6. Improve fractionation tower operation and reduce maintenance
7. Reduce fugitive VOC emissions

There are some limitations to consider in liquid-liquid coalesce:

1. Generally, the solids range that liquid-liquid coalescers can operate economically with disposable filters is <10 ppm. Above this level of solids, further pretreatment will be required
2. If the clarified stream leaving the coalescer is then cooled, condensation of a previously dissolved contaminant can occur, leading to a hazy fluid at the lower temperature.
3. Coalescers typically will have a service life of 1 to 2 years when protected adequately by prefiltration.
4. For liquid-liquid coalescers constructed from glass fiber medium, the problem of surfactant disarming must also be considered and for low IFT emulsion systems (<20 dyne/cm) they will not operate efficiently for separation.

High-efficiency liquid-liquid coalescers are finding increasing applications in industry where problematic emulsions exist. They are used to protect equipment, to recover

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 16 of 49
		Rev: 01
		Oct 2012

valuable streams, and to meet environmental discharge limits. Some examples are given.

1. Pipeline Condensate - to separate the difficult emulsions to purify both water and hydrocarbon phases.
2. Produced Water - offers a reliable way to meet environmental limits. Petrochemical Final Products. Can lead to water condensation and off specification hazy final products.
3. Caustic Treating. to be an effective solution to recover the caustic carryover
4. Recover Liquid Catalysts.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 17 of 49
		Rev: 01
		Oct 2012

Liquid-Gas Coalescer

The coalescers are able to intercept the aerosol droplets by direct interception (sieving) as well as by the method of diffusional interception. Separation by the diffusion mechanism is caused by the random (Brownian) motion of the fine aerosol droplets that increase the probability of collision with coalesce fibers. The diffusional interception and direct interception differ from inertial impaction in that as the gas flow rate is decreased, the removal efficiency increases and, therefore, provides for a high turn down ratio. Properly designed high efficiency liquid-gas coalescers can provide separation of aerosols as low as 0.1 μm .

The liquid-gas coalescer is constructed of an inner rigid stainless steel core around which is placed the active pleated glass fiber coalescer medium. The pore structure in the coalescer medium is tapered by using layers of increasing pore size. The inlet gas first encounters the smallest pores that increase with penetration distance to allow for more space as the coalesced droplets grow. The pleated coalescer medium is supported by a mesh structure to provide mechanical strength which is then followed by a coarse outer wrap which serves as a drainage zone. The entire coalescer cartridge is treated with an aqueous fluorocarbon emulsion which penetrates through the depth of the glass fiber coalescer medium and drainage layers leaving a thin fluorocarbon coating on all of the surfaces. The result is that the surface energy of the coalescer medium is lowered sufficiently to prevent most liquids from wetting out the coalescer fibers.

Another significant benefit of the liquid-gas coalescer is that this type of separation device can be operated at significantly lower flow rates than the initial design flow rate which means it has a high turn down ratio. This is due to the fact that the separation mechanisms are based primarily on diffusion and direct interception unlike vane separators and mesh pads that rely heavily on inertial separation principles. This allows the high efficiency liquid-gas coalescer systems a greater degree of flexibility and they can operate at peak performance even for high turn down ratios (reduced flow rates) which can occur during commonly encountered partial plant shutdowns and upset conditions.

The inlet gas with liquid aerosol contamination first enters at the bottom of the housing into a first stage knock out section. The gas then travels upward through a tube sheet and flows radially from the inside of the cartridges through the coalesce medium to the

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 18 of 49
		Rev: 01
		Oct 2012

annulus.. As the gas leaves the coalescer cartridge and travels upward in the annulus it contributes to the total flow, thereby increasing the annular velocity.

Once the coalesced droplets are formed, they immediately drain vertically downward in the coalescer medium pack. The surface treatment greatly enhances this drainage and, as a direct consequence of the treatment, the coalesced droplets are shielded from the upward gas flow in the annulus in most of the length of the coalesce cartridge. The coalesced droplets are first exposed to the annular gas flow when they appear on the external face of the coalescer medium pack at the bottom third of the coalesce cartridge

Once the coalesced droplets are released to the annular space they are subject to the force of the upward flowing gas. The trajectory of the coalesced droplets is modeled on a force balance between gravity settling and the drag force created by the gas flow past the droplets. This analysis leads to the calculation of a critical annular velocity for re-entrainment.

Below is some matter that should be considered to the successful design of a liquid-gas coalescer starts.

1. Generally, the high efficiency liquid/gas coalescers are used for inlet aerosol concentrations of less than 1,000 ppmw (0.1%) and are placed downstream of other bulk removal separators as the final stage.
2. Outlet concentrations for these high efficiency liquid/gas coalescers are as low as 0.003 ppmw.
3. The inlet aerosol distribution is in the size range of 0.1 μm - 300 μm and after passing through the coalescer medium is transformed to enlarged coalesced droplets in the size range of 0.5 - 2.2 mm
4. In most industrial applications, the coalesced droplets will range in size from 0.5 - 2.2 mm and will be mostly influenced by the interfacial tension which is significantly affected by the liquid density, system temperature, and system pressure.
5. As the pressure is increased, the gas density will increase while the liquid density is only slightly affected.
6. The solubility of the gas in the liquid is enhanced with increasing pressure. This leads to a substantial decrease in interfacial tension with increasing pressure and, consequently, to significantly smaller coalesced droplets at the higher pressures.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 19 of 49
		Rev: 01
		Oct 2012

There are some limitations to consider in liquid-gas coalesce and some of the important aspects of measuring coalesce performance addressed in this test include the following.

1. Difficult aerosol challenge with drops ranging from 0.1 to 1 μm created in an atomizer — representative of condensation aerosols.
2. Test operated under pressurized conditions — not vacuum.
3. Coalescer evaluated after it is saturated with liquids — representative of field operation.
4. Outlet contaminant collected by a full flow sampler that collects any aerosols or liquids flowing along the walls of the pipe.
5. Coalescer systems are usually sized for a clean differential pressure (DP) of 2–5 psi, and when this DP reaches 15 psi, they are replaced with new elements.
6. Outlet concentrations for these high efficiency liquid/gas coalescers are as low as 0.003 ppmw

The separation of liquid aerosol contamination with high-performance liquid/gas coalescer cartridge systems has found widespread acceptance in refinery and gas plants in recent years for a number of applications

1. Compressor Protection
2. Amine/Glycol Contactor Protection
3. Well Head Hydrate Inhibition
4. Molecular Sieve Protection
5. Low and Ultra Low NO_x Burner Protection

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 20 of 49
		Rev: 01
		Oct 2012

DEFINITIONS

Air standard - Air having a temperature of (20°C), a relative humidity of 36 percent, and under a pressure of 14.70 PSIA. The gas industry usually considers (16°C) as the temperature of standard air.

Annular velocity - the actual flow rate divided by the annulus area. Modeled as a linear function with vertical distance, and the annular velocity is zero at the bottom of the cartridge and increases to a maximum value at the top of the cartridge.

Annulus - A ring-like part or, the orifice of a hollow die, through which extruded metal flows from the press.

Coalescence - Liquid particles in suspension that unite to create particles of a greater volume.

Coalescer - a mechanical process vessel with wettable, high-surface area packing on which liquid droplets consolidate for gravity separation from a second phase (for example gas or immiscible liquid), where small particles of one liquid phase must be separated or removed from a large quantity of another liquid phase.

Demister Mist Extractor- A device installed in the top of scrubbers, separators, tray or packed vessels, etc. to remove liquid droplets entrained in a flowing gas stream.

Entrainment - A process in which the liquid boils so violently that suspended droplets of liquid are carried in the escaping vapor.

Extraction column - Vertical-process vessel in which a desired product is separated from a liquid by countercurrent contact with a solvent in which the desired product is preferentially soluble.

Filter- A piece of unit operation equipment by which filtration is performed.

Gas filter - A device used to remove liquid or solid particles from a flowing gas stream

Immiscible - Not capable of mixing (as oil and water)

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 21 of 49
		Rev: 01
		Oct 2012

Laminar flow - Streamlined flow of a fluid where viscous forces are more significant than inertial forces, generally below a Reynolds number of 2000.

Liquid-liquid extraction - The removal of a soluble component from a liquid mixture by contact with a second liquid, immiscible with the carrier liquid in which the component is preferentially soluble.

Media velocity - the actual flow rate divided by the coalescer filter area.

Mesh- The "mesh count" (usually called "mesh"), is effectively the number of openings of a woven wire filter per 25 mm, measured linearly from the center of one wire to another 25 mm from it.

mmscfd - Abbreviation for million standard cubic feet per day; usually refers to gas flow.

Mud sump - Upstream area in a process vessel where, because of a velocity drop, entrained solids drop out and are collected in a sump.

Process analyzer - An instrument for determining the chemical composition of the substances involved in a chemical process directly, or for measuring the physical parameters indicative of composition.

Separator - a cylindrical or spherical vessel used to isolate the components in mixed streams of fluids.

Stokes' law - the law that the force that retards a sphere moving through a viscous fluid is directly proportional to the velocity of the sphere, the radius of the sphere, and the viscosity of the fluid.

Suspension - a system consisting of a suspension of solid particles in a liquid

Terminal Velocity - The velocity at which a particle or droplet will fall under the action of gravity, when drag force just balances gravitational force and the particle (or droplet) continues to fall at constant velocity.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 22 of 49
		Rev: 01
		Oct 2012

NOMENCLATURE

$ \Delta\rho $	Absolute value of the difference between the densities of the continuous and dispersed phase, lb/ft ³
A	Cross sectional area, ft ²
A_{ann}	Cross sectional annular area, ft ²
A_{med}	Media area for one coalescer, ft ²
C	Drag coefficient.
C1	Sheet coefficient
d	Droplet Diameter, in
d	Droplet Diameter, microns
D_C	Diameter of house, ft
d_p	Droplet diameter, microns or ft
E	Effective Length Multiplier
g	Gravitational constant, ft/s ²
h	Corrugated plate spacing or structured packing crimp height, in
K	Kuwabara's Hydrodynamic Factor
L	Element length required for removal of all droplets, in
M	Mass flow at standard condition, lb/s
N	Number of coalescers
Q_a	Actual system flow rate, ft/s
Ql	Liquid/liquid emulsion flow, US GPM
Q_s	Standard system flow rate, ft/s
R_c	Radius of coalescer end cap, ft
R_h	Radius of the housing, ft
S_g	Specific gravity
t _{dr}	Droplet Rise Time, s
t _r	Droplet Residence Time, s
V_C	Coalescer volume, ft ³
v_{max}	Emulsion velocity, ft/s
v_s	Superficial Velocity, ft/s
v_t	Terminal Settling Velocity, ft/s
α	Volume Fraction of Fibers or Wires
ΔS_g	Specific Gravity Difference between the Continuous and Dispersed
η_D	Collection Efficiency of a Single Target by Direct Interception
η_s	Fractional Collection Efficiency by Stokes Settling, typically 0.999

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	COALESCER (ENGINEERING DESIGN GUIDELINES)	Page 23 of 49
		Rev: 01
		Oct 2012

Greek Letters

μ	Continuous Phase Viscosity, cP
ρ_{air}	Density of air at standard temperature and pressure, lb/ft ³
ρ_g	Density of gas, lb/ft ³
ρ_L	Density of liquid, lb/ft ³
Σ	Overall collection efficiency by direct interception

Superscript

A	Cross sectional area, ft ²
E	Effective Length Multiplier
K	Kuwabara's Hydrodynamic Factor
L	Element length required for removal of all droplets, in
M	Mass flow at standard condition, lb/s
N	Number of coalescers

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