A Brief Discussion on the Removal of Oil From Small Steam Systems

By Peter G. Heid
September 14, 2002

Separation of lubricating oils and other debris from exhaust steam is a major concern to eliminate contamination of boiler feed water in a condensing cycle. There is also an environmental concern when exhausting to the atmosphere and when blowing down, if oil remains in the boiler water. In most steam generators the residual oils will remain at the point of evaporation as the water is turned to steam, and the elevated temperatures cause it to turn to asphaltic or carbon deposits on the interior walls of the boiler tubes. Once there, the carbon deposits form an insulating barrier, slowing thermal conductivity and eventually burnout results. Carbon formations absorb oil from the feed water which increases the deposit thickness, multiplying the troubles. A layer of carbonaceous deposits only 0.020 inches thick has the equivalent insulating ability as 0.200 inches of boiler scale. Oily feed waters can cause foam formation by increasing the surface tension under which the steam bubbles are formed, creating a skin that rises with the bubble formation. The boiler heat exchange surface can also become coated with oil, giving uneven heat transfer and a violent surging of boiler water called priming can occur. The thermal resistance of oil is about 1000 times greater than that of steel. Either condition can be the cause of carry over, when water and suspended matter leave the boiler, and if allowed to continue, the super heater can under go severe corrosion, also damage to down stream equipment may result. New, clean boilers seem to be more prone to the insulating effects of an oil film than those with a layer of scale on the boiler surfaces. In extreme cases, new installations have been known to fail with oil coatings thought to be less than 0.001 inches. A coating of this thickness can increase the temperatures of the boiler metal several hundred degrees. As an indication of the troubles and stated in many older texts, insurance companies handling boiler claims have adopted a policy to deny claims on the basis of failure due to oil contamination of feed water. In the condenser the oil tends to coat the condensing surfaces there by lowering thermal transfer and overall efficiency. The thermal conductivity of 30W motor oil is about 1/4 that of water (1), so the thicker the film, the less heat transfer there is available to condense with.

Oil can be removed from the steam system in many ways, all of which may not lend themselves to the field of compact transportation due to space limitations and the agitation due to vehicle movement. Large marine and stationary steam plants have little space consideration compared to compact mobile designs for personal transport and the continued movement and extreme angles of operation would prevent the use of most separator designs relying on gravity. No mater the method used, the oil will be removed from the exhaust steam, from the condensate or from both. The oil can be removed by separation from the exhaust steam, though more difficult to do, it will prevent the oil, or at least the bulk of it, from reaching the condenser. In a compact mobile steam system physical size and weight are prime considerations for all components and complete oil removal from the exhaust steam would allow a reduced overall system size. The vaporization of the oil due

to high temperatures is a limiting factor when separating oil from steam as the vapors will pass through any separator and will re-condense in the steam condensate. Lower separator temperatures and quality oils reduce the quantity of oil that is vaporized and passes to the condenser. Oil removal can be accomplished after the condenser by filtering the condensate and many oil/water filter designs exist. Filtering of condensate is often done after the bulk of the oil is separated from the steam to insure the feed water is completely free of oil.

The first step toward efficient oil removal starts with the proper oil delivered in the correct quantity and handled properly. Poor quality oils and animal based oils tend to emulsify and otherwise break down more quickly than those of greater quality. Also oils of high viscosity are not self-cleaning and tend to trap particulate matter, decreasing their lubricating qualities and shortening the oils life. For this reason high viscosity oils tend to emulsify more readily than those of lower viscosity and should be avoided if possible. If oil is contained in feed water, it should not be exposed to any violent pumping action such as cavitation and it should not be subjected to choking by forcing it through any restricting orifice, or the oil may tend to emulsify causing greater difficulty in separation.

In today's modern steam world the oil separator has mostly disappeared with the emergence of the turbine as the leader in the industrial steam expander race. While the reciprocating steam engine has been phased out of most fields of operation, such as power generation and large marine uses, it is still viable hardware for small propulsion fields including air, land and water transport as well as small stationary units. While much design work has been done in recent years to improve the small reciprocating steam engine, little has been done to improve the designs of oil separators required by these modern systems. Even so, the industrial field has kept pace with steam condensate separator development and condensate is removed in the same fashion as oil and most other impurities. The design information available to today's experimenter is derived from old sources or from newer sources in related fields such as drying of gasses, oil field and refining methods, industrial steam condensate separation and even the study of fluid separation in the food industry. The latest written materials with oil/steam separators seem to have died off in the 1960s but even this information is based on older designs and is usually a rehash or reprint of older books. Little if any design information is available on modern steam condensate separators and they are available in several types with the centrifugal leading the way as the most common, and often combined with impact separators and or filters. In large marine practice it is common to use centrifugal water/oil separators to remove oil from feed water and to clean up any spills in the bilge before the wash water is pumped overboard. Stationary engineering books detail many oil removal practices including gravitational sedimentation and flotation with coagulants, inertial separation, filtering and others.

Oil is contained in water as a suspension in the form of globules that tend to float and retain the properties of oil. Also minute particles of water become coated with an oil film, an emulsion, with particle sizes well under 1.0 micron possible, causing impurities that won't separate under the influence of gravity even after several years. Emulsions can readily absorb impurities such as rust and scale giving them a mass very close to water. This makes them harder to separate from condensate and they may carry impuri

ties to the engine. No detectable levels of oil can be allowed to enter the boiler feed water, requiring 100% complete removal from the exhaust steam or condensate unlike inorganic impurities where certain levels can be tolerated before deposits form. Most texts agree that complete removal would be less than one part per million of oil remaining in feed boiler water. Asphaltic deposits formed by oily feed water, like most boiler deposits, are cumulative in nature.

Often the removal of oil from steam is incomplete and filtering of the condensate is required to remove the smallest particles of emulsified oil (2). The coalescing filters finding the greatest effect in oil/water separation are the parallel plate interceptor (PPI) and the corrugated plate interceptor (CPI), removing as much as 42 % of the particulate matter in the 0 to 30 micron range.(4) The flow diagram for a plate type of coalescing, water/oil interceptor is shown in figure 1 below. There are coalescing filters that use oleophilic materials to separate water and oil and work with good effect. A pilot test at a flood water oil well near Denver City, Texas showed a reduction of oil in the feed water from 1660 mg/L to only 1 mg/L.(4) The water flows up through the open end of the cartridge and is forced through the corrugated material at a rate of .64 gal/min/sq ft. The fluids decreasing velocity allows the oil to float to the top where it can be drawn off and heavier particles sink to the bottom. Cartridge life is said to be affected only by the dissolved solids in the solution, oil alone will not plug the element. Precoat filtration of condensate will effectively remove very small particles including bacteria (3). A supporting media such as screen is coated with a slurry of diatomaceous earth which acts as the filter media and when the pressure drop becomes to great, the media is back flushed from the screen and it is precoated with a new layer. Due to the extremely fine filtering media, the precoat filter is only used for final filtration of previously cleaned water. Coagulation, or the accumulation of particles, is not usually required with precoat filtration but it is often used with gravational and air flotation separation methods. Air flotation uses tiny air bubbles to aid in the rise of oil particles to the waters surface in a large tank. Coagulation can be performed by the use of chemicals such as soda ash or sulphate of alumina and can aid in the removal of oil but these chemicals can cause down stream troubles with high pressures and temperatures. The aluminum hydroxide is thought to have an electrolytic action which neutralizes the like charges on the tiny oil particles, allowing them to coalesce for easier removal. Graphite has been found to aid in the coagulation of the oil for easier removal and any remaining graphite will only act to provide greater lubrication qualities. Flotation

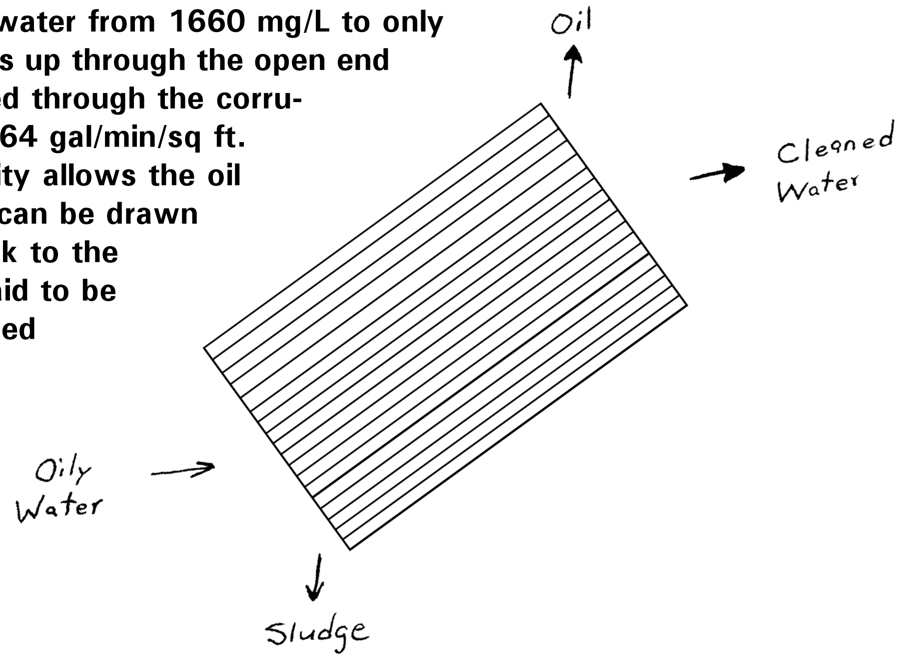


Fig 1)

increases the dissolved oxygen and other gasses in the water so their removal must follow flotation. The electrolytic action has also been produced by passing a DC electric current through the condensate to neutralize the repelling charges. A Dutch engineer produced an experimental separator where 110 volts DC were passed through the condensate to produce the desired results, and allow down stream filtering. The current is imposed on iron plates immersed in the water and the coagulating oils tend to cling to the iron oxide given off by the plates. This increases the size and weight of the particles and allows for their easier removal. Electrical consumption is stated to be one Board of Trade Unit per 1000 gallons of water treated. It must be noted that the use of any DC current will produce an electrolytic action in the water and hydrogen and oxygen will evolve requiring their subsequent removal.

Oil separation from steam can be accomplished in one of two fashions, by coalescing or by inertia. A coalescing separator uses a great amount of surface area to accumulate the tiny droplets of oil, under the actions of gravity, as they cling to the intercepting surfaces. This method relies on the steam passing across the surfaces and all the droplets making contact with the surface as they fall from the stream of fluid. This is very hard to achieve due to the tiny size of the oil droplets and the great space required to provide enough surface area for the oil to coalesce on. This type of separator has little or no ability to remove emulsified oils as the particle size is greatly reduced from that of a non-emulsified oil droplet and emulsification reduces the oils cohesive and adhesive properties, generally reducing the ability for it to collect on the coalescing surface. These separators have a large oil reservoir capacity due to the large physical size and occasional cleaning is needed, but it may be less frequent than smaller inertial and cyclonic types. The larger size also means a longer residence time is needed to accomplish the separation. This thereby enlarges the steam system capacity and the need for extra insulation to prevent condensation from forming and mixing with oil in the separator reservoir or drain. When operated in a condensing mode the size would be prohibitive for separators of this type in a mobile system. Oil like most liquids has strong cohesion, the ability to stick to itself better than to many other surfaces, so a dirty coalescing separator may work better than a newly installed one. Many plastics such as polypropylene seem to work well at attracting the oil but they are limited to maximum temperatures around 250 degrees F. or so. The oil intercepting surface can be made of plates, mesh or beads, plates are generally scraped clean while the beads and mesh are flushed to clean them. The pressure drop through a properly designed and maintained separator of this variety should remain below about 3 to 4 PSI. Above this point the coalescing media will need to be cleaned. There is little flow dependance in this type of separator, at least until the residence time will no longer allow enough contact for effective oil removal. Due to the reduced flow rate in the separator the solids also tend to fall out of the stream and stick to the coalescing media. Most coalescing separators are generally reserved for oil/water separation and are often followed by a down stream filter.

Inertial separators seem to be of three general types, the impact, the cyclonic and centrifugal variety and the first two are often combined in the same housing. The impact inertial separator, such as the Cochrane by the Harrison Safety Boiler Works or the Wright-Austin, relies in the inertia of the particles and droplets to not make a sharp turn around a baffle while the lighter steam flows around. The baffle is fined to prevent the impinging

steam from washing the collected oil off before it can drain into the reservoir below. This type of separator also keeps the steam passage(s) above the baffle drain to prevent oil from reentering the vapor stream. Many designs of this type have been produced to allow separation without changing the general direction of steam flow. They have been built with up flow and down flow designs, as well as many types of side input and output designs. A horizontal flow separator of this type is shown in figure 2 (11) and a partial listing of the size chart is shown below. The inertial impact separator relies on the velocity of the steam to drive the particulate mater against the baffle so reduced flow rates will reduce the effectiveness and a cutoff point of operation will follow. This type of separator is suitable for condensing operation if engineered for the resulting increased flow rate, which of course demands a larger separator. To compensate for different flow rates, more than one size separator could be put in the same housing but some distance should be allowed for the flow of the vapor stream to straighten out before the next baffle is reached. The effectiveness can be improved by an increased number of smaller baffles, the same total impingement surface area is more efficient if it is divided into a greater number of smaller targets (5). The reason for the improvement is because of the reduced distance a particle must travel to leave the vapor stream as it impinges on the target baffle. The use of smaller baffles may also decrease the pressure drop across the unit as the distance the steam must flow around the baffles is reduced. A problem that may crop up in use is the accumulation of residues on the baffle surface requiring occasional cleaning. This trouble is most common with separators that employ more than one set of baffles in a row as the flow of steam with some condensate is thought to keep the first set of baffles clean. A nonstick coating of Teflon, Xylan or similar material may reduce the adhesion of oil and other matter on the baffle surface reducing the need for cleaning. Some separators of this type have an access cover that allows the baffles to

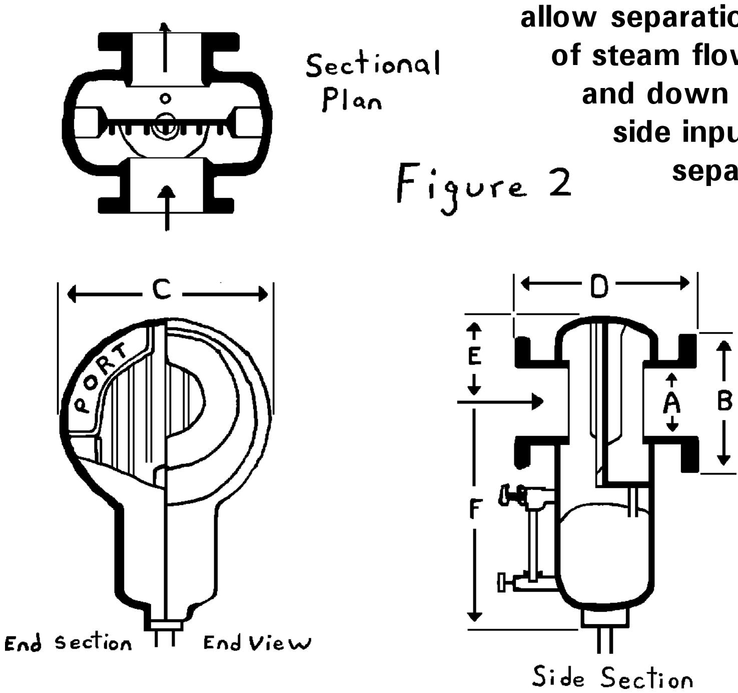


Figure 2

A	B	C	D	E	F	DRIP	Code Word
3"	7 1/2"	10 1/2"	11"	4 3/8"	17"	3/4"	Murador
3 1/2	8 1/2	11 1/2	11 3/4	4 3/4	17	3/4	Muraglione
4	9	12 3/4	12 1/4	5 3/8	17	3/4	Muramento
4 1/2	9 1/4	13 3/4	12 3/4	5 3/4	18	1	Murcharas
5	10	15	13 1/4	6 3/8	19	1	Murciana

be withdrawn and cleaned should accumulations occur. The pressure drop seen across this type of separator is very low, around 1 PSI or less and there is almost no change in pressure drop from accumulation of oil but the reservoir must be drained at regular intervals to prevent impurities from reentering the flow.

Modern versions of this type of separator are generally used as the first stage in a cyclonic separator for larger particulate matter. This type of separator is most effective when the particle size is larger than about 10 microns and the target efficiency is a function of the dimensionless separation number (5) as shown in in equation 1 (7). The target efficiency can then be found from the graph in figure 3 (5) for three different shaped particles. In actual tests conducted at Massachusetts Institute of Technology, in 1909, on baffle plate oil separators, it was shown that the amount of oil removed in actual use was about 75% of the total contained in the steam.

1) Separation Number

$$S = \frac{U_t V_o}{g D_B}$$

S = Separation Number Dimensionless

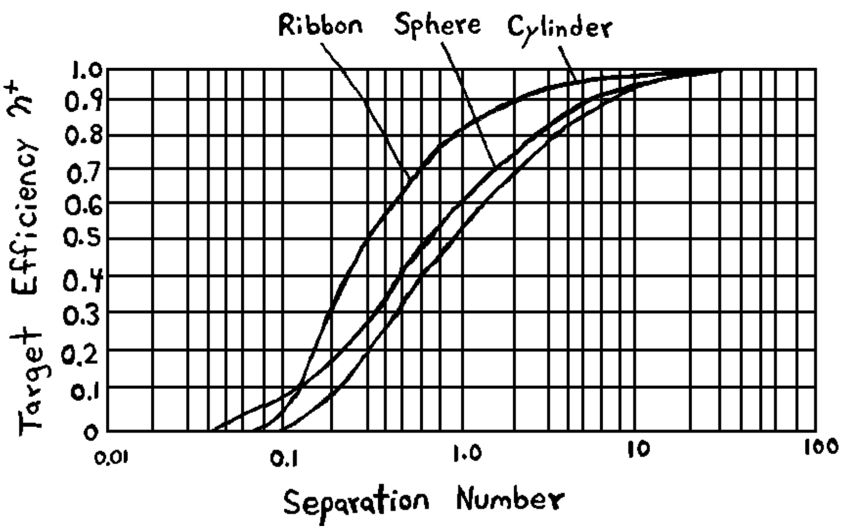
U_t = Terminal Velocity from Stokes Law

V_o = Average Velocity of flow

g = Acceleration Due to Gravity

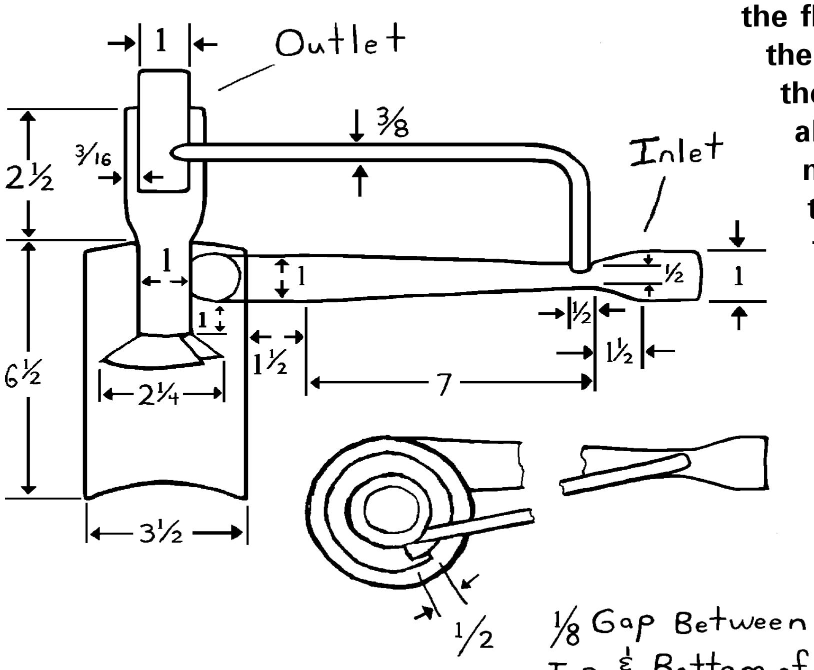
D_B = Total Diameter of Baffle(s)

Figure 3



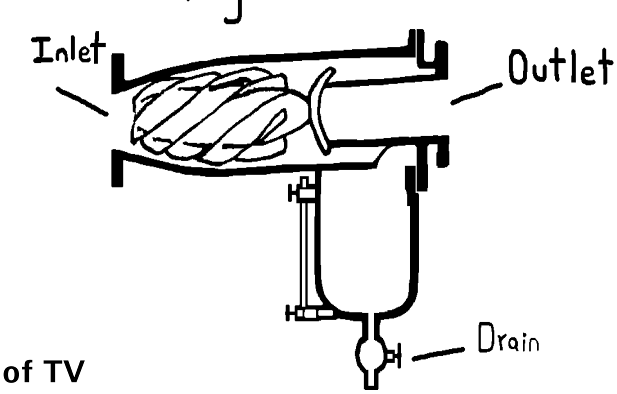
Cyclonic separators use the velocity of the steam to effect the separation and the action of gravity is replaced with centrifugal force to aid in the rapid removal of particulate matter. The cyclonic separators can be further divided into two basic designs, tangential entry and those that use radial spiraled fins as can be seen in figures 4 and 5 respectively. The centrifugal forces generated are so great that the effect of gravity can be ignored when designing this type of separator. A spun particle will accelerate until the frictional resistance of the fluid it is passing through equals the accelerating force. The radius of the particle, its density and the density of the fluid or vapor it is removed from, all play a part in the separation, as well as the distance a particle must travel. Generally speaking, twice the distance the particle has to travel equals twice the time it takes to get there. The time of acceleration is negligible so particles are assumed to always be at their maximum velocity. When separating oil from low pressure steam, the frictional resistance, due to the reduced viscosity of the steam, is very low and allows for effective separation conditions. Cyclonic separators, being dependant on the steam velocity for their effectiveness, have limited ranges of operation. As the steam velocity is reduced, the centrifugal forces from the cyclonic action are reduced. Modern condensate separators of this type such as the Anderson model "L" use a baffle separator at the inlet and will remove 90% of the particulate matter in the 8 to 10 micron range and larger(6). The volume of the steam flow is the determining factor in the proper selection of this type of separator. If run with a inlet pressure of between 10 and 50 PSIG, the flow rate of the steam will vary with the pressure based on the density of the steam. At 10 PSIG the density is about 40% that of 50 PSIG steam meaning under ideal circumstances a turndown ratio of 2.5:1 is possible, in this pressure range without changing the velocity of the flow. Below this velocity, the effectiveness drops off, and excessive flow rates will push some impurities through the separator. In the modern world the turn down rate seems to be about to 2:1 in this pressure range, on separators such as the Anderson model "L" to stay within the rated separation limits. Some separator units of this type are offered that claim 99.9% removal of impurities but these are followed by a filter. A model "L" type 100 Anderson separator, with a 1.00 inch inlet and outlet, is rated for 145 lb/hr at 10 PSIG and 285 lb/hr at 50 PSIG.(6) To operate under exhaust vacuum conditions will require a much larger physical size due to the much increased volume of steam. Cyclonic separators relying on steam velocity use rates of 40 to 100 feet per second and most are equipped with a reservoir that requires periodic draining unless an automatic drain is provided. Separators of this type are most often used for removal of particles around 5 micron and larger but they can be successfully used for the removal of particles down to 0.01 micron (7). The flow profiles of cyclonic separators are very complex and not fully understood so practical performance predictions are greatly varied and seem to be of little value for design parameters. Some mathematical models have been suggested based solely on particle trajectories shown in a cyclone flow field by the insertion of TV cameras in the separator body. This information involves some very complex math and most designs are based on proven standard dimensions, such as those in figure 4 (8), and scaled from them to accommodate the rate of flow.

Figure 4



1/8 Gap Between Top & Bottom of Offtake flaire Over lap

figure 5



Because the centrifugal forces increase as the radius decreases, it is common to use two or more smaller cyclonic separator in parallel to achieve better results than one large one.

A cyclonic separator using the tangential entry, developed in England by the British Coal Utilization Research Association (BCURA) laboratories for the separation of condensate and debris in steam lines, seems to be the most promising of that type of design(8). It was designed for use without oil in the lines but oil droplets react in the same fashion as water, under the forces of inertia. The design may possibly be fine tuned for the density of the oil that is to be removed as it is slightly less dense than water but this should not be necessary in most cases. The design shown in figure 4 was tested at a pressure of 50 PSIG and at an optimum flow rate of 90 ft/sec velocity, it removed the condensate from steam that was 25% water by weight with excellent results and only a 3 PSI drop existed. The tangential entry causes a downward spiral, flinging larger particles against the wall of the chamber while part of the liquid clings to the offtake 'D' where it is thrown off of the broken flare of the spiral by the centrifugal action of the steam. The steam, with any remaining foreign matter, then enters the offtake where the reduced diameter and cyclonic action act to deposit the smaller particles. The particles are swirled to the top of the chamber and kept outside sleeve 'E' where they drain back to the throat of the venturi through the tangential outlet. The pressure differential caused by the venturi allows a flow of steam to drain the entrapped matter back to the main chamber, and without this flow, drainage from around the sleeve would not be possible. This is the reason for the venturi, and any device creating a pressure drop could be used but the venturi has the benefit of excellent pressure recovery. The bottom of the chamber is curved to allow the splash of fluids to turn toward the walls, not splash into the swirling flow of steam. The dimensions of the separator are critical to keep the radial velocity of the steam high enough to draw the liquid that enters the secondary stage out through the tangential outlet. The depth of the sleeve is not very critical as long as it is deep enough to prevent the formation of droplets across it. The ideal dimension between the sleeve opening and the re-entrant pipe should be 0.6 times the diameter of offtake. All other dimensions are shown in figure 4 and they may be changed as needed if kept in proper proportion.

2) Separating Force

$$C_p g = \tfrac{1}{2}\omega^2 D_p$$

$$\text{or } C_p = \frac{D_p N^2}{5866}$$

C_p = Separating Force Lb

ω = Radian/Sec

g = Acceleration Due to Gravity

D_p = Diameter at Periphery

N = RPM

Centrifugal separators use an external, mechanical drive to provide the separating action and are not dependant on the rate of flow, so the limits of operation are mainly dependant upon the mechanical design and proper maintenance. A separating force equal to several thousand times that of gravity can be generated in this type of separator. The separating force is directly related to the radius of the periphery of the rotating fluid and as a square of the rotating velocity in radians, see equation 2 (6). The second half of the equation shows that by conversion and substution, the separating force can be shown in relation to the diameter and RPM. The linear speed of the displaced particle at the periphery can be found through the equation 3 (5). The point of separation can be expressed as a relation to the critical radius or minimum particle size that can be effectively removed, by equation 4 (5), using the value of centrifugal or separating force found in equation 2. The minium particle size is plotted in relation to a centrifugal force of from 0 to 50,000 lbs, in the graph of figure 6, which is based on saturated steam at atmospheric pressure and an oil density of 55 Lb/cu ft. Low flow rates are handled as well as high rates with great effectiveness but this type of separator, like all others, requires that the rate of steam flow through it, is low enough so that the rate of motion of the separating particle is greater than velocity of the fluid or vapor it is separated from. As the steam enters the separation chamber, the diameter greatly increases allowing the flow rate to drop low enough for effective removal. This type of separator is most commonly found separating two or more liquids and solids of different densities in many fields including the food industry, dry cleaning, chemical research and more. Though no separators of this design, for separation of impurities from steam, are shown in the books referenced by this article, the same principals apply as those used for the separation of liquids of different specific gravities. Most industrial separators operate at speeds of from 8,000 to 20,000 RPM with laboratory centrifuges reaching over 100,000 RPM driven

3) Linear Speed at Periphery

$$V_p = \pi D_p N$$

V_p = Velocity at Periphery ft/sec

D_p = Diameter at Periphery ft

N = Revolutions per Second

4) Critical Radius

$$q_c = \sqrt[3]{\frac{9\eta^2}{2C_p g\, p(r-p)}}$$

q_c = Critical Radius cm

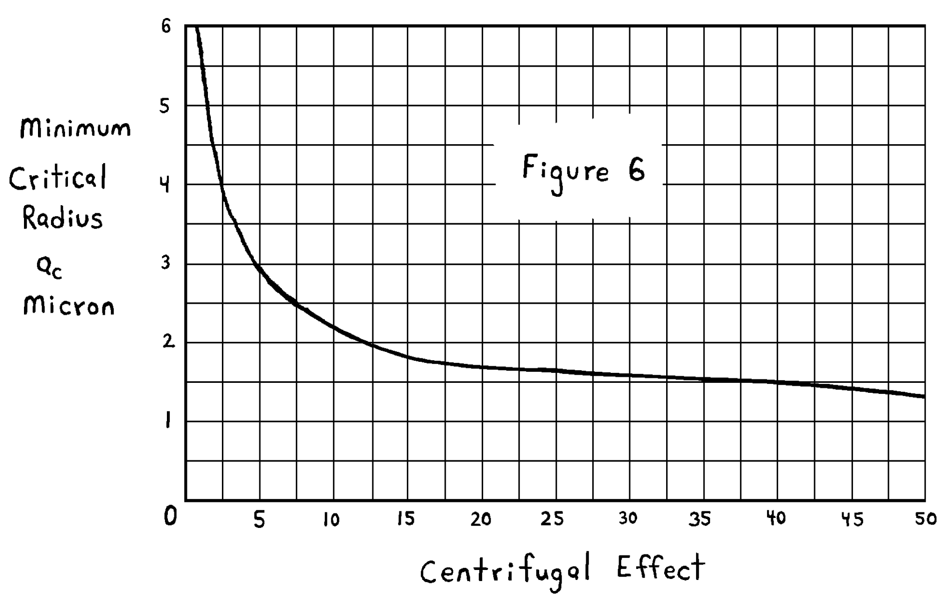
η = Viscosity Poise

C_p = Separating force from Equation 5

g = Acceleration Due to Gravity 981 cm/sec^2

p = Density of Steam gm/cm^3

r = Density of Particle gm/cm^3



by small turbines. The diameter of industrial models ranges from 6 to 36 inches and discs are generally inclined at an angle of 35 to 50 degrees to provide flow rates up to 3500 cubic feet per hour. Proper balance must be observed in manufacture and self stress forces, based solely on peripheral speed, are an important design consideration. Corrosion can cause imbalance and weaken the spinning parts to the point of self destruction, possibly causing a hazzard. Instead of tiny oil droplets, think of a piece of spinning metal flying off at 10,000 times the force of gravity and the destruction it might do. Periodic inspection for corrosion and stress cracks should be undertaken but separators of this type normally see many years of continuous service without failure.

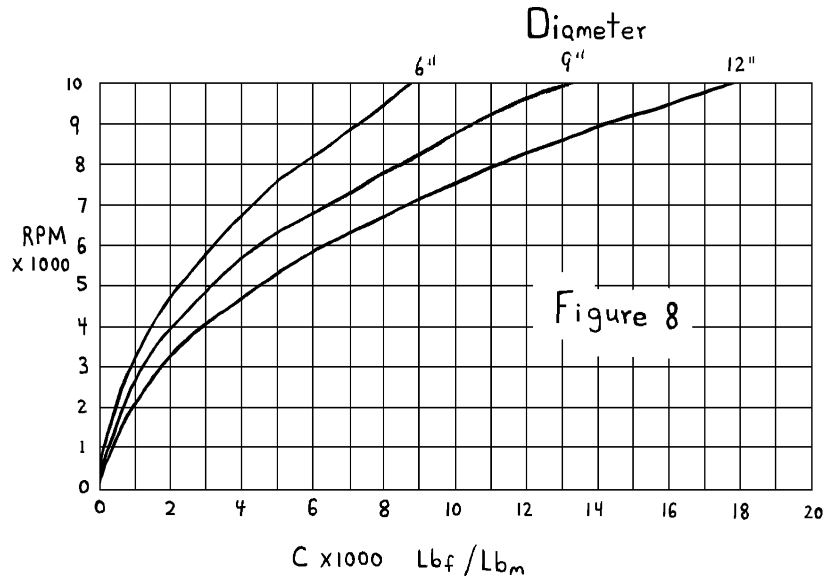


Figure 8

Measurement of centrifugal effect can be given as a ratio in proportion to the gravitational force as shown in equation 2, and it is expressed in pounds of force per pound of mass. The force values for three different diameters at various rotational speeds is shown in the graph in figure 8. Centrifugal force should not be confused with centripetal force, although they are equal but opposite at any given moment. Centripetal force is that which is required to hold a spinning object around the axis of rotation and centrifugal force is that force which tries to fling the object from the rotational path. The centrifugal force increases proportionately with a decrease in rotational radius and increases by the square of the velocity. This is shown diagrammatically in figure 7. In a

Figure 7

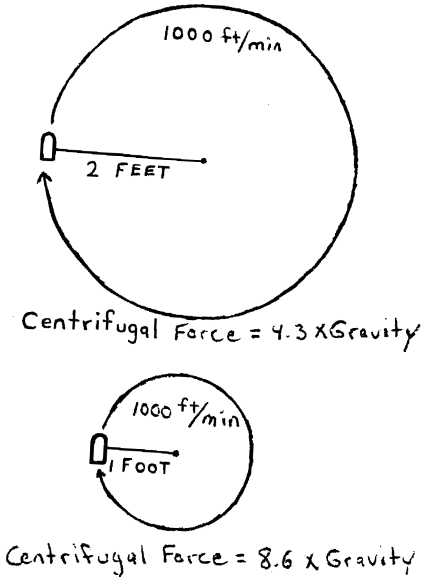
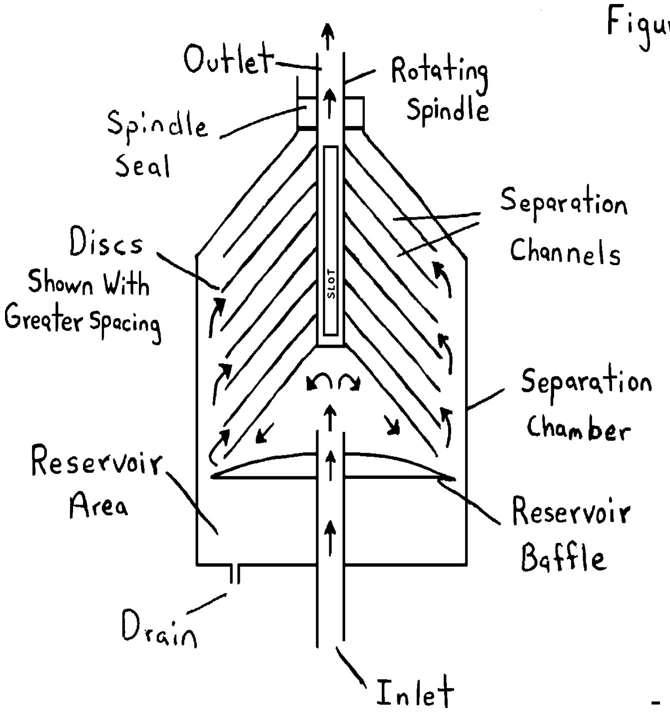


Figure 9



mechanically driven unit, the centrifugal force is that which throws the particle through the fluid stream and centripetal force is that which the particles and fluid stream must overcome to exit the separator.

A proposed design for an externally driven steam/oil centrifugal separator can be seen in figure 9. This design is based somewhat on a disc or cone type of liquid/liquid separator often used for the purification of lubricating oils and removal of cream from raw milk. The steam enters the chamber from the bottom, first impinging on bottom disc where the larger particles will cling, to then be thrown to the chamber wall. The steam then passes to the area outside of the rotating discs where it is swept along with the rotating motion of the discs. The flow is assumed to be divided equally as it goes through the channels between the discs and is then subjected to increasing centrifugal action as works its way to the exit, through the center spindle. The particles affected by the centrifugal action are deposited by radial forces, in a horizontal direction, on the undersides of the discs where they accumulate and slide to the rim to then be thrown to the chamber wall and drain to the reservoir below. When entering the chamber, the flow is slowed due to the increased volume of the chamber and this prevents the particles that are thrown from the discs from being drawn back into the steam flow. The particles thrown from the discs are much larger than those which may be removed from the flow of steam as they accumulate before sliding to the edge and being thrown off. This also helps prevent re-entrainment in to the steam. The walls are ribbed vertically on the inside of the chamber to allow the particles to fall by gravity to the reservoir after impact without being swept back into the swirling flow. The discs are closely spaced on the hollow spindle and the flow must exit through the slots in the spindle after passing across the discs. Spindle spacing on liquid / liquid separators is often as little as 0.020 inches providing a large surface area in a small volume. The oil particles have a very short distance to travel before they impact the underside of the cones because they are thrown horizontally between the closely spaced discs. The baffle plate around the inlet is to prevent the re-entrainment of oil by the rotational action of the steam acting above the reservoir. The required speed is dependant on the minimum particle size to be removed and on the diameter of the discs used.

The normal measurement for small particles is in microns or 1/1000 of a millimeter. Under the influence of gravity, the laws governing the rate at which particles settle depend upon their diameter, the difference between the density of the particle and the surrounding fluid, as well as the fluid viscosity. Stokes law is the most common formula used to determine the settling velocity and it is the most conservative but the rate of settling changes with the conditions

5) Reynolds Number for Particle movement

$$R_e = \frac{D_{ps} U_t \rho}{\mu}$$

R_e = Reynolds Number Dimensionless

D_{ps} = Diameter of Spherical Particle ft

U_t = Terminal Velocity from Stokes Law ft/sec

ρ = Density of Steam Lb/ft^3

μ = Viscosity cP

of flow and is often associated with the Reynolds number (5). The Reynolds number is based on the flow of the particles through the fluid they are being separated from, not on the flow through a vessel as is shown by equation 5 (6). The exact Reynolds number used for the determination of the range corresponding to the specific equations varies from text to text but the numbers given here should work in most instances. For a Reynolds number from 2.0 to 200, Stokes law applies with the Cunningham factor shown in equations 6 & 7 (13), from 200 to 2,000,000 stokes law applies by equation 6 alone, and above 2,000,000, Newton's law of gravity applies as in equation 8. These particles all settle with a constant velocity and those that don't settle with constant velocity, with Reynolds numbers below 2.0, are governed by Brownian movement, where molecular collisions provide more force for movement than gravity. These particles, in the range of vapors and smokes, are smaller than oil separators are normally designed for and are of little concern when removing oil from steam, therefore they are not included in the scope of this paper. When determining the terminal velocity of a particle not accelerated by an external force, stokes law is most commonly used as it is the most conservative. If after using stokes law, the Reynolds number is found to be in a range suited to a different equation, the correct terminal velocity can then be found using that equation and the Reynolds number re-checked. If the particle is accelerated by an external rotational force then the terminal

6) Stokes Law

$$U_t = \frac{18.5\, D_{Ps}^2 (P_s - P)}{\mu}$$

U_t = Terminal Velocity ft/sec

D_{Ps} = Diameter of Spherical Particle In

P_s = Particle Density Lb/ft^3

P = Steam Density Lb/ft^3

μ = Steam Viscosity cP

7) Cunningham Factor

$$U_t = U_t'\left(1 + K\frac{\lambda}{r}\right)$$

U_t' = U_t of Stokes Law

K = .80 - .86

λ = 10^{-5} cm (Average Distance Between gas molecules)

r = Radius of Particle cm

8) Newtons Law

$$F = ma$$

Combined With Radial Acceleration

$$a_r = \frac{V^2}{R} \quad \text{or} \quad \frac{F}{m} = \frac{V^2}{R}$$

Then $F_{cp} = \dfrac{V^2 m}{R}$

Or $F_{cp} = \dfrac{V^2 W}{R g}$

F = Force / F_{cp} = Centrifugal Force

m = Mass

a = Acceleration / a_r = Radial Acceleration

V = Velocity

R = Radius

g = Acceleration Due to Gravity

W = Weight

velocity can be figured from equation 3, and a correlation to the Reynolds number is not usually needed.

Oil in feed water can generally be detected visually when a film is present on the surface, but if not visible, laboratory means are usually employed for quantitative analysis. A water sample of a known volume is washed with a selective solvent such as ether. Caution, ether is very hazardous due to its low boiling point and high flamability and its use should not be attempted until a full understanding of its properties has been acquired. A 0.5 liter sample of water can be washed 3 times, each with 150 ml of ether and separated each time. Due to the great selectivity of ether, no water soluble impurities will be removed, only the oils. The 450 ml of ether should be carefully distilled down to about 30 ml and the remaining ether then evaporated to leave only the oil, the weight of which can be determined to find the percentage contained in the original water sample. The distillation and evaporation should be kept at a temperature below the vaporization temperature of the oil so none is lost to the atmosphere. A common test found in older manuals is to drop a very small piece of camphor into the water, and if it zipped around quickly, there was very little or no oil in it. If the camphor acts sluggish and slow, there is oil in the water. This test is for positive or negative results only and quantitative analysis is not possible. For quantitative analysis of emulsified oil in filtered feed water, the Tyndall light-cone test is quite accurate and can detect oil particles down to 0.2 micron (9) in quantities as little as 0.1 PPM (7). The test uses a narrow beam of light passing through a filtered sample of water, contained in a clear glass vessel to visually determine the emulsified oil content. Light is reflected by the oil in such a way that a glowing cone is of light will be seen if any oil is present. With no cone visible, there is no emulsified oil present and different levels of oil concentration can be discerned by comparison to cone pictures of standardized test samples. Even with no reference pictures to compare to, relative measurements are possible. The apparatus is very simple, consisting of a 60W light bulb under an inverted tin can with a number 50 drill size hole, drilled in the bottom for the passage of light. To test, turn on the bulb, set the can over it, place a filtered sample in a clean clear glass container over the hole and turn down the room lights.

In conclusion, regardless of the method of separation used, several important conditions must be considered when separating oil and particulate matter from steam. The minimum size of the particle is the major determining factor for the type of separator chosen and for its design parameters. Particles larger than the chosen minimum are removed with greater ease and are of little concern until they physically plug the separator. The pressure of the steam changes the volume considerably which effects the steams flow rate and viscosity. At atmospheric pressure saturated steam requires more than 4 times the volume of that occupied by 50 PSIG saturated steam. This decrease in steam density can aid in the removal of oil and other matter as the density of the impurities remains almost constant but at a cost of increased seperator size. Equal sized particles of oil or water are about 400 times heavier than the same volume of 50 PSIG saturated steam and at least 1500 times heavier at atmospheric pressure. The separation chamber must allow the steam flow rate to drop below the velocity of the particles removed from it and the flow should not be allowed to impart momentum to the particles that would hinder their removal where possible. The distance the particle has to travel to be removed from the flow should be as short as possible to allow the shortest length of

time for settling. Proper oil selection aids in the removal by a reduced tendency to break down or emulsify and although the oil density changes little, the viscosity varies greatly between oils and at varying temperatures. High viscosity oils are more apt to stick to the surfaces of the separator and may result in the need for more frequent cleaning though no easier to separate. The temperature of steam / oil separators must be low enough to prevent the passage of oil vapors that will condense with the steam. Oil water mixtures subject to mechanical sheer stresses tend to form emulsions which require greater effort in removal. Of the steam / oil separator designs discussed in this article, those that are mechanically driven, the centrifugal separators, are able to remove the smallest sized particles but do so at the expense of a some auxiliary power and at a higher initial cost. Those that don't use external drive, if properly designed, may remove an adequate amount of oil under most operating conditions to provide the required system protection but condensate filtering may also be required.

Density of SAE30 engine oil	**53 Lb/cu ft**
Density of mineral oils:	**54.94 to 58.68 lb/ cu ft**
Density of saturated steam at atm pressure	**0.037 Lb/cu ft**
Density of saturated steam at 50 PSIG:	**0.149 Lb/cu ft**
Acceleration due to gravity:	**9.8m/sec/sec = 32.17 ft/sec/sec**
Absolute viscosity of sat steam at 50 PSIG:	**0.034 Lbm/ft hr**
Absolute viscosity of sat steam at atm press	**0.029 Lbm/ft hr**
Specific gravity of mineral oils:	**0.88 to 0.94**

1 micron = 0.001MM = .00003937 In

1cP = 0.0000209 Lbf sec / sq ft = 2.42 Lbm/ft/sec

Alum = Aluminum Sulphate **Soda Ash = Sodium Carbonate**

1 Board of Trade Unit = 1 Kilowatt Hour

1) "Heat Exchanger Design", John Wiley & Sons, Arthur P. Fraas & M. Necati Ozisik 1965
2) "Boiler Plant Technology 3rd Ed", Sir Isaac Pitman & Sons, R. L. Batley & E. Gordon Barber, 1965
3) "Handbook of Industrial Water Conditioning 5th Ed", Betz Laboratories inc, 1986
4) "Two Oilfield Water Systems", Robert E. Krieger Publishing Co. Inc., Bryant W. Bradley & C.C. Patton & Asscoiates, Inc., 1987
5) "Handbook of Separation Techniques for Chemical Engineers", McGraw-Hill, Philip A. Schweitzer, 1979
6) Anderson web brochure at: http://www.nciweb.net/anderson.htm
7) "Solid-Liquid Separation", Butterworth & Company, Ladislov Svarokski, 1977
8) "Steam Generation", George Allen and Unwin LTD J.N. Williams, 1967
9) "Centrifugal Dryers and Separators", Ernest Benn Ltd., Eustace A. Alliott, 1926
10) "Modern Marine Engineering Vol 2", Marine Engineers Beneficial Association District 1, (AFL-CIO), 1954
11) "Cochrane Separator Catalog", Harrison Safety Boiler Works, 1913
12) "Naval Auxiliary Machinery", United States Naval Institute, 1953
13) "Standard Handbook for Mechanical Engineers 7th edition", McGraw-Hill, Edited by Theodore Baumeister 1967

14) "Boiler Feed and Boiler Water Softening 3rd Ed", Nickerson & Collins Company, H.K. Blanning & A. D. Rich, 1942

15) "Power Plant Theory & Design 2nd Ed", Ronald Press Company, Philip J. Potter, 1959
16) "Theory and Practice of Heat Engines", Longmans, Green and Company, R. H. Grundy, 1943
17) "Steam Power Stations 4th Ed", McGraw-Hill, Gustaf .A Gaffert, 1952
18) "Verbal Notes and Sketches for Marine Engineer Officers Vol 1 18th Ed, James Monroe and Company, J. W. Sothern
19) "Boiler Feed Water Teratment", Chemical Publishing Company, F. J. Mathews, 1951
20) "Introduction to Marine Engineering", Naval Institute Press, Robert F. Latham, 1958
21) "Steam Plant Operation 5th Ed", McGraw-Hill, Evert B. Woodruff / Herbert D. Lammers / Thomas F. Lammers, 1982
22) "The Steam Boiler Year Book and Manual 4th Ed", Paul Elek Publishing, Sydney D. Scorer, 1948
23) "Understanding Stationary Engineering", Checker Books Inc., 1981
24) "Principals of Industrial Water Treatment 6th Ed", Drew Chemical Corporation, 1983
25) "Boiler-Water-Treatment Manual for Federal-Plant Operators, Handbook 5", U.S. Department of the Interior / Bureau of Mines, 1951
26) "Bulletin E-1" (Separators), Elliott Company Power Plant Equiptment, February 1927
27) "The Practice of Lubrication 3rd Ed", McGraw-Hill, T.C. Thompson, 1937

Notes: My apologies to those of you that patiently waited for information I offered so long ago. I got caught up in a confusing swirl and came to the realization that nothing less than my full understanding of the subject would be of value to those I offer that information to. Admittedly I have no practical experience with steam systems and their auxiliaries so this paper is based on the research and experiences of others. Any equations not given terms can be solved using any like terms. The graph in figure 8 would be better represented on a logarithmic scale, it and all other figures were hand drawn and they may not be to scale. Most of all, thanks to George Nutz for a little help and a lot of confidence in my ability to write this paper.