

Monographs on Refinery Environmental Control— Management of Water Discharges

Design and Operation of Oil-Water Separators

API PUBLICATION 421
FIRST EDITION, FEBRUARY 1990



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FOREWORD

The *Monographs on Refinery Environmental Control* consist of four series—*Management of Emissions to Air*, *Management of Water Discharges*, *Management of Solid Wastes*, and *Management of the Subsurface Environment*. The monograph series are ongoing projects of the Committee on Refinery Environmental Control of the API Refining Department and are intended to be used by engineers responsible for the design, construction, operation, and maintenance of disposal systems for wastes generated in refineries.

This monograph provides design guidance for gravity-type oil–water separators for use in petroleum refineries, provides practical advice on solving operating problems and improving separator performance, and presents information on performance of existing refinery separators.

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Suggested revisions are invited and should be submitted to the director of the Refining Department, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005.

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Design and Operation of Oil–Water Separators

SECTION 1—GENERAL

1.1 Introduction

The purpose of this monograph is to provide design guidance on gravity-type oil–water separators for use in petroleum refineries, to provide practical advice on solving operating problems and improving separator performance, and to present information on the performance of existing separators.

This monograph deals solely with gravity-type oil–water separators, that is, those that rely on differences in specific gravity to separate oil globules from a wastewater stream. Two types of oil–water separators are covered in this monograph:

- a. The conventional, rectangular-channel unit.
- b. The parallel-plate separator.

Note: Throughout this monograph, the term *conventional oil–water separator* is used in place of the term *API separator* and refers to rectangular-channel units designed in accordance with the criteria published earlier by API. The term *API separator* has become almost a generic term, sometimes used incorrectly to refer to any gravity-type oil–water separator.

Historically, the design of conventional oil–water separators was based on criteria developed from a 3-year, API-funded research study initiated in 1948 at the Engineering Experiment Station at the University of Wisconsin [1]. Since then, numerous oil–water separators based on the API-developed design criteria have been designed and put into operation throughout the petroleum industry. The criteria were developed as voluntary guidelines for designing conventional oil–water separators. Many other separators based in part on the API-developed design criteria have been adapted for a variety of other industrial wastewater treatment applications.

This monograph retains pertinent information from Chapters 5 and 6 of the 1969 edition of the *API Manual on Disposal of Refinery Wastes, Volume on Liquid Wastes*, and incorporates the recent findings of a literature review and 1985 survey of refinery separators. Data from this survey of the design and operation of oil–water separators have been incorporated in this monograph.

Although the theory of oil–water separators is briefly discussed, the emphasis of this monograph is on practical guidance for those involved in the design or operation of oil–water separators.

1.2 Background

A refinery wastewater stream may contain oil in three major forms: free, emulsified, and dissolved. Some pertinent features of each of these are briefly discussed below:

Free oil is in the form of discrete oil globules of a size sufficient so that the globules can rise as a result of buoyant forces and form an oil layer on top of the water. Under proper quiescent flow conditions, free oil can be removed by gravity separation. This removal is a function of residence time, differences in specific gravity and temperature, and the stability of the emulsion. Some coarse oily solids have a specific gravity greater than 1.0 and will settle to the bottom of a separator. Most of the oil and associated fine solids in refinery wastewater have a specific gravity of less than 1.0 and will rise to the water's surface.

Emulsified oil is in the form of much smaller oil droplets or globules with a diameter of less than 20 microns (mostly in the 1–10-micron range). These globules form a stable suspension in the water as a result of the predominance of interparticle forces over buoyant forces. The presence of particulates also contributes to emulsion formation. Regardless of how long a true oil–water emulsion stands under quiescent conditions, a separate oil phase will not form. Emulsified oil may be removed by chemical addition and coalescing or by flotation but not by gravity separation alone.

Dissolved oil is the petroleum fraction that forms a true molecular solution with water. Dissolved oil cannot be removed by gravity separation; further wastewater treatment (for example, biological treatment) is necessary if removal of dissolved oil is required.

The fraction of oil that is removable from a wastewater stream by gravity separation is affected by the type of oily material present. The method of measuring oil concentration can also affect the apparent efficiency of removal. Conventional oil–water separators remove only free oil; stable emulsions and dissolved oil require additional treatment.

1.3 Basic Theory

In essence, an oil–water separator is a chamber designed to provide flow conditions sufficiently quiescent so that globules of free oil rise to the water surface and coalesce into a separate oil phase, to be removed by mechanical means.

Oil–water separation theory is based on the rise rate of the oil globules (vertical velocity) and its relationship to the surface-loading rate of the separator. The rise rate is the velocity at which oil particles move toward the separator surface as a result of the differential density of the oil and the aqueous phase of the wastewater. The surface-loading rate is the flow rate to the separator divided by the surface area of the separator. In an ideal separator, any oil globule with a rise rate greater than or equal to the surface-loading rate will reach the separator surface and be removed. An ideal separator is

assumed to have no short circuiting, turbulence, or eddies. The required surface-loading rate for removal of a specified size of oil droplet can be determined from the equation for rise rate. The derivations of the basic equations for oil-water separator design are given in Appendix A. The mathematical relationship for the rise rate is provided by a form of Stokes' Law:

$$V_i = (g/18\mu)(\rho_w - \rho_o)D^2 \quad (1)$$

Where:

V_i = vertical velocity, or rise rate, of the design oil globule, in centimeters per second.

g = acceleration due to gravity
= 981 centimeters per second squared.

μ = absolute viscosity of wastewater at the design temperature, in poise.

ρ_w = density of water at the design temperature, in grams per cubic centimeter.

ρ_o = density of oil at the design temperature, in grams per cubic centimeter.

D = diameter of the oil globule to be removed, in centimeters.

The vertical velocity of an oil globule in water depends on the density and diameter of the oil globule, the density and viscosity of the water, and the temperature. The oil globule's vertical velocity is highly dependent on the globule's diameter, with small oil globules rising much more slowly than larger ones. It has been determined from the API research mentioned above that, using the example design procedures described in this monograph, oil globules with a diameter greater than or equal to 0.015 centimeter (150 microns) can be expected to be removed effectively in a gravity separation chamber without plates.

With the oil globule diameter fixed at 0.015 centimeter, Equation 1 can be simplified (see Appendix A) to yield, in English units,

$$V_i = 0.0241 \frac{S_w - S_o}{\mu} \quad (2)$$

Where:

V_i = vertical velocity of the oil globule, in feet per minute.

S_w = specific gravity of the wastewater at the design temperature (dimensionless).

S_o = specific gravity of the oil present in the wastewater (dimensionless, not degrees API).

μ = absolute viscosity of the wastewater at the design temperature, in poise.

Procedures for determining specific gravities for oil and wastewater and for wastewater viscosity are given in 2.1.1.

Equation 2 embodies two fundamental principles that should always be kept in mind when designing and operating oil-water separators:

- a. The performance of the separator will be highly dependent on the difference between the specific gravity of the water and that of the oil. the closer the specific gravity of the oil is to that of the water, the slower the oil globules will rise.
- b. Since the oil globules' rise rate is inversely proportional to the viscosity of the wastewater, oil globules will rise more slowly at lower temperatures.

Both of these factors play an important role in selecting design conditions in the design procedure for oil-water separators presented in 2.1.

For those further interested in the theoretical aspects of particle settling, a derivation of Equations 1 and 2 is presented in Appendix A.

1.4 Application

As stated above, oil-water separators are designed to remove free oil only. If emulsified or dissolved oil is present, one cannot expect an oil-water separator to remove it, and additional downstream treatment may be required. A principal function of the oil-water separator is to remove gross quantities of free oil before further treatment. In this capacity, the oil-water separator protects more sensitive downstream treatment processes from excessive amounts of oil. Since separator skimmings are typically recycled, and oil not recovered can end up as sludge, efficient recovery results in minimization of waste.

The performance of gravity oil-water separators varies with changes in the characteristics of the oil and wastewater, including flow rate, specific gravity, salinity, temperature, viscosity, and oil-globule size. Performance is also a function of design and operational constraints and of the analytical methods used to measure performance. The API survey data included in this monograph reflect the large amount of variability that is a result of these many factors. However, the survey data indicate that increasing separator size, as measured by surface-loading rate, results in improved performance, as measured by effluent oil and grease. Unit design needs to take into account the impact on downstream oil removal processes (for example, dissolved-air flotation) to determine whether incremental improvements in performance can be justified.

Parallel-plate separators are based on a newer technology. They require less space than do conventional oil-water separators and are theoretically capable of achieving lower concentrations of effluent oil. Petroleum industry data are insufficient to conclude that parallel-plate units offer overall superior performance.

There are petroleum industry applications in which oil-water separators are the only end-of-pipe treatment provided. These are usually cases in which the only effluent restrictions specified are for oil or suspended solids and the wastewater in question consistently contains sufficiently low amounts of emulsified and dissolved oils. In some applica-

tions, the oil-water separator is provided as a protective device for containment of spills and leaks (for example, on once-through cooling water). Another example is an instance in which a stream is discharged to a publicly owned treatment works and the oil-water separator is used to ensure compliance with requirements for pretreatment of oil and grease.

It should be stressed that whenever an oil-water separator is considered for an application where it must stand alone, the amount of emulsified and dissolved oils in the wastewater stream must be properly quantified, because these oils will not be removed by the separators. More important, the design procedures in this monograph relate to refinery pretreatment of contaminated wastewater. Other applications require special consideration.

One aspect of oil-water separator design that is sometimes overlooked is that whether intended to or not, an oil-water separator also functions as a sedimentation basin. Solid particles more dense than water (for example, soil and coke particles) will tend to settle out in the separator. Provision must therefore be made to deal with the removal of settleable solids that accumulate in the separator.

1.5 Referenced Publications

The following publications are cited in this monograph:

ASTM¹

- D 445 *Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)*
- D 1429 *Test Methods for Specific Gravity of Water and Brine*
- D 1888 *Test Methods for Particulate and Dissolved Matter in Water*
- D 3921 *Test Method for Oil and Grease for Petroleum Hydrocarbons in Water*

EPA²

- "Standards of Performance for VOC Emissions from Petroleum Refinery Wastewater Systems" (40 *Code of Federal Regulations* Part 60, Subpart QQQ)
- "Hazardous Wastes from Specific Sources" (40 *Code of Federal Regulations* Part 261.32)

SECTION 2—CONVENTIONAL OIL-WATER SEPARATORS

2.1 Design Procedures

2.1.1 GENERAL

API has established certain design criteria for determining the various critical dimensions and physical features of the separator. These are presented in a series of step-by-step design calculations. The design calculations require that certain characteristics of the wastewater be known. The more thoroughly the wastewater is characterized, the more predictable the performance of the separator will be.

2.1.2 WASTEWATER CHARACTERIZATION

2.1.2.1 General

When selecting test methods for oil in wastewater, one must consider the test objective. A number of methods are available for measuring oil, and the solids fraction includes total, filterable, settleable, and dissolved fractions. Depending on the objective, any of the methods may be applicable.

2.1.2.2 Free, Emulsified, and Dissolved Oil

The total oil and grease content of a wastewater can be determined by the U.S. Environmental Protection Agency's (EPA's) Methods 413.1, "Gravimetric Separation," and 413.2, "Infrared Spectrophotometry" [2]. Corresponding tests are Standard Methods 503A and 503B [3], published

jointly by the American Public Health Association (APHA), the American Water Works Association (AWWA), and the Water Pollution Control Federation (WPCF). The presence of compounds such as organic sulfur compounds can cause artificially elevated results in the oil-and-grease determination. Since oil is a complex mixture of different compounds, different test methods can give different results. These differences may not be consistent between waste streams. A summary of the applicability of these tests is given in Table 1.

An analogous ASTM method for determining oil and grease and petroleum hydrocarbons in water is D 3921. This method is similar to EPA Method 413.2, except that the valid concentration range is 0.5–100 milligrams per liter. Again, none of these methods distinguishes among free, emulsified, or dissolved oils.

Over thirty years ago, API developed an operational method for determining the emulsified and dissolved oil fraction. This method, entitled "Determination of Susceptibility to Oil Separation," is presented in Appendix B. The method employs the use of a separatory funnel to roughly

¹American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103.

²U.S. Environmental Protection Agency. The *Code of Federal Regulations* is available from the U.S. Government Printing Office, Washington, D.C. 20402.

Table 1—Applicability of EPA Methods
413.1 and 413.2

Method	Concentration Range for Which the Method Is Valid ^a (milligrams per liter)	Representativeness of Analytical Results
EPA 413.1	5–1000	Measures only nonvolatile hydrocarbons (volatilizing at >70°C), excluding residue materials insoluble in Fluorocarbon 113
EPA 413.2	0.2–1000	Measures most volatile hydrocarbons in addition to heavier compounds, excluding residue materials insoluble in Fluorocarbon 113

^aWastewaters with oil concentrations greater than the maximum can be readily analyzed by sample dilution.

simulate the quiescent settling conditions in an oil–water separator. Wastewater is allowed to separate in the funnel for 30 minutes. Settleable solids are then withdrawn from the water phase, and the water phase is analyzed for oil and grease (the more current EPA Methods 413.1 or 413.2 or the equivalent APHA/AWWA/WPCF Standard Methods 503A and 503B should be used in lieu of older API methods.) The amount of oil and grease remaining in the water phase after the separation period represents the oil that is not susceptible to gravity separation.

The amount of free oil can be determined by analyzing a comparable wastewater sample for total oil and grease using the EPA methods or the APHA/AWWA/WPCF standard methods discussed above and subtracting the amount of oil and grease remaining in the water phase, as found using Appendix B.

It is recommended that Appendix B or a comparable method be used in designing an oil–water separator, particularly in applications where the separator must stand alone.

2.1.2.3 Solids Content

Although the primary function of an oil–water separator is to remove free oil from aqueous waste streams, the solids content of the wastewater is important in selecting separator appurtenances. Total suspended solids can be measured using Standard Method 209C [3], EPA Method 160.2 [2], or ASTM D 1888. The suspended-solids content of an oily wastewater may not be accurately measured by these methods if compounds that volatilize at temperatures at or below 103°C are present. These compounds may adsorb to particulate matter in the sample and cause difficulties in determining when the sample has been dried to constant weight.

Ignition of the dried sample from Standard Method 209C or an equivalent (following Standard Method 209D [3] or EPA Method 160.4 [2]) indicates the quantity of organic and inorganic materials present in the wastewater's solid component. Sand and similar materials may be removed by design-

ing for low velocities in the channel preceding the main separator basin. This channel can serve as a type of grit chamber and can be beneficial in reducing solids problems within the separator itself.

Settleable solids (those that settle by gravity over a given period of time) are usually measured on a volumetric basis (see Standard Method 209E.3.a [3] or EPA Method 160.5 [2]). The results of this procedure indicate the approximate volume of settled materials that will need to be removed from the bottom of an oil–water separator. The characteristics of the settleable solids should be noted to determine how much grit is present. Based on the tradeoff between the quantity of grit in the wastewater and the amount of separator down time required for grit and sludge cleanout, a grit collector may be advisable.

2.1.2.4 Other Wastewater Characteristics

No less important than the two parameters discussed in 2.1.2.2 and 2.1.2.3 are the specific gravities of the oil and water phases and the absolute viscosity of the wastewater, which are both evaluated at the minimum design temperature. Assuming all other conditions are equal, the greater the difference in specific gravity between the water and oil phases, the better the oil–water separation will be. The specific gravity of the oily phase can be determined using the procedure given in Appendix B. The specific gravity and absolute viscosity of the wastewater should be determined experimentally where possible. In the absence of such data, values for the specific gravity and absolute viscosity of fresh and saline water can be estimated from Figures 1 and 2. ASTM D 1429 can be used to determine the specific gravity of wastewater. ASTM Method D 445 can be used to measure the viscosity of wastewater. The temperature of the wastewater can have a pronounced effect on the efficiency of the separator. In general, for the temperature range experienced in refinery wastewaters, the lower the temperature, the poorer the oil–water separation will be.

2.1.3 ESTABLISHING A DESIGN FLOW

The design flow for a conventional oil–water separator is primarily determined by two factors: the expected wastewater flow rate, and the safety factor desired to accommodate flow variations. Consideration should also be given to possible future refinery expansion. Unless flow equalization is provided upstream of the separator, the design flow should be based on the maximum flow rate attributable to current and future oil-contaminated process wastewaters and stormwater runoff. Regulatory requirements for spill control can also be a factor in identifying stormwater treatment requirements.

Uncontrolled surface runoff or storm drainage can greatly increase flow to a separator for a short period of time. In such a case, flow equalization upstream of the oil–water sep-

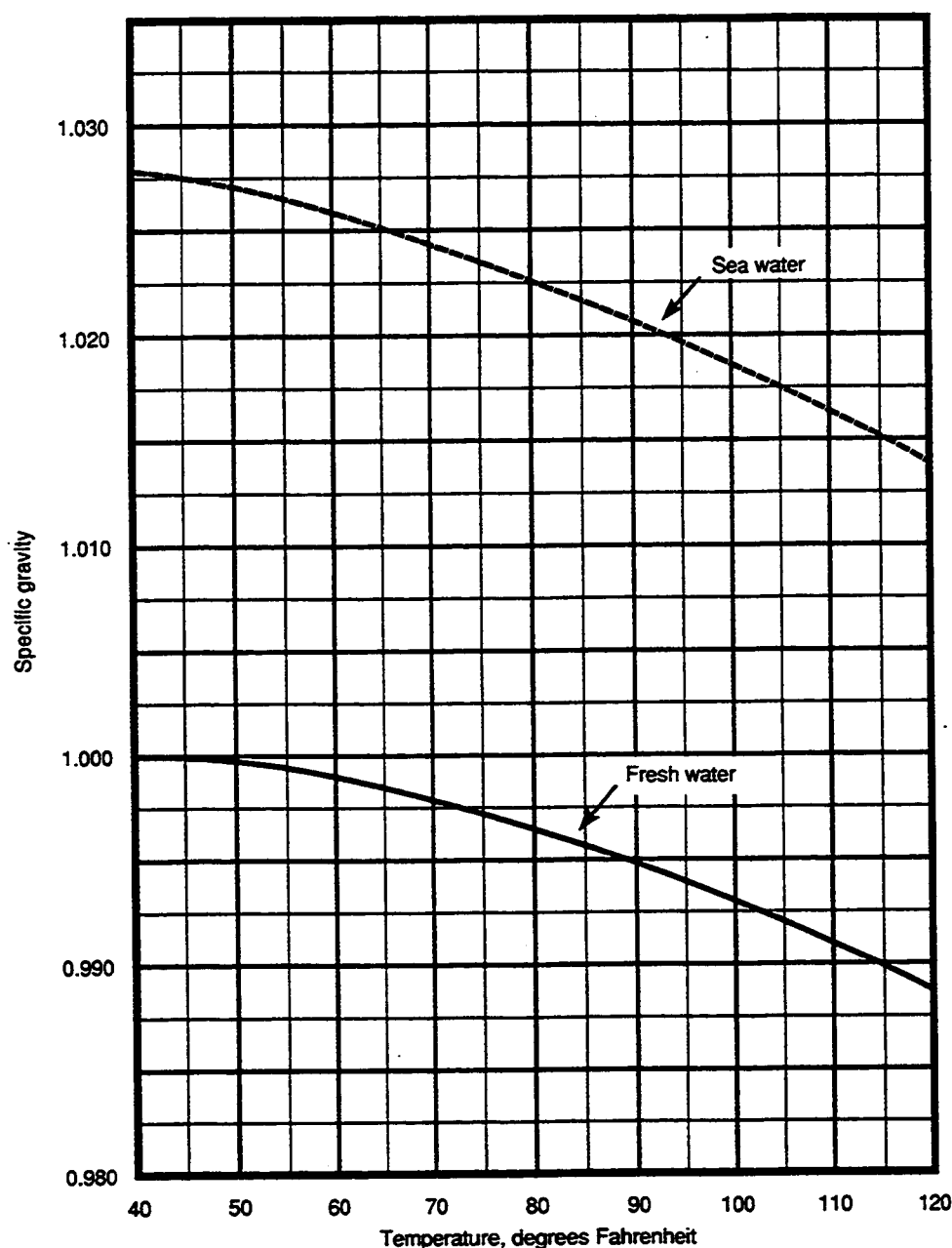


Figure 1—Specific Gravity of Clear Water (Fresh and Sea) for Temperatures Between 40°F and 120°F

arator is beneficial. In the event that such equalization cannot be provided, the separator must handle the design storm flow of direct runoff from the drainage area. The size of the storm flow load on a separator can be estimated based on frequency, intensity, and duration of rainfall. Data on these factors for various localities can be obtained from state and federal agencies. The amount of runoff is a function of rainfall intensity, soil porosity, the size of the drainage area, and the percentage of the area that is paved. If practical, surface

runoff that never contacts oil should be excluded from the process wastewater separator system.

When flow exceeds the design capacity of the separator, the separator continues to function, but it does so with reduced efficiency. The frequency and duration of hydraulic overloads can be reduced by providing additional separator capacity. Alternatives are to divert flow that exceeds the design flow allowance to an impounding basin for temporary storage or to separate extraneous flow from the system for

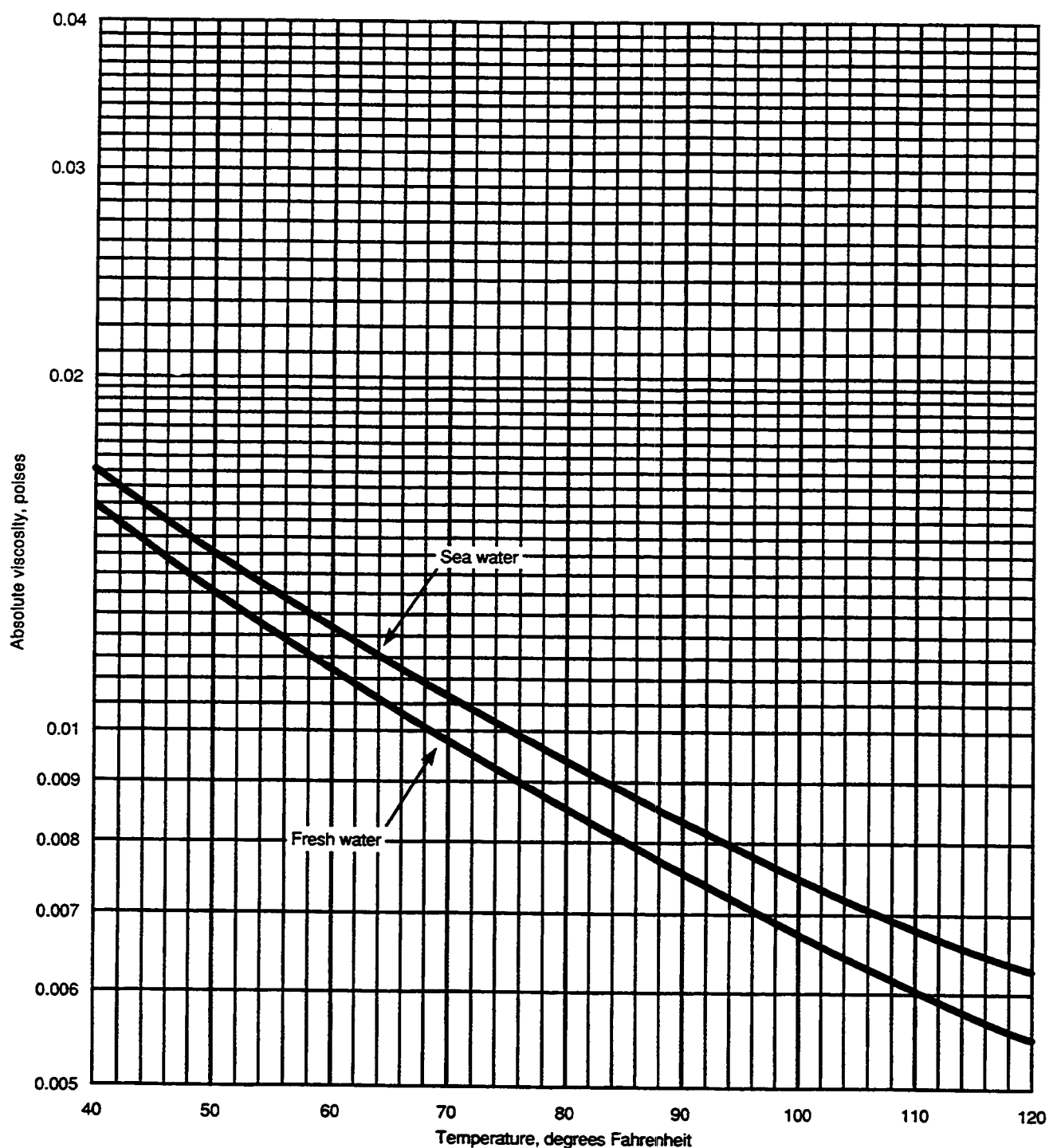


Figure 2—Absolute Viscosity of Clear Water (Fresh and Sea) for Temperatures Between 40°F and 120°F

example, uncontaminated runoff, utility blowdowns, and non-oily process wastewater) for separate handling or tie-in to the wastewater treatment system downstream of the oil-water separator. In certain cases, diversion of low-oil, high-pH waste streams from the separator can enhance its performance.

2.1.4 STEP-BY-STEP DESIGN CALCULATIONS

2.1.4.1 General

As discussed above, the following parameters are required for the design of an oil-water separator

- Design flow (Q_m), the maximum wastewater flow. The design flow should include allowance for plant expansion and stormwater runoff, if applicable.
- Wastewater temperature. Lower temperatures are used for conservative design.
- Wastewater specific gravity (S_w).
- Wastewater absolute (dynamic) viscosity (μ).
- Wastewater oil-fraction specific gravity (S_o). Higher values are used for conservative design.
- Globule size to be removed. The nominal size is 0.015 centimeter, although other values can be used in conjunction with Equation 1 if indicated by specific data.

The design of conventional separators is subject to the following constraints:

- Horizontal velocity (v_H) through the separator should be less than or equal to 3 feet per minute or equal to 15 times the rise rate of the oil globules (V_i), whichever is smaller.
- Separator water depth (d) should not be less than 3 feet, to minimize turbulence caused by oil/sludge flight scrapers and high flows. Additional depth may be necessary for installations equipped with flight scrapers. It is usually not common practice to exceed a water depth of 8 feet.
- The ratio of separator depth to separator width typically ranges from 0.3 to 0.5 in refinery service.
- Separator width is typically between 6 and 20 feet and conforms to standard dimensions for flight scraper shaft lengths specified for sludge removal.
- By providing a minimum of two separator channels, one channel is available for use when it becomes necessary to remove the other from service for repair or cleaning.

The following design suggestions are also made:

- The amount of freeboard specified should be based on consideration of the type of cover to be installed and the maximum hydraulic surge used for design.
- A length-to-width ratio (L/B) of at least 5 is suggested to provide more uniform flow distribution and to minimize the effects of inlet and outlet turbulence on the main separator channel.
- When the target diameter of the oil globules to be removed is known to be other than 0.015 centimeter, Equation 1 should be used to compute oil-globule rise rates. Equation 2 assumes an oil-globule size of 0.015 centimeter and represents a typical design approach.

Figure 3 shows an oil-water separator and depicts the design variables listed above. Repeating Equations 1 and 2,

$$V_i = (g/18\mu)(\rho_w - \rho_o)D^2 \quad (1)$$

$$V_i = 0.0241 \frac{S_w - S_o}{\mu} \quad (2)$$

Where:

- V_i = vertical velocity, or rise rate, of the design oil globule, in centimeters per second.
- g = acceleration due to gravity
= 981 centimeters per second squared.
- μ = absolute viscosity of wastewater at the design temperature, in poise.
- ρ_w = density of water at the design temperature, in grams per cubic centimeter.
- ρ_o = density of oil at the design temperature, in grams per cubic centimeter.
- D = diameter of the oil globule to be removed, in centimeters.
- S_w = specific gravity of the wastewater at the design temperature (dimensionless).
- S_o = specific gravity of the oil present in the wastewater (dimensionless, not degrees API).

After an oil-globule rise rate (V_i) has been obtained from Equation 1 or 2, the remaining design calculations may be carried out as described in 2.1.4.2 through 2.1.4.7.

2.1.4.2 Horizontal Velocity (v_H)

The design mean horizontal velocity is defined by the smaller of the values for v_H , in feet per minute, obtained from the following two constraints:

$$v_H = 15V_i \leq 3 \quad (3)$$

These constraints have been established based on operating experience with oil-water separators. Although some separators may be able to operate at higher velocities, 3 feet per minute has been selected as a recommended upper limit for conventional refinery oil-water separators. Most refinery process-water separators operate at horizontal velocities much less than 3 feet per minute at average flow. All separators surveyed had average horizontal velocities of less than 2 feet per minute, and more than half had average velocities less than 1 foot per minute, based on typical or average flow rates (see Appendix C). Maximum flow rates were not reported in the survey; however, design flow rates were typically 1.5–3 times the typical average flow rates.

2.1.4.3 Minimum Vertical Cross-Sectional Area (A_c) (See Figure 3)

Using the design flow to the separator (Q_m) and the selected value for horizontal velocity (v_H), the minimum total cross-sectional area of the separator (A_c) can be determined from the following equation:

$$A_c = Q_m / v_H \quad (4)$$



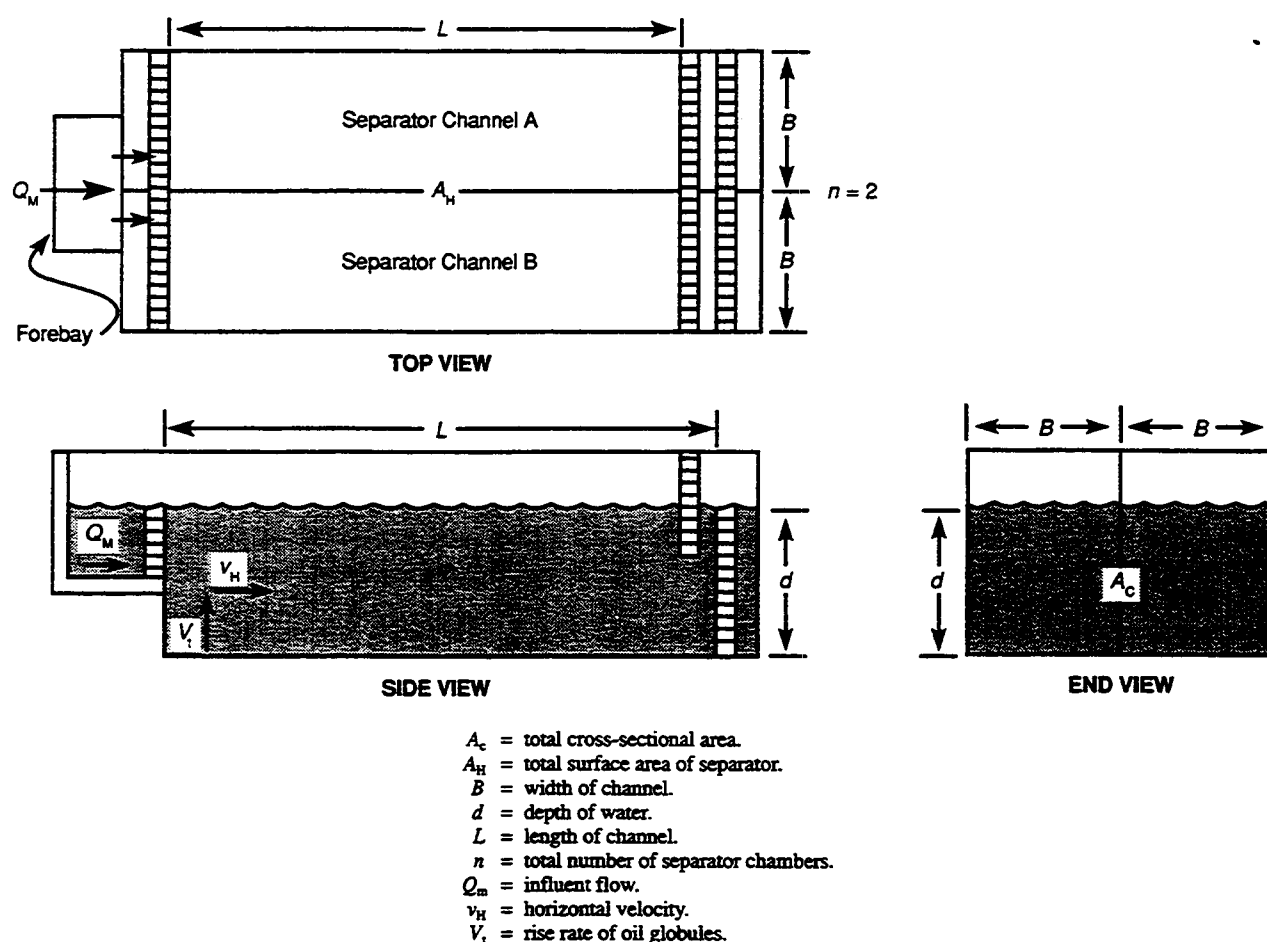


Figure 3—Design Variables for Oil–Water Separators

Where:

A_c = minimum vertical cross-sectional area, in square feet.

Q_m = design flow to the separator, in cubic feet per minute.

v_H = horizontal velocity, in feet per minute.

2.1.4.4 Number of Separator Channels Required (n)

In general, the most economical installation is one that minimizes the number of channels required. However, a minimum of two channels is recommended to allow for separator maintenance without bypassing the entire separator. To minimize the number of channels, the cross-sectional area should be maximized in conformance with the design constraints set above. Typically, the maximum cross-sectional dimensions recommended for a single channel are 20 feet wide and 8 feet deep (160 square feet). On this basis, the number of channels (n) required is calculated as follows:

$$n = A_c / 160 \quad (5)$$

Where:

A_c = minimum vertical cross-sectional area, in square feet.

Fractional numbers of channels are rounded up to the next whole number, based on engineering judgment.

2.1.4.4 Channel Width and Depth

Given the total cross-sectional area of the channels (A_c) and the number of channels desired (n), the width and depth of each channel can be determined. A channel width (B) of between 6 and 20 feet should be substituted into the following equation, solving for depth (d):

$$d = A_c / Bn \quad (6)$$

Where:

d = depth of channel, in feet.

A_c = minimum vertical cross-sectional area, in square feet.

B = width of channel, in feet.

n = number of channels (dimensionless)