



DESIGN PRACTICES

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Revision Memo

12/00 General revision of all text sections, along with editorial changes to entire practice.


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SCOPE

This section describes vaporizing equipment, provides design guidelines, and presents simplified hand calculation procedures for the heat transfer and hydraulic balance of vaporizers. The calculation procedures are based on methods presented in the Heat Transfer Research, Inc., (HTRI) Design Manual, Volumes 2 and 3, and Design Practices [Section XIV, Fluid Flow](#). The recommended design procedure is to use the appropriate computer program as described in [Section IX-K](#). Tube selection, circulation rate, and general design criteria for steam generators are also covered in this section. [Sections IX-A, B, and C](#) describe basic vaporizer considerations such as tube size and pitch, fouling factors, etc. [Section IX-A](#) also includes a brief description of enhanced boiling tubes that can be used to increase the nucleate boiling coefficient.

REFERENCES

HTRI

Report BG1-1, *Nucleate Pool Boiling of Hydrocarbon Mixtures*, May 1983
 Report BT-1, *Boiling Heat Transfer in a Vertical Thermosiphon Reboiler*, May 1978
 Report BT-3, *Boiling of Mixtures inside Vertical Tubes*, Sept. 1978
 Report BT-4, *Two-Phase Flow Instability in Vertical Thermosiphon Reboilers*, Dec. 1978
 Report BK-1-1, *Thermal Design of Kettle Reboiler Bundles*, July 1969
 Design Manual, Volumes 2 and 3

EQUIPMENT TYPES AND APPLICATIONS

REBOILER TYPES

General

Distillation column reboilers can be divided into three groups according to their method of fluid circulation:

1. Thermosiphon or natural circulation reboilers - The driving force is provided by the liquid head from the bottom of the tower. The available head must be sufficient to overcome pressure drops in the inlet and outlet piping and in the exchanger. The boiling fluid can be placed on the tubeside, or on the shell side of a conventional shell-and-tube exchanger, or on the shell side of a kettle type exchanger.
2. Pump-through or forced circulation reboilers - A pump is used to circulate the boiling fluid through the exchanger and back to the tower. The boiling fluid is generally placed on the tubeside of a conventional shell-and-tube exchanger.
3. Internal or stab-in reboilers - A tube bundle is inserted into the tower eliminating the need to provide for circulation of the fluid.

Figure A1 shows sketches of different reboiler types and lists the advantages and disadvantages of each. The selection of the type of unit is based on the heat transfer performance, fouling tendency, and the economics of the design; hydrodynamic performance varies widely for the different types of exchangers, and is an important consideration. The economic factors include foundation and piping costs, exchanger shell and bundle costs, tower elevation, and operating costs. The performance factors are the rate of heat transfer and vaporization, pressure drop, and flow stability. The Reboiler Selection Chart below is a guide to equipment selection. This is a rough guide and the ultimate selection depends on many more specific criteria.

Kettle Reboilers

The components of a typical kettle reboiler are shown in **Figure A2**. The bundles are normally two-pass, and U tubes if a clean heating fluid such as steam is used, or a pull through floating head (T type) if the heating fluid is fouling. The bundle is inserted in an enlarged shell to provide vapor-liquid disengaging space above the bundle. An overflow weir is normally provided to maintain the liquid level above the top of the tubes.

Kettle reboilers may have 100% vaporization for clean fluids such as refrigerants. If the boiling fluid tends to foul then an intermittent blowdown connection is provided at the bottom of the shell to remove fouling material accumulating at the bottom of the shell.

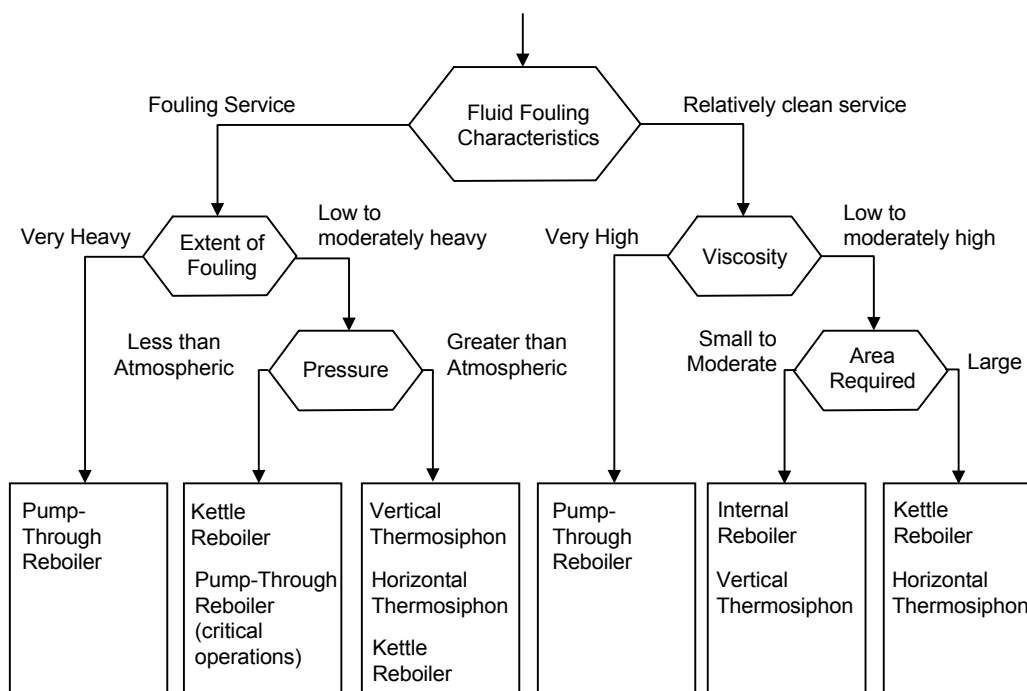
With kettle reboilers the bottom section of the column is simplified. Product hold-up or vapor-liquid disengaging space is not required in the tower, so internal baffling is minimized. If the necessary liquid hold-up beyond the weir in the exchanger requires more than 4 ft of shell length a thermosiphon should be considered. Kettles require the lowest tower elevation of the various reboiler types and so find application where the tower bottoms are not pumped away.

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EQUIPMENT TYPES AND APPLICATIONS (Cont)

Kettles are more expensive than the other types of reboiler units because of the enlarged shell. Their use is, therefore, limited to process conditions that find it more suitable, i.e. fluids with narrow boiling range, heat-sensitive materials, vacuum services, low temperature difference to the heating medium. Kettle reboilers are not well suited for fluids with wide boiling range and high pressure conditions.

REBOILER SELECTION CHART



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Vertical Thermosiphon Reboilers

These are usually single tube-pass units with vaporization in the tubes. Installation costs are low since the exchanger may be directly mounted on the tower minimizing foundation, structures, and plot area; on the other hand, if independently supported in the vertical orientation, these installation costs are probably the same as a horizontal unit or sometimes even higher. Bottoms product hold-up and vapor-liquid disengaging space are provided in the tower bottom. Piping must be short but of large diameter to reduce the pressure drop and ensure flow stability. The shell side fluid should be non-fouling so as to reduce the cost of having to remove the bundle vertically and to permit fixed tubesheet construction.

Vertical thermosiphons should be restricted to a maximum of 50% vaporization because at higher rates of vaporization hydrodynamic head losses may exceed the available driving force and cause unstable flow by creating temporary backflow of vapor. It is common industrial practice to limit vaporization to 30%.

Flow instability can be prevented by increasing tube diameter, especially for low pressure services. Tubes of 3/4 in. (19.05 mm) OD should be avoided if possible. Increasing tube length may promote instability by increasing pressure drop. Rules of thumb to obtain a stable design are: (a) the pressure drop in the exit piping should be less than 0.3 times the total driving head, (b) the flow area of the exit piping should be no less than the total flow area of the tubes, and (c) the flow area of the inlet piping should be in the range of 0.1 to 0.3 times the total flow area of the tubes.

Detailed information on operational characteristics and design suggestions are given in **Tables 1 and 2**. Thermosiphons should be avoided for viscous fluids and for operations where the available liquid head is variable.

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EQUIPMENT TYPES AND APPLICATIONS (Cont)

Horizontal Thermosiphon Reboilers

The boiling fluid is placed on the shell side and multiple inlets and outlets, and split horizontal baffles are often used to provide good distribution and higher velocities. Bottoms product hold-up and vapor-liquid disengaging are provided in the bottom of the tower. This type is limited to moderately fouling services and the use of a removable bundle with square tube pitch is recommended.

Horizontal thermosiphons require separate foundations, more plot area than vertical units, and more complex piping. Thus their overall cost is generally higher than vertical thermosiphons.

Vaporization should be restricted to 50% for hydrocarbons and 10% for aqueous solutions for clean services and 25% for relatively more fouling services. The advantage of horizontal thermosiphons is their lower pressure drop and larger liquid volume hold-up than the vertical thermosiphons, that allows for greater operational flexibility and their lower head requirements. Horizontal thermosiphons can handle fluid mixtures with wider boiling range; however, viscous services and those with variable liquid head should be avoided.

Pump-Through Reboilers

In a pump-through reboiler the vaporizing fluid is circulated by a pump accommodating a higher pressure drop and correspondingly higher heat transfer coefficients. Piping diameters may be smaller than for other reboiler types and the exchanger can be located away from the tower. Initial pump costs and operating costs are high, but they can be justified under the following circumstances:

1. The service is very viscous or highly fouling.
2. A high circulation rate, about 10:1, or a low increase in temperature is required to prevent thermal degradation of the bottoms product.
3. The liquid head available from the tower is limited. However, tower elevation must be high enough to provide the required NPSH.

In highly fouling services the vapor fraction at the outlet should be limited to about 5% by weight.

Internal Reboilers

An internal reboiler consists of a tube bundle inserted directly into the tower using a flange in the side of the tower. This eliminates the costs of a shell and piping. The flange can be relatively expensive, but on an installed cost per square foot basis internal reboilers are frequently the least expensive of all the types. A major limitation of this type is that the length of the bundle is restricted by the tower diameter, so that an uneconomically large bundle diameter may be required. As a rule of thumb, if the bundle diameter is 36 in. (914 mm) or greater, internal reboilers should not be considered. The major disadvantage of internal reboilers is that they cannot be serviced and cleaned without shutting the tower down. For that reason welded tube-to-tubesheet joints should be provided.

In sizing the bundle and the flange connection, sufficient clearance should be provided between the bundle and the flange neck inside diameter to allow vapor to escape into the tower and avoid vapor blanketing of that portion of the tubes. Fouling tendencies of internal reboilers are similar to kettles.

REBOILERS AND TOWER ELEVATION

The bottom of the shell of a reboiler is located at the minimum practical distance above grade. This distance is set by space requirements for piping, and is usually about 3 ft (1 m).

For natural-circulation reboilers a pressure balance through the reboiler circuit determines the exact tower elevation. The usual points of reference for the pressure balance are the bottom tangent line of the tower and the bottom of the reboiler shell or the bottom tubesheet for a vertical thermosiphon reboiler. As a rough guide, the distance between these points will normally be 6 to 10 ft (1.8 to 3 m) for kettle reboilers and 8 to 20 ft (2.4 to 6.1 m) for thermosiphon reboilers.

For forced-circulation reboilers, the tower is normally elevated 15 ft (4.6 m) above grade to provide an adequate pump NPSH. If necessary this elevation can be decreased by reducing the pump NPSH requirement to a minimum consistent with pump availability. However, this will usually cause a considerable increase in the cost of the pump.

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EQUIPMENT TYPES AND APPLICATIONS (Cont)

REBOILER STAGE EFFICIENCY

The stage efficiency of recirculating type reboilers (that are not baffled to prevent bottom tray liquid from bypassing the reboiler) may be estimated from the following equation.

$$S_F = (1 - N_L / (N_V K / A + B)) / (1 - N_L / (N_V K + B))$$

where: A = $1 + y(K - 1)$
B = Bottoms product rate, moles/hr
 S_F = Fraction of theoretical stage
K = Equilibrium constant of light key component
 N_L = Liquid rate from bottom tray, moles/hr
 N_V = Vapor rate from reboiler, moles/hr
y = Mole fraction vaporized in the reboiler

CHILLERS

The operation of a chiller is like that of a reboiler. The fluid being cooled on the tube side vaporizes refrigerant on the shell side. A chiller is normally constructed like a kettle reboiler, but without a weir. It may also be made from a regular shell and tube exchanger by eliminating tubes in the top portion of the shell to provide a space for vapor-liquid disengaging. The calculation procedure for chillers is the same as for kettle reboilers.

PREHEATERS

A preheater, like a pump-through reboiler, consists of a conventional shell-and-tube exchanger with the liquid to be vaporized fed either by a pump or pressurized from upstream equipment. Most preheaters add both latent heat and sensible heat to the fluid being vaporized (one exception would be the vaporization of a pure component under very little back pressure). The fluid to be vaporized is generally placed in the tubes to avoid potential phase separation that would occur if fluid is placed on the shellside. Preheaters are most often used for feed streams to distillation columns. A lower level of heat can be used in tower feed preheating rather than in reboilers. Also, tower loadings can be balanced by trading off between feed preheat and heat input to the reboiler.

WASTE HEAT BOILERS

Applications

Waste heat boilers (steam generators) are commonly used to recover heat from catalytic cracker regenerator flue gas, thermal reactor and condensers in a sulfur plant, reformer effluent, gas turbine exhaust, catalyst-oil slurries, and fixed bed reactors.

Types of Units

There are two types of units used for waste heat boilers (WHB): firetube or water tube. In firetube units (the more common type) the heating fluid passes through the tubes and steam is generated outside the tubes (shell side).

Firetube Units

Firetube units usually come as thermosiphon or kettle type waste heat boilers. Generally, kettles are provided for such services as hot product coolers (Resid, FCC Bottoms), or for Sulfur Condensers. Maximum heat flux normally does not exceed 35,000 Btu/hr ft² (110,000 W/m²) and maximum process inlet temperature is 800°F (430°C). Where the maximum heat flux is greater than 40,000 Btu/hr ft² (125,000 W/m²) and where the process inlet temperature is greater than 900°F (480°C), a thermosiphon type WHB is generally recommended. In a thermosiphon type WHB, steam is generated on the shellside of a tube bundle but the steam disengagement occurs in a separate shell, called the Steam Drum. Flow between the WHB and the Steam Drum is maintained by natural circulation because of the large density difference between the water "leg", i.e., the downcomer, and the steam "leg", i.e., the riser. The circulation rate for thermosiphon-type WHB, is generally between 15 to 20:1, depending on the severity of the process and the design maximum heat flux. Reliable designs for the WHB would take into account the possibility of vapor blanketing at the hot end, where the maximum heat flux is encountered. WHB having a high inlet process temperature, > 1000°F (535°C), are supplied with a protective refractory lining inside the inlet channel and on the tubesheet; metallic or ceramic ferrules are supplied at each tube end.

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Water Tube Units

Water tube units which generate steam inside the tubes are commonly used in flue gas exhaust from gas turbines, CO boilers, FCC units, etc., resulting in a low gas pressure drop. Water-tube WHB are normally built into three sections: a steam generator, a superheater and an economizer. For process streams with catalyst fines, i.e. FCC Gas Cooler, maximum gas velocity across the tube bank should not exceed 100 fps; a deresonating baffle is also furnished to prevent acoustic vibration; cleaning lanes are provided for steam lancing.

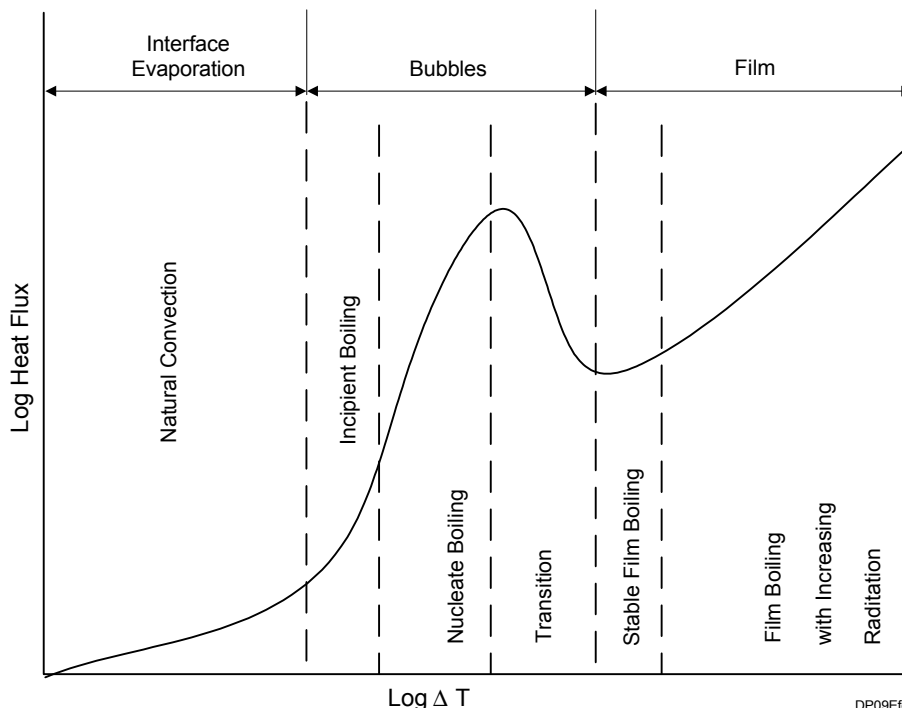
DESIGN CONSIDERATIONS

MAXIMUM AND DESIGN HEAT FLUX (FILM BOILING, VAPOR BLANKETING, CHOKE FLOW)

Pool Boiling

This type of boiling takes place when the heating surface is surrounded by a pool of liquid which is not flowing at any appreciable velocity. The main boiling mechanism is the formation of bubbles and is known as nucleation. Kettles and internal reboilers operate in pool boiling. The typical pool boiling curve, plotted as heat flux vs. the temperature driving force (ΔT), is shown in the figure below. As ΔT is increased heat transfer takes place by natural convection and eventually bubbles are formed at the tube wall and are carried away by convection and buoyancy. This is known as nucleate boiling. Liquid fills in the space vacated by the bubbles so that the tube wall always has liquid in contact with it. As ΔT is further increased (usually in the range of 40 - 90°F for pure hydrocarbons, 22 - 50°C) liquid can no longer exist in contact with the metal surface. Bubbles are formed faster than they can be removed and a vapor film blankets the tube surface. This is known as film boiling. The transition region between nucleate boiling and stable film boiling consists of unstable nucleate and unstable film boiling. This transition begins when the maximum heat flux possible in nucleate boiling, also called the critical heat flux, is reached. Because heat transfer coefficients are highest in the nucleate boiling region for practical values of ΔT , the film boiling region is avoided in design. To ensure operation in nucleate boiling the design heat flux should be limited to 70% of the calculated maximum flux. If the design ΔT is such that film boiling cannot be avoided then the heat flux should be kept above the minimum value required for stable film boiling.

TYPICAL POOL BOILING CURVE



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Flow Boiling

In flow boiling, two-phase fluid is forced over the heating surface. Vertical thermosiphons and pump-through reboilers operate in flow boiling. The same principles of boiling apply to pool and flow boiling. The major difference is that due to the two-phase flow, usually occurring in a restricted channel like a tube, hydrodynamic effects are more pronounced in flow boiling. The limitations on the hydrodynamic effects become even greater at low pressure. The maximum heat flux is limited not only by transition to film boiling but also by mist flow and potential flow instability.

Mist flow occurs when the shear force of the vapor at the vapor-liquid interface is sufficient to strip the liquid film from the wall, producing a dry wall condition. This can be prevented by keeping the exit vapor weight fraction (y_o) less than 0.5. When the pressure drop required for vaporization (acceleration loss) exceeds the available driving head, a backflow condition results that causes flow instability (also known as choke flow). The maximum heat flux under such condition is a function of the operating pressure and a geometry correction factor. The film boiling phenomenon is the same as in pool boiling except that the maximum heat flux may be lower. The calculation procedure for vertical tubeside boiling shows calculations for the mist flow limit (y_{mist}) and the maximum heat flux (q_{max}). For good operation keep $y_o \leq y_{mist}$ and $q \leq (0.6) q_{max}$.

VERY LOW TEMPERATURE DIFFERENCE

When process conditions or economics require the use of a very low ΔT (8°F, 4°C), the ability to produce bubbles may differ drastically for different surfaces. This makes design, performance prediction, and operation difficult. One possible solution is to use tube surfaces which enhance nucleate boiling. Special coatings and specially formed fins are commercially available as described in [Section IX-A](#).

In thermosiphons, a low temperature difference will suppress the pumping action and cause low circulation rates. For vertical tubeside thermosiphons, it is recommended to maintain a minimum heat flux of 2000 Btu/hr ft² (6000 W/m²) to provide good circulation. At lower flux levels it is preferable to use a kettle type exchanger.

VERY HIGH TEMPERATURE DIFFERENCE

A transition flow regime and mist flow condition can occur in reboilers operating at a high temperature difference, leading to local hot spots and thermal cycling; such operating conditions should be avoided. In the transition region, small shifts in operating conditions can cause large changes in performance. Also, this region has reverse control characteristics. That is, because of a mixture of nucleate and film boiling conditions an increase in ΔT may sometimes cause a decrease in the heat transfer. If the reboiler must be designed for film boiling it should be designed to operate in the stable region and not in the transition region.

FOULING

Design fouling factors have a major impact on the operation of reboilers, especially under clean start-up conditions. If a large fouling factor is used, the unit may be so oversurfaced at start-up that the required ΔT will be too small for proper operation. Also, if the design ΔT is applied at start-up it may cause excessively high heat fluxes resulting in film boiling and higher than normal tube wall temperatures, which may promote fouling.

Realistic fouling factors suggested by HTRI are shown in the table below (also refer to [Table 3, Section IX-B](#)). Fouling can be minimized by ensuring good flow distribution on the shell side. Some ways to prevent bad distribution are: use Double Split Flow (TEMA type H) design, avoid large bypass areas, avoid stagnant zones. For fluids with high fouling tendencies, keeping the vapor fraction below 0.2 also helps to minimize fouling.



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DESIGN CONSIDERATIONS (Cont)

SUGGESTED FOULING FACTOR RANGES

SERVICE	FOULING RESISTANCE, R_F	
	$\text{ft}^2 \text{ F hr/Btu}$	$\text{m}^2\text{K/W}$
Boiling Side C ₁ – C ₈ normal hydrocarbons Heavier normal hydrocarbons Diolefins and polymerizing hydrocarbons	0 - 0.0015	0 - 0.00026
	0.002 - 0.003	0.00036 - 0.0005
	0.003 - 0.005	0.0005 - 0.0009
Heating Side Condensing steam Condensing organics Sensible heating, organic liquids	0 - 0.0005	0 - 0.00009
	0.0005 - 0.001	0.00009 - 0.00018
	0.001 - 0.002	0.00018 - 0.00035

CALCULATION PROCEDURES

KETTLE AND INTERNAL REBOILERS

The calculation forms for heat transfer and hydraulic balance for kettle and internal reboilers are given in the Appendix. The heat transfer method is taken from the HTRI Design Manual.

Heat Transfer

The heat transfer procedure assumes a known geometry and calculates the nucleate and film boiling curves for clean and fouled conditions. To rate an existing exchanger, perform the calculation and estimate the required temperature driving force (ΔT) for a given heat duty, or if the ΔT is known, estimate the heat duty. A sample rating calculation is shown following the blank calculation forms. To size a kettle reboiler (design calculation) an iterative procedure is required, as outlined in the steps below. Reboilers should be designed for a heat flux less than 70% of the calculated maximum for nucleate boiling or greater than the calculated minimum for film boiling.

1. Estimate an overall heat transfer coefficient (U , Btu/hr ft^2 °F or W/m² K) from [Table 1, Section IX-B](#).
2. Calculate the required area (A , ft^2 or m^2)

$$A = Q_T / (U \Delta T)$$

where: Q_T is the total heat duty (Btu/hr or W)

ΔT is the difference between the average temperature of the heating medium and the exit vapor temperature (°F or °C)

3. Calculate the number of tubes (NTT) required to provide the area A

$$\text{NTT} = 12(A) / (\pi d_o L) \text{ or } \text{NTT} = 1000(A) / (\pi d_o L)$$

where: d_o is the tube outside diameter (in. or mm)

L is the tube length (ft or m)

4. Perform the calculations and construct a boiling curve.
5. Use the ΔT from step 2 to find an operating heat flux, q (Btu/hr ft^2 or W/m²), using the curve constructed in Step 4.
6. Calculate the required area (A_r)

$$A_r = Q_T / q (\text{ft}^2 \text{ or } \text{m}^2)$$

7. If A_r doesn't match A repeat steps 3-6 using A_r to calculate NTT.

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CALCULATION PROCEDURES (Cont)

Kettle Sizing

The calculation for kettle diameter sizing assumes a known maximum permissible entrainment ratio and calculates the maximum permissible velocity and the actual velocities. For design calculations the kettle size should be guessed and the calculation repeated until the calculated velocities are less than the maximum.

In addition to sizing the kettle diameter to ensure that liquid entrainment is maintained below the design criterion, splash baffles may be provided to prevent splashing of the liquid into the nozzle entrance area. Other methods, such as the "dry-pipe" are widely used in the industry to assure splashed water does not get the outlet nozzle and also achieve a vapor quality of 95%. Higher quality can be achieved by the use of demisters. The size and locations of the splash baffles are shown in **Figure A13**, along with other recommended dimensions for kettle designs. The area A_2 should be about 40% of the area S_h . The 18 in. minimum spacing in the shell should be from the top of the liquid level which is usually at the top of the weir. For high liquid flow rates, it is necessary to calculate a liquid crest height above the weir and size the area S_h above this crest level.

Hydraulic Balance

The hydraulic balance procedure calculates the elevation required for a given mass flow rate. The variable (or unknown) dimension is the height from the tower bottom tangent to the top of the shell. For existing piping, the calculated height should be checked against the actual. For new designs, if the calculated height is greater than desired, line sizes should be increased and a new value calculated.

VERTICAL THERMOSIPHON TUBESIDE REBOILERS

The calculation forms for heat transfer and hydraulic balance for vertical tubeside thermosiphon reboilers are given in the Appendix. The heat transfer method is taken from the HTRI Design Manual.

Heat Transfer

The heat transfer procedure calculates the area required for a given heat flux. To rate an existing exchanger, compare the calculated area to the actual area. A sample rating calculation is shown following the blank calculation forms. To size a new exchanger (design calculation) a geometry must be assumed and an iterative calculation done according to the steps below. Vertical thermosiphons should be designed such that the outlet vapor fraction is less than that required for mist flow and the heat flux is less than 70% of the calculated maximum for choke flow.

1. Estimate an overall heat transfer coefficient (U , Btu/hr ft² F or W/m² K) from **Table 1, Section IX-B**.
2. Calculate the heat flux (q) and the area (A)

$$q = U\Delta T \text{ (Btu/hr ft}^2 \text{ or W/m}^2\text{)}$$

$$A = Q_T / q \text{ (ft}^2 \text{ or m}^2\text{)}$$

where: Q_T is the total heat duty (Btu/hr or W)

ΔT is the temperature driving force (defined in the calculation)

3. Calculate the number of tubes (NTT) required to provide the area A

$$NTT = 12(A)/(\pi d_o L) \text{ or } NTT = 1000(A)/(\pi d_o L)$$

where: d_o is the tube outside diameter (in. or mm)

L is the tube length (ft or m)

4. Perform the calculations and find the actual overall heat transfer coefficient (U_o) and required area (A_r).
5. If A_r doesn't match A repeat steps 2-4 using U_o to calculate q .

Hydraulic Balance

The hydraulic balance procedure calculates the elevation required for a given mass flow rate. The variable (or unknown) dimension is the height from the tower bottom tangent to the bottom of the bundle. For existing piping, the calculated height should be checked against the actual. For new designs, if the calculated height is greater than desired, line sizes should be increased and a new value calculated.



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CALCULATION PROCEDURES (Cont)

HORIZONTAL THERMOSIPHON SHELLSIDE REBOILERS

Heat Transfer

The hand calculation method for heat transfer in horizontal shell side thermosiphon reboilers is the same as for kettle reboilers. Additional convective effects due to the flow are usually small but can be significant at high flow rates. These effects are neglected as a safety factor.

For horizontal thermosiphons the heat flux should be limited to 70% of the calculated maximum heat flux to ensure operation in nucleate boiling, and the weight fraction vaporized should be in the range of 0.1 to 0.5 to prevent slug flow at lower weight fractions and mist flow at higher weight fractions.

Hydraulic Balance

The form for hand calculation of the hydraulic balance for shellside reboilers is given in the Appendix. The procedure calculates the elevation required for a given mass flow rate. The variable (or unknown) dimension is the height from the tower bottom tangent to the bottom of the bundle. For existing piping, the calculated height should be checked against the actual. For new designs, if the calculated height is greater than desired, line sizes should be increased and a new value calculated.

PUMP-THROUGH REBOILERS

The calculation form for heat transfer calculations for tubeside pump-through reboilers is given in the Appendix. The method is the same as that for vertical tubeside thermosiphons except that the correction to the boiling coefficient due to the subcooled liquid zone is calculated differently.

WASTE HEAT BOILERS

The following procedure is based on steam generation using conventional tubes (no extended surface).

Exchanger Orientation - The units can be installed in either a vertical or horizontal position, and can have one or more tube passes. In general, one tube pass vertical units have been used most successfully in the past (in cat regenerator flue gas and fixed bed reactor service). However, in recent years, one tube pass horizontal units have been used with increasing frequency (e.g., reformer effluent waste heat boilers).

Shell Side or Tube Side Vaporization - Steam is normally generated in the shell (fired tube design) for the following reasons:

1. The hot fluid is frequently so fouling that it must be passed through the tubes.
2. With clean boiler water, it is permissible to use a non-removable tube bundle (fixed tube sheet unit) with triangular tube pitch. This type of construction results in a compact unit with a low initial cost.
3. There is less differential expansion between the tube and the shell.

Tube Selection

1. For installations that recover heat from cat regenerator flue gases or reformer effluent, the number of tubes is based on maintaining an inlet gas velocity of 100 ft/sec (31 m/s). For cat regenerator flue gases use 2-1/2 in. (63.5 mm) O.D., 5 BWG tubes. For reformer effluent, the minimum nominal tube size is 1-1/2 in. (50.8 mm) O.D., 10 BWG. The length of the tubes will vary for each installation, depending on the surface area required. If necessary, the tube length may be 25 ft (7.6 m) or more (see [Section IX-C](#)).
2. Fixed-bed reactors for exothermic processes are often constructed as shell-and-tube exchangers. In these units, the hydrocarbon passes through the tubes, which are filled with catalyst. Steam is generated on the shell side. For this service, use 2-1/2 in. (63.5 mm) O.D., 5 BWG tubes. The number and length of tubes will vary for each installation, depending on process requirements as well as on heat transfer requirements. Steam generator-reactors for polymerization plants have been designed with 4 ft (1.2 m) I.D. shells, and 180 (9.1 m) thirty-foot-long tubes.



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CALCULATION PROCEDURES (Cont)

Water Circulation Rate - To eliminate the possibility of dry tubes, design for a water/steam weight ratio of approximately 15/1 for a heat density of 40,000 Btu/hr ft² (125,000 W/m²). A Baton Rouge design with extended surface tubes requires a 40/1 circulation rate to ensure a wetted wall condition at a heat density of 100,000 Btu/hr ft² (315,000 W/m²). (Note that a wetted wall condition is dependent upon other variables, such as: temperature difference, geometry, orientation, etc., in addition to the circulation rate). Proprietary designs that assure wet-wall conditions at the hot tubesheet for severe services of high temperature and high steam pressure are available from vendors such as Borsig and Schmidchte. Transfer line exchangers (TLE), which fall in this category, and are designed for very high heat flux, > 80,000 Btu/hr ft² (250,000 W/m²), are usually specified as double pipes.

Elevation of Steam Disengaging Drum - It is necessary to calculate a detailed pressure balance through the water-steam circuit to determine the elevation of the steam drum above the generator. See the applicable (horizontal or vertical thermosiphon) hydraulic balance calculation form.

Steam Generation on Shell Side

- Tube Side Design** - Follow the calculation procedure outlined for no change of phase, [Section IX-D](#), or for condensation, [Section IX-F](#), assuming an overall coefficient, area, etc.
- Shell Side Design**
 - Shell Side Pressure Drop** - Calculate the shell side pressure drop using the procedure for reboilers.
 - Shell Side Heat Transfer Coefficient, h_o** - (See Equation 1.)

$$\frac{1}{R_o} = h_o = 80 \left(\frac{Q}{1000 A_s} \right)^{\frac{2}{3}} P^{\frac{1}{3}} \quad \text{(Customary)} \quad \text{Eq. (1)}$$

OR

$$= 353.2 \left(\frac{Q}{5680 A_s} \right)^{\frac{2}{3}} P^{\frac{1}{3}} \quad \text{(Metric)}$$

where: R_o = Outside film resistance to heat transfer corrected to outside area $\left[\frac{\text{hr ft}^2 \text{ } ^\circ\text{F}}{\text{Btu}} \text{ or } \frac{\text{m}^2 \text{ K}}{\text{W}} \right]$

h_o = Outside film coefficient $\left[\frac{\text{Btu}}{\text{hr ft}^2 \text{ } ^\circ\text{F}} \text{ or } \frac{\text{W}}{\text{m}^2 \text{ K}} \right]$

Q = Total rate of heat transfer, [Btu/hr or W]

P = Average pressure in boiler, [psia or kPa abs]

Steam Generation on Tube Side

- Tube Side Design**
 - Tube Side Pressure Drop** - Calculate the tube side pressure drop using the procedure for reboilers.
 - Tube Side Heat Transfer Coefficient, h_{io}**

$$h_{io} = \frac{1}{R_{io}} = 1000 \left[\frac{\text{Btu}}{\text{hr ft}^2 \text{ } ^\circ\text{F}} \right]$$

OR

$$= 5680 \left[\frac{\text{W}}{\text{m}^2 \text{ K}} \right]$$

- Shell Side Design** - Follow the calculation procedure outlined for no change of phase, [Section IX-D](#), or for condensation, [Section IX-F](#), assuming an overall coefficient, area, etc.

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CALCULATION PROCEDURES (Cont)

Overall Heat Transfer Rate

1. Calculate U_o , the overall heat transfer coefficient:

$$\frac{1}{U_o} = R_t = R_{io} + r_{io} + r_w + r_o + R_o \quad \text{Eq. (2)}$$

where: U_o = Overall coefficient of heat transfer, [Btu/hr ft² °F or W/m² K]

R_t = Total resistance (duty) to heat transfer, $\left[\frac{\text{hr ft}^2 \text{ °F}}{\text{Btu}} \text{ or } \frac{\text{m}^2 \text{ K}}{\text{W}} \right]$

R_{io} = Inside film resistance to heat transfer corrected to outside area, $\left[\frac{\text{hr ft}^2 \text{ °F}}{\text{Btu}} \text{ or } \frac{\text{m}^2 \text{ K}}{\text{W}} \right]$

r_{io} = Inside fouling factor referred to the outside surface area, + $\left[\frac{\text{hr ft}^2 \text{ °F}}{\text{Btu}} \text{ or } \frac{\text{m}^2 \text{ K}}{\text{W}} \right]$

r_w = Resistance of tube wall metal at average wall temperature, $\left[\frac{\text{hr ft}^2 \text{ °F}}{\text{Btu}} \text{ or } \frac{\text{m}^2 \text{ K}}{\text{W}} \right]$

r_o = Outside fouling factor, $\left[\frac{\text{hr ft}^2 \text{ °F}}{\text{Btu}} \text{ or } \frac{\text{m}^2 \text{ K}}{\text{W}} \right]$

R_o = Outside film resistance to heat transfer based on outside area, $\left[\frac{\text{hr ft}^2 \text{ °F}}{\text{Btu}} \text{ or } \frac{\text{m}^2 \text{ K}}{\text{W}} \right]$

2. If U_o (calculated) does not agree with U_o (assumed), repeat the calculations with a new U_o (assumed) until agreement is reached.
3. In all cases the designer should satisfy himself that a reasonably good economic balance has been obtained between pressure drop and transfer surface area (see [Section IX-C](#)).
4. Determine the mechanical design features as outlined in [Sections IX-C and IX-D](#).



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NOMENCLATURE

A	Heat transfer surface area, [ft ² , m ²]
AOI	Ratio of outside to inside surface area
A _r	Required heat transfer surface area, [ft ² , m ²]
BR	Boiling range, [°F, °C]
CB	Bundle correction factor
C _{pb}	Heat capacity of bottoms drawoff, [Btu/lb °F, kJ/kg K]
C _{pℓ}	Liquid heat capacity, [Btu/lb °F, kJ/kg K]
DR	Effective temperature range, [°F, °C]
D _b	Bundle diameter, [in., mm]
D _s	Shell diameter, [in., mm]
d _i	Tube inside diameter, [in., mm]
d _o	Tube outside diameter, [in., mm]
dT/dP	Slope of vapor pressure curve, [°F/psi, °C/kPa]
d ₁	Inlet line inside diameter, [in., mm]
d ₂	Outlet line inside diameter, [in., mm]
E	Entrainment ratio, [lb liquid/lb vapor, kg liquid/kg vapor]
F _b	Bundle convection correction factor
F _c	Boiling range (mixture) correction factor
F _d	Sensible heating correction factor
F _f	Fin tube correction factor
F _p	Pressure correction factor for nucleate boiling
F _{tz}	Subcooled liquid zone correction for intube boiling
f ₂	Two-phase friction factor
f _ℓ	Liquid friction factor
f _v	Vapor friction factor
H _W	Weir height, [in., mm]
ΔH	Head losses as defined in calculation forms, [ft, m]
ΔH _F	Sum of fixed head losses in hydraulic balance calculations, [ft, m]
h ₁	Single tube nucleate boiling coefficient, [Btu/hr ft ² °F, W/m ² K]
h _{1r}	Single tube boiling reference coefficient, [Btu/hr ft ² °F, W/m ² K]
h _{ab}	Average boiling heat transfer coefficient, [Btu/hr ft ² °F, W/m ² K]
h _n	Heating medium heat transfer coefficient, [Btu/hr ft ² °F, W/m ² K]
h _ℓ	Liquid phase heat transfer coefficient, [Btu/hr ft ² °F, W/m ² K]
h _{nb}	Intube nucleate boiling coefficient, [Btu/hr ft ² °F, W/m ² K]
h _{nc}	Natural convection heat transfer coefficient, [Btu/hr ft ² °F, W/m ² K]
h _{tp}	Convective boiling heat transfer coefficient, [Btu/hr ft ² °F, W/m ² K]



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NOMENCLATURE (Cont)

J	Friction head loss in unknown elevation X, [ft, m]
J'	Head gain in fixed lengths, [ft, m]
K _i	Total inlet piping resistance coefficient
K _o	Total outlet piping resistance coefficient
k _ℓ	Liquid thermal conductivity, [Btu/hr ft °F, W/m K]
k _w	Tube wall thermal conductivity, [Btu/hr ft °F, W/m K]
L	Tube length, [ft, m]
L _c	Chord length above weir, [in., mm]
NN	Number of exit nozzles
NTT	Number of tube holes in tubesheet
P	Pressure, [psi, kPa]
P _c	Critical pressure, [psi, kPa]
P _ℓ	Inlet liquid pressure drop per 100 ft (per 1 m) of line, [psi, kPa]
P _r	Reduced pressure
P _v	Outlet vapor pressure drop per 100 ft (per 1 m) of line, [psi, kPa]
Pr	Prandtl Number, dimensionless
PR	Tube pitch ratio
ΔP _h	Static pressure head [psi, kPa]
ΔP ₁	Inlet line head loss per foot (per m) of line, [ft, m]
ΔP ₂	Outlet line head loss per foot (per m) of line, [ft, m]
Q _s	Sensible heat duty [Btu/hr, W]
Q _T	Total heat duty [Btu/hr, W]
Q _v	Volume flow rate, [gpm, dm ³ /s]
q	Heat flux, [Btu/hr ft ² , W/m ²]
q ₁	First reference heat flux, [Btu/hr ft ² , W/m ²]
q ₂	Second reference heat flux, [Btu/hr ft ² , W/m ²]
q _{max}	Maximum allowable heat flux, [Btu/hr ft ² , W/m ²]
q _{maxr}	Choke flow reference maximum heat flux, [Btu/hr ft ² , W/m ²]
q _{1max}	Single tube maximum allowable heat flux, [Btu/hr ft ² , W/m ²]
q _{bmax}	Bundle maximum allowable heat flux, [Btu/hr ft ² , W/m ²]
q _{bmin}	Minimum film boiling heat flux, [Btu/hr ft ² , W/m ²]
q _n	Effective minimum heat flux for nucleate boiling, [Btu/hr ft ² , W/m ²]
Re _ℓ	Liquid Reynolds number
Re _v	Vapor Reynolds number
r _{fi}	Inside fouling resistance, [hr ft ² °F/Btu, m ² K/W]
r _{fo}	Outside fouling resistance, [hr ft ² °F/Btu, m ² K/W]
r _w	Tube wall resistance, [hr ft ² °F/Btu, m ² K/W]
S _h	Horizontal velocity area, [ft ² , m ²]
S _v	Vertical velocity area, [ft ² , m ²]
S1-S3,	
S4, S6	Distances as defined in calculation forms, [ft, m]
S2	Equivalent length of inlet fittings, [ft, m]
S5	Equivalent length of outlet fittings, [ft, m]
T _{bi}	Boiling side inlet temperature [°F, °C]
T _{bo}	Boiling side outlet temperature [°F, °C]



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NOMENCLATURE (Cont)

T_{bs}	Boiling side saturation temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
T_d	Bottoms drawoff temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
T_f	Feed temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
T_{hi}	Heating medium inlet temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
T_{ho}	Heating medium outlet temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
T_{hs}	Heating medium saturation temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
T_h	Average heating medium temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
T_s	Bubble point temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
T_v	Exit vapor temperature [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
ΔT	Temperature driving force, [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
ΔT_a	Available temperature driving force, [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
ΔT_c	Clean required nucleate boiling temperature driving force, [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
ΔT_f	Fouled required nucleate boiling temperature driving force, [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
ΔT_{fc}	Clean required film boiling temperature driving force, [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
ΔT_{ff}	Fouled required film boiling temperature driving force, [$^{\circ}\text{F}$, $^{\circ}\text{C}$]
U	Overall heat transfer coefficient [Btu/hr ft ² $^{\circ}\text{F}$, W/m ² K]
U_c	Clean overall heat transfer coefficient [Btu/hr ft ² $^{\circ}\text{F}$, W/m ² K]
U_f	Fouled overall heat transfer coefficient [Btu/hr ft ² $^{\circ}\text{F}$, W/m ² K]
U_o	Actual overall heat transfer coefficient [Btu/hr ft ² $^{\circ}\text{F}$, W/m ² K]
V_e	Effective velocity for entrainment, [ft/s, m/s]
V_h	Horizontal velocity for entrainment, [ft/s, m/s]
V_i	Liquid inlet velocity, [ft/s, m/s]
V_{max}	Maximum velocity for entrainment, [ft/s, m/s]
V_v	Vertical velocity for entrainment, or vapor velocity, [ft/s, m/s]
W_B	Bottoms drawoff flowrate [lb/hr, kg/hr or kg/s]
W_T	Total flowrate [lb/hr, kg/hr or kg/s]
W_V	Vapor flowrate [lb/hr, kg/hr or kg/s]
X	Unknown elevation in hydraulic balance calculations, [ft, m]
X_{tt}	Martinelli parameter for two-phase flow
x_r	Vapor to liquid density ratio
y	Weight fraction vapor
y_a	Average weight fraction vapor
y_o	Weight fraction vapor at outlet
y_{mist}	Weight fraction vapor limit for mist flow
Λ	Correction to q_{maxr}
ρ_{ℓ}	Liquid density, [lb/ft ³ , kg/m ³]
ρ_v	Vapor density, [lb/ft ³ , kg/m ³]
ρ_x	Average two-phase mixture density, [lb/ft ³ , kg/m ³]
μ_{ℓ}	Liquid viscosity, [lb/ft hr, kg/m-s]
μ_v	Vapor viscosity, [lb/ft hr, kg/m-s]
σ	Surface tension, [dynes/cm]
θ	Chord angle
λ	Latent heat, [Btu/lb, kJ/kg]



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TABLE 1
OPERATIONAL CHARACTERISTICS FOR VERTICAL THERMOSIPHON REBOILERS

CATEGORY (Examples are Given in Parentheses)	CHARACTERISTICS				
	Heat Transfer Coefficients	Circulation Rate	Maximum Heat Flux Limit	Mean Temperature Difference	Fouling
1. Narrow boiling range saturated hydrocarbons, moderate pressure (C ₅ -C ₇ , 100 psia)	Fairly high	High	High, usually limited by film boiling	No problems	Low
2. Narrow boiling range, aqueous solution of organics (alcohols and water)	High	High	High	Usually non-ideal VLE. Should be carefully calculated	Usually very low
3. Vacuum reboilers with heavy hydrocarbons (mixed xylenes, 1 psia)	Low. Long non-boiling zone. Suppressed nucleation	Low. High friction, momentum and liquid zone static heat losses	Low. Instability or mist flow limitation	Nonlinear. Maximum bulk temp. at top of liquid zone	May be high if mist flow is permitted
4. Very high pressure (near critical). Light hydrocarbon	Very high. Nucleate low due to boiling controlled. Low if in film boiling, but more predictable.	Low due to decreased net driving head. High vapor density.	Low. Film boiling limit	Boiling temp. profile may be difficult to predict because of uncertainty in VLE data	Usually low
5. Wide boiling range mixtures, low to moderate viscosity (pentane-octane, or water glycol)	Fairly low. Nucleate boiling suppressed. Convection controlled.	Can be high with good design	Can be fairly high	Function of circulation rate. Exit temp. increases with vapor fraction	Moderate
6. Very wide boiling range, high viscosity (pentane and 1400 MW butylene polymer oil) BR > 400°F, viscosity > 50 cP	Very low, < 50 Btu/hr ft ² °F (< 280 w/m ² °C. Nucleate boiling suppressed. Poor radial mixing	Very low	Low. Early film boiling due to hindered vapor release	Nonequilibrium effects. Difficult to calculate	Can be high (high wall temperature)
7. Sparged reboilers (steam injected rerun column reboiler)	Can be high, but may have mass transfer limitations at too high sparge rate	Greatly increased by sparging	Mist flow limitation at too high sparge rate	Boiling temp. a function of partial pressure of sparge gas	Lower wall temp. can decrease fouling
8. Total vaporization (LNG revaporizer) (special cases only). Not recommended for general design.	Part of tube in mist flow with low coefficient.	Forced flow	Top of tube above mist flow limit	Nonlinear, superheating above mist flow boundary	Suitable only for non-fouling fluids
9. Polymerizing (unsaturated hydrocarbons (butene-butadiene mixture)	High	High	High	Limit wall temp.	Can be very rapid above certain wall temp. and certain vapor fraction
10. Aqueous solutions of inorganic salts (aluminum sulfate solution)	High, similar to water. Solids do not impede boiling process except at very high solids concentration	High	High	Similar to water except at very high solids concentration	Inverse solubility salts deposits on surface similarly to case of single phase flow. Regular solubility salts may deposit at high vapor fraction
11. Heavy hydrocarbon mixture with heavy fouling (solvent cleanup column bottoms)	Fairly low	Can be low. Should be made as high as possible.	Fairly high. But, due to very high design fouling factor, startup with full steam pressure can cause film boiling.	May be a function of circulation rate.	Fouling factor usually > 0.005 hr ft ² °F/Btu. Sedimentation, polymerization coking. Sensitive to temp., velocity, and trace elements
12. Low temp. boiler-condensers (boiling ethylene-condensing propylene)	Moderately high. Boiling side sensitive to surface characteristics due to low T. Condensing side resistance also significant.	Can be high	High	Very low producing low design heat flux	Very low except for the effects of compressor lubricants
13. Refrigerants (R11, R22, R113)	Fairly high	Generally high but may be lower than hydrocarbons due to higher vapor density	High	No problems if good vapor pressure data are used	Very low except for the effects of compressor lubricants
14. Cryogenics (boiling O ₂ with condensing N ₂)	May be about the same as light hydrocarbons	Expected to be high	T's may be high so watch for film boiling	Adjust for design either in complete nucleate or complete film boiling, not partial film boiling	Very low
15. Waste heat boiler (steam from hot gas)	Very high for boiling side. Heating medium resistance is controlling.	High for good design	Carefully check for mist flow and film boiling as T may be very high	Use concurrent flow to provide maximum T at bottom of tube	Usually low



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TABLE 2
DESIGN SUGGESTIONS FOR VERTICAL THERMOSIPHON REBOILERS

CATEGORY (Examples are Given in Parentheses)	RECOMMENDATIONS (SUGGESTED RANGES AND COMMENTS)			
	Tube Diameter	Tube Length	Static Head	General Comments
1. Narrow boiling range saturated hydrocarbons, moderate pressure (C ₅ -C ₇ , 100 psia)	3/4 - 1 in. (19.1 - 25.4 mm)	Up to 20 ft (6.1 m) if exit weight fraction vapor < 0.35	Equal to tube length.	Few problems and generally good operation
2. Narrow boiling range, aqueous solution of organics (alcohols and water)	3/4 - 1 in. (19.1 - 25.4 mm)	Up to 20 ft (6.1 m) if exit weight fraction vapor < 0.35	Equal to tube length.	High heat transfer coefficients cause design to be sensitive to fouling factor. Feed in boiling temperature profile available.
3. Vacuum reboilers with heavy hydrocarbons (mixed xylenes, 1 psia)	1-1/4 - 1-3/4 in. (31.8 - 44.5 mm)	Usually 12 ft (3.65 m) or less	Less than tube length. Optimum exists	Limit exit vapor weight fraction to less than 0.5. Check for instability. Increase inlet resistance if unstable.
4. Very high pressure (near critical). Light hydrocarbon	1 - 1-1/4 in. (25.4 - 31.8 mm)	Usually 12 ft (3.65 m) or less	As large as possible	Low confidence in physical properties. Operation is sensitive to pressure level. Some safety factor is required. May be better to design for film boiling in critical cases.
5. Wide boiling range mixtures, low to moderate viscosity (pentane-octane, or water glycol)	1 - 1-1/2 in. (25.4 - 38.1 mm). Large enough to allow high circulation rate	Short enough to allow high circulation with tube diameter used	As large as possible	Design for low exit vapor weight fraction (0.1 to 0.25). This increases h, MTD, and confidence in prediction. Always specify boiling range.
6. Very wide boiling range, high viscosity (pentane and 1400 MW butylene polymer oil) BR > 400°F, viscosity > 50 cP	1-3/4 - 2 in. (44.5 - 50.8 mm)	Short	As large as possible. Forced circulation or sparging may be necessary	Thermosiphon reboilers do not operate effectively for these extreme conditions. Consider also shellside horizontal thermosiphons (possibly better mixing) or falling film evaporators.
7. Sparged reboilers (steam injected rerun column reboiler)	1 - 1-1/4 in. (25.4 - 31.8 mm)	Usually 12 ft (3.65 m) or less	Equal to tube length.	Evaluate downstream handling problems. Carefully calculate bulk temperature profile.
8. Total vaporization (LNG revaporizer) (special cases only). Not recommended for general design.	3/4 - 1 in. (19.1 - 25.4 mm)	Length above mist flow boundary is very ineffective	Forced flow only	Use valve in inlet line to damp out instability and regulate location of mist flow boundary. Specify some excess capacity.
9. Polymerizing (unsaturated hydrocarbons (butene-butadiene mixture)	1 - 1-1/4 in. (25.4 - 31.8 mm)	8 ft (2.4 m) or more. Limited by recommended exit vapor fraction	Equal to tube length.	Limit wall temperature and exit vapor fraction below rapid polymerization threshold
10. Aqueous solutions of inorganic salts (aluminum sulfate solution)	1 - 1-1/4 in. (25.4 - 31.8 mm)	Can be long if exit vapor fraction not above 0.1	Equal to tube length.	Design to low vapor fraction. Limit tube wall temperature for inverse solubility.
11. Heavy hydrocarbon mixture with heavy fouling (solvent cleanup column bottoms)	1-1/4 - 2 in. (31.8 - 50.8 mm)	12 ft (3.65 m) or less	May need forced flow for extreme cases	Design for as high velocity as possible with low vapor fraction and low wall temperature. Provide spare reboiler in critical cases with low P valves to isolate unit for cleaning.
12. Low temp. boiler-condensers (boiling ethylene-condensing propylene)	3/4 - 1-1/4 in. (19.1 - 31.8 mm)	Can be long if exit vapor fraction is less than 0.35	Equal to tube length.	Evaluate as a condenser also on CST Program. Feed in nucleate boiling curve if available. Consider enhanced surface for both boiling and condensing sides.
13. Refrigerants (R11, R22, R113)	3/4 - 1-1/4 in. (19.1 - 31.8 mm)	Can be long if exit vapor fraction is less than 0.35	Equal to tube length.	Be specific with properties. Operation near critical pressure is very uncertain due to limited data.
14. Cryogenics (boiling O ₂ with condensing N ₂)	3/4 - 1 in. (19.1 - 25.4 mm)	Can be long if exit vapor fraction is less than 0.35	Equal to tube length.	Little field experience available in applying process reboiler methods to cryogenics. Feed in nucleate boiling curve if available. Check against field experience where possible.
15. Waste heat boiler (steam from hot gas)	1 - 1-1/4 in. (25.4 - 31.8 mm)	Can be long if exit vapor fraction is low	Can be large if subcooled liquid zone is not greater than 1/4 of the tube length	Design for around 10 weight percent vapor. Check instability. Provide additional inlet piping resistance if necessary. Watch for mist flow and for film boiling at high T end. If boiling is shellside, use strip baffles. Design for even flow distribution and eliminate vapor accumulation regions.

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APPENDIX A
HEAT TRANSFER CALCULATION FORM FOR KETTLE AND INTERNAL REBOILERS

Exchanger No. E - Plant Done by
Service Date

Customary

Metric

A. BOILING SIDE SPECIFICATIONS

- | | | |
|--|-----------------------------------|-----------------------------------|
| 1. Pressure, P | <u> </u> psia | <u> </u> kPa |
| 2. Exit Vapor Temperature, T_v | <u> </u> °F | <u> </u> °C |
| 3. Feed Temperature, T_f | <u> </u> °F | <u> </u> °C |
| 4. Bottoms Drawoff Temperature, T_d | <u> </u> °F | <u> </u> °C |
| 5. Bottoms Drawoff Flowrate, WB | <u> </u> lb/hr | <u> </u> kg/hr |
| 6. Average Heating Medium Temperature, T_h | <u> </u> °F | <u> </u> °C |
| 7. Available Temperature Driving Force, $\Delta T_a = T_h - T_v$ | <u> </u> °F | <u> </u> °C |

B. BOILING FLUID PROPERTIES

- | | | |
|---|--|---|
| 1. Boiling Range, BR | <u> </u> °F | <u> </u> °C |
| 2. Bubble Point, T_s | <u> </u> °F | <u> </u> °C |
| 3. Critical Pressure, P_c | <u> </u> psia | <u> </u> kPa |
| 4. Heat Capacity of Bottoms Drawoff, C_{pb} | <u> </u> Btu/lb-°F | <u> </u> kJ/kg-K |
| 5. Reduced Pressure, (P / P_c) | <u> </u> | <u> </u> |
| 6. Average Vapor Density, ρ_v | <u> </u> lb/ft ³ | <u> </u> kg/m ³ |
| 7. Average Liquid Density, ρ_ℓ | <u> </u> lb/ft ³ | <u> </u> kg/m ³ |
| 8. Average Latent Heat, λ | <u> </u> Btu/lb | <u> </u> kJ/kg |
| 9. Liquid Surface Tension, σ
At exit Temperature
[Required for kettle sizing only] | <u> </u> dynes/cm | <u> </u> dynes/cm |



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HEAT TRANSFER CALCULATION FORM FOR KETTLE AND INTERNAL REBOILERS (Cont)

C. EXCHANGER GEOMETRY

- Number of Tube Holes in Tubesheet, NTT

- Bundle Length, L
_____ ft _____ m
- Tube Inside Diameter, d_i
_____ in. _____ mm
- Ratio of Outside to Inside Surface Area, AOI

- Tube Pitch Ratio, PR

- Number of Vapor Exit Nozzles, NN

- Tube Wall Thermal Conductivity, k_w
_____ Btu/hr-ft-°F _____ W/m-K

D. FOULING RESISTANCES

- Tubeside, r_{fi}
_____ hr-ft²-°F/Btu _____ m²-K/W
- Shellside, r_{fo}
_____ hr-ft²-°F/Btu _____ m²-K/W

E. NUCLEATE BOILING CALCULATIONS

- Single Tube Maximum Heat Flux, q_{1max} , **Figure A3**
_____ Btu/hr-ft² _____ W/m²
- Bundle Correction Factor, CB, **Figure A4**

- Bundle Maximum Heat Flux, $q_{bmax} = CB (q_{1max})$
_____ Btu/hr-ft² _____ W/m²
- Reference Heat Fluxes. Use two to construct a plot.

$q_1 = 0.1(q_{bmax})$ _____ Btu/hr-ft² _____ W/m²
 $q_2 = 0.6(q_{bmax})$ _____ Btu/hr-ft² _____ W/m²
- Single Tube Nucleate boiling Reference Coefficient h_{1r} , **Figure A5**

At q_1 , h_{1r1} _____ Btu/hr-ft²-°F _____ W/m²-K
 At q_2 , h_{1r2} _____ Btu/hr-ft²-°F _____ W/m²-K



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HEAT TRANSFER CALCULATION FORM FOR KETTLE AND INTERNAL REBOILERS (Cont)

6. Pressure Correction, F_p ,

Figure A6

7. Mixture Correction, F_c

- 7.1 Effective Minimum Heat Flux for Nucleate Boiling, q_n

$24858 / (BR)^{0.8}$
(if > 1000, use 1000)

$78365 / (BR)^{0.8}$
(if > 3150, use 3150)

_____ Btu/hr-ft² _____ W/m²

- 7.2 (q/q_n) , for **Figure A8**

At q_1

At q_2

- 7.3 Density Ratio, $x_r = (\rho_v / \rho_\ell)$, Limit $x_r \leq 0.2$

- 7.4 Effective Temperature Range, DR, **Figure A7**

_____ °F _____ °C

- 7.5 (BR / DR)

- 7.6 F_c , **Figure A8**

At q_1 , F_{c1}

At q_2 , F_{c2}

8. Single Tube Boiling Coefficients, $h_1 = (h_{1r})(F_p)(F_c)^{0.67}$

At q_1 , h_{11} _____ Btu/hr-ft²-°F _____ W/m²-K

At q_2 , h_{12} _____ Btu/hr-ft²-°F _____ W/m²-K

9. Bundle Convection Correction, F_b ,

Figure A9

10. Sensible Heating Correction, F_d

- 10.1 Sensible Heat Duty, Q_s

$(WB)(C_{pb})(T_d - T_f)$

$(WB)(C_{pb})(T_d - T_f) / 3.6$

_____ Btu/hr _____ W



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HEAT TRANSFER CALCULATION FORM FOR KETTLE AND INTERNAL REBOILERS (Cont)

10.2 Bundle Surface Area, A

$$0.262(d_i)(AOI)(L)(NTT)$$

$$0.00314(d_i)(AOI)(L)(NTT)$$

$$\text{_____ ft}^2$$

$$\text{_____ m}^2$$

10.3 Sensible Heating Correction, $F_d = (1 - Q_s / (q A))^{1/3}$ [If ≤ 0 , return to step E4, change q_1 to $0.2(q_{bmax})$ and repeat]

At $q = q_1$,

At $q = q_2$,

11. Finned Tube Correction, $F_f = (F_e)(F_s)$, **Figures A10 or A11, and A12**. Use 1.0 for Plain Tubes

12. Average Bundle Boiling Coefficients (Including 0.75 Safety Factor)

$$h_{ab} = (h_1)(F_b)(F_d)(F_f)(0.75)$$

At q_1 , h_{ab1}

_____ Btu/hr-ft²-°F

_____ W/m²-K

At q_2 , h_{ab2}

_____ Btu/hr-ft²-°F

_____ W/m²-K

13. Wall Resistance, r_w , Plain or Finned Tubes

Carbon Steel

_____ 0.0004 hr-ft²-°F/Btu

_____ 0.00007 m²-K/W

Other

_____ 0.0004 (28/ k_w)

_____ 0.00007 (48/ k_w)

_____ hr-ft²-°F/Btu

_____ m²-K/W

14. Tubeside Heat Transfer Coefficient, h_h

14.1 For Steam

$$2000 + 0.033[(q)(L)]^{0.8}$$

$$11357 + 0.193[(q)(L)]^{0.8}$$

At q_1

_____ Btu/hr-ft²-°F

_____ W/m²-K

At q_2

_____ Btu/hr-ft²-°F

_____ W/m²-K

14.2 Other than Steam, **Section IX-F**

At q_1

_____ Btu/hr-ft²-°F

_____ W/m²-K

At q_2

_____ Btu/hr-ft²-°F

_____ W/m²-K



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HEAT TRANSFER CALCULATION FORM FOR KETTLE AND INTERNAL REBOILERS (Cont)

15. Overall Heat Transfer Coefficients

15.1 Clean

$$U_c = \frac{1}{\frac{1}{h_{ab}} + \frac{AOI}{h_h} + R_w}$$

At q_1 $U_{c1} =$ _____ Btu/hr-ft²-°F _____ W/m²-K

At q_2 $U_{c2} =$ _____ Btu/hr-ft²-°F _____ W/m²-K

15.2 Fouled

$$U_f = \frac{1}{\frac{1}{U_c} + (AOI)(r_{fi}) + (r_{fo})}$$

At q_1 $U_{f1} =$ _____ Btu/hr-ft²-°F _____ W/m²-K

At q_2 $U_{f2} =$ _____ Btu/hr-ft²-°F _____ W/m²-K

F. OVERALL ΔT CALCULATION FOR NUCLEATE BOILING

ΔT is the difference between the average heating medium (or condensing) temperature and the exit vapor temperature.

1. Clean

$$\Delta T_c = q / U_c$$

At $q = q_1$ $\Delta T_{c1} =$ _____ °F _____ °C

At $q = q_2$ $\Delta T_{c2} =$ _____ °F _____ °C

2. Fouled

$$\Delta T_f = q / U_f$$

At $q = q_1$ $\Delta T_{f1} =$ _____ °F _____ °C

At $q = q_2$ $\Delta T_{f2} =$ _____ °F _____ °C

G. OVERALL ΔT CALCULATION FOR FILM BOILING

[Calculations may be skipped if ΔT_a is in the nucleate boiling region]

1. Minimum Film Boiling Heat Flux, q_{bmin2}

$q_{bmin} = (q_{1max})(0.12)$ _____ Btu/hr-ft² _____ W/m²

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2. Film Boiling Heat Transfer Coefficients, h_{fb}

At q_{bmin} , h_{fb1}	$50 (P_c)^{0.25} (P/P_c)^{0.43}$	$176 (P_c)^{0.25} (P/P_c)^{0.43}$
	_____ Btu/hr-ft ² -°F	_____ W/m ² -K
At $(2)(q_{bmin})$, $h_{fb2} = 0.71(h_{fb1})$	_____ Btu/hr-ft ² -°F	_____ W/m ² -K

3. Clean ΔT (with the approximation $U = h_{fb}$)

$\Delta T_{fc1} = q_{bmin} / h_{fb1}$	_____ °F	_____ °C
$\Delta T_{fc2} = (2)(q_{bmin}) / h_{fb2}$	_____ °F	_____ °C

4. Fouled ΔT

$\Delta T_{ff1} = \Delta T_{fc1} + q_{bmin} [(AOI) (r_{fi}) + r_{fo}]$	_____ °F	_____ °C
$\Delta T_{ff2} = \Delta T_{fc2} + 2 (\Delta T_{ff1} - \Delta T_{fc1})$	_____ °F	_____ °C

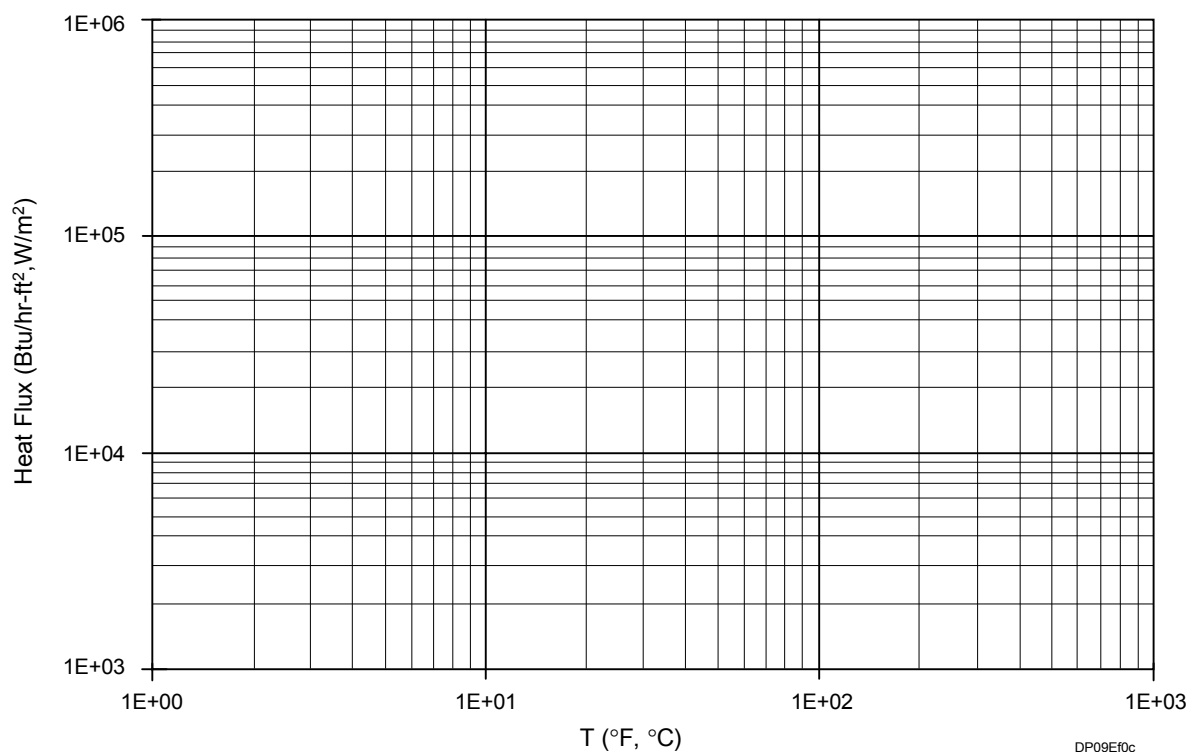


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HEAT TRANSFER CALCULATION FORM FOR KETTLE AND INTERNAL REBOILERS (Cont)

H. CONSTRUCT PLOT

- Plot heat flux vs. overall ΔT on a log-log graph for each of the four ΔT s in items F and G.



I. CALCULATE HEAT DUTY AND VAPOR FLOW

- Heat Flux, q_a , at ΔT_a _____ Btu/hr-ft² _____ W/m²
- Total Heat Duty, $Q_T = (q_a)(A)$ _____ Btu/hr _____ W
- Vaporizing Duty $Q_V = Q_T - Q_s$ _____ Btu/hr _____ W
- Vapor Flow, W_V

Q_V / λ
 _____ lb/hr

$Q_V / \lambda / 1000$
 _____ kg/s

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HEAT TRANSFER CALCULATION FORM FOR KETTLE AND INTERNAL REBOILERS (Cont)

J. KETTLE SIZE CALCULATION

[See **Figure A13**]

1. Maximum Permissible Entrainment Ratio, E , (lb (kg) liquid/lb (kg) vapor)

2. Entrainment Coefficient, $K = J_2 (E)^{0.33} (\sigma / (\rho_\ell - \rho_v))^{0.25}$

$J_2 = 0.916$

$J_2 = 0.558$

_____ ft/s

_____ m/s

3. Maximum Velocity, $V_{\max} = K(\rho_\ell / \rho_v - 1)^{0.5}$

_____ ft/s

_____ m/s

4. Bundle Diameter, D_b ,

_____ in.

_____ mm

5. Kettle Diameter, D_s ,
[guess for design]

_____ in.

_____ mm

6. Weir Height, H_w

_____ in.

_____ mm

7. Chord Length above Weir,
 $L_c = (4H_w(D_s - H_w))^{0.5}$
[If $D_s > 2D_b$, $L_c = D_s$]

_____ in.

_____ mm

8. Vertical Velocity Area, S_v

$(L_c)(L) / 12$

$(L_c)(L) / 1000$

_____ ft²

_____ m²

9. Chord Angle,

$$\theta' = 2 \sin^{-1} (L_c/D_s)$$

_____ deg

_____ deg

$$\theta = \theta' (\pi/180)$$

_____ rad

_____ rad

10. Horizontal Velocity Area, S_h

$$D_s^2 (\theta - \sin\theta) / 1152$$

$$D_s^2 (\theta - \sin\theta) / (8 \times 10^6)$$

_____ ft²

_____ m²

11. Vertical Velocity, V_v

$$W_v / (3600 \rho_v S_v)$$

$$W_v / (\rho_v S_v)$$

_____ ft/s

_____ m/s



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HEAT TRANSFER CALCULATION FORM FOR KETTLE AND INTERNAL REBOILERS (Cont)

12. $V_v \leq V_{\max}$? _____

[If NO, then for design cases reguess D_s and repeat from step 7]

13. Horizontal Velocity, V_h $W_v / (3600 \rho_v S_h^{2 NN})$ $W_v / (\rho_v S_h^{2 NN})$
 _____ ft/s _____ m/s

14. Effective Velocity, $V_e = (V_v V_h)^{0.5}$ [limit $V_e \geq V_v$]
 _____ ft/s _____ m/s

15. $V_e \leq V_{\max}$? _____

[If NO, then for design cases reguess D_s and repeat from step J5]

