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DIRECT CONTACT CONDENSERS -
A LITERATURE SURVEY

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ABSTRACT

A review is given of the literature pertinent to the design of direct contact condensers using water to condense an organic fluid. Both overall performance and fundamental concepts are examined. Recommendations are made regarding the work required to evaluate this concept for use in binary cycles for geothermal power plants.

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Direct Contact Condensers -
A Literature Survey

I INTRODUCTION

Direct contact condensers have been known for a considerable period of time; however, little is published as to their design[1]. Primarily they have been used for condensing steam, as open feedwater heaters or for solvent recovery in petroleum refineries. In most cases the same fluid is used for condensing as is the vapor, and as such they are known as single phase condensers. The most common form of direct contact condenser is the barometric or low level condenser used in steam power plants. This type of condenser works by having drops of cold fluid falling through a saturated vapor. Another method, more commonly applied to feedwater heaters is having the hot vapor, either saturated or superheated, bubble through a liquid pool or stream.

The direct contact condenser that might be applied to the direct contact geothermal power plant would of necessity be condensing a mixture of steam and an immiscible working fluid. In general the working fluid would consist of more than 90-95% by mass of the vapor. It thus differs from the previously mentioned condensers in that two phases are present in the condensed liquids. As both steam and working fluid are condensing the heat transfer is not necessarily reduced, as is the case when a non-condensible gas is present within the vapor.

For the case of vapor condensing on drops the heat transfer is limited by the fraction of the volume occupied by the drops, the surface area of the drops and their transfer properties. Thus, the rate of condensation may well be limited by the rate of conduction into the nucleation drop. A small initial diameter drop of high thermal diffusivity is therefore desirable. In order to keep the system simple, one of the two fluids present in the vapor should be used. The obvious selection is the water as most organic fluids have poor thermal properties. (For the geothermal binary working fluid, light hydrocarbons or the halogenated hydrocarbons have been normally recommended.(2)) For the bubbling systems, the choice of the liquid may not be as obvious; however, the liquid phase would still have to be cooled in a closed cooling tower. Thus, the higher thermal conductivity of water and normally lower pumping costs would make it the logical choice. The direct contact condenser for geothermal use will thus entail the condensation in or on water of the binary mixture of steam and working fluid. Designs will have to account for the possibility of non-condensible gases being present.

The use of direct contact devices instead of tubular heat exchangers for the geothermal application are not justified on the basis of scaling or fouling as were the primary heat exchangers for a binary power plant. Their justification must be established on the basis of lower capital costs, closer approach temperatures, and separation of the non-condensibles (degasification of the working fluid). With these facts in mind a literature survey was made dealing with direct contact condensers.

The present literature survey is directed toward the following:

(a) Types of Equipment that might be used as a Condenser

(b) Design methods for direct contact condensers

(c) Identification of needed Research

This literature survey is restricted to those sources that may be available in either the United States or Britain. Thanks to the British Heat Transfer Literature Computer Survey at Harwell are gratefully extended.

II DIRECT CONTACT CONDENSER EQUIPMENT

The types of equipment that can be used for direct contact condensers are primarily based on whether one chooses to have condensation on drops or by collapsing bubbles as mentioned earlier. However, condensation on thin films is also possible. The type of equipment can also be selected on the basis of whether desuperheating makes up part of the heat load. Thus, duty as well as the basic mechanism constitute the means of categorizing equipment. This discussion will be organized according to first, heat duty, and second, basic mechanism.

II-A Saturated Vapor

For condensation of saturated vapor there is no advantage of countercurrent versus co-current flow. Thus, most direct contact condensers for this application are in fact really co-current devices. The actual physical arrangement of counter current flow may be advantageous, if appreciable amounts of non-condensible gases are present, to aid in deaereating the condenser, however.

II-A-1 Film Type Direct Contact Condensers

In order to obtain large surface areas and thus large volumetric heat transfer coefficients in a film type condenser, this type of condenser is designed as a packed bed and is shown schematically in Figure 1. A variety of bed materials can be used for packing such as Raschig, Lessing and Pall rings and Berl and Intalox saddles. Expanded metal lath could also be used.

Packed beds have been used in designs of sea water evaporation plants at the University of California and some information was published by Wilke and Co-workers(3). Details are given in an M.S. Thesis (4). Steam condensing on Aroclor in a 12 inch diameter tower packed with 1 inch Raschig rings was represented in terms of the height of the transfer unit, HTU.

For saturated vapor the expression derived was

$$HTU_{Lh} = HTU_{L,d} (D/\alpha)^{0.5} \left(\frac{\mu H}{\mu_d}\right)^{.55} \left(\frac{\rho_d}{\rho_h}\right)^{.33} \left(\frac{\sigma_d}{\sigma_h}\right)^{.551-0.157 \log L} \tag{1}$$

based on Sherwood and Holloway's(5) mass transfer data. These values correspond to volumetric heat transfer coefficients of about 6000 Btu/hr ft^3 °F.

Harriott and Wiegandt(6) designed a packed bed condenser using ½ inch Intalox saddles for the condensation of methelene chloride using water. The values of the volumetric heat transfer obtained in their experiments varied with the liquid flow rate (superficial velocity) raised to between 0.4 and 0.6 power. Values as high as 150,000 Btu/hr ft^3 °F were obtained with a superficial mass velocity of 40,000/lb hr ft^2. The flooding rate for their tower was 136,000 lb/hr ft^2 at zero gas flow. They found that the packed tower condenser results could be predicted fairly well by applying penetration theory(7). When applying the theory to the data of Wilkie et al (3) they predicted values of 25,000 Btu/hr ft^3 °F as compared to the 6000 Btu/hr ft^3.°F obtained. They suggested the fourfold difference was due to the high viscosity of Aroclor 1248 which increased the contact time and may have also induced channeling. A later study by Rai and Pinder (8) confirmed the strong dependence on the liquid viscosity and resulted in the HTU varying with the viscosity raised to between the powers 1.1 and 1.2. Depending on the range of superficial velocities, nearly linear dependence of the HTU were found for highly viscous liquids in contrast to the work of Harriott and Wiegandt.(6) This indicated that further complicating factors were not accounted for. Data for a less viscous fluid than Aroclor 1248, Aroclor 1242, gave a non linear dependence as was obtained in Reference 6.

Other studies concerned with packed beds include the work of S.C. Hu(9) on a gasoline condenser and Wiegandt (10) for condensation of isobutane on packed ice. Fair(1) gives some information on packed bed condenser design based on analogies with mass transfer and points out the pertinent references for design of the hydrodynamics.

Detailed information related to condensation on thin films have been discussed by Tamir and Rachmilev(11) and Murty and Sastri(12). The first deals with the condensation of an immiscible fluid on a thin laminar film of water flowing over a sphere while the latter applies to condensation on a falling film of coolant the same as the vapor. These papers offer a semi-theoretical rational that could be applied to local heat transfer coefficients in packed beds. The latter of course could also apply to the heat exchanger shown in Figure 2; however, the volumetric heat transfer would be less than for a packed bed due to the reduced surface area per unit volume.

II-A-2 Drop-Type-Direct Contact Condensers

Although referred to as "drop-type-direct contact condensers" this classification includes all types of condensers where the vapor is the continuous media and the condensation takes place on either drops or jets of the dispersed phase. Typical of such devices are the so called barometric or low level condensers sometimes used in steam power plants and shown in Figure 3. These systems are variations on a simple spray tower as shown in Figure 4. In attempting to obtain more compact exchangers, tray type condensers sometimes referred to as "jet type condensers" are also used. (See Figure 5). Still other variations on the same basic theme are the pipe condensers shown in Figure 6. In the later type device the turbulence of the vapor stream is used to maintain small drop size and thus large surface area per unit volume. The tray type devices all enhance the heat transfer by allowing the coolant and condensate to mix on the trays and thus offer a higher heat transfer by eliminating temperature gradients within the drops and controlling drop coalescence as well as increasing the vapor holdup.

Barometric condensers are described in a Standards(13) which deals with the mechanical design and installation but provides no information as to their sizing. When used for condensing steam it is claimed that terminal temperature differences of 3-5°F are obtainable depending upon the amount of non-condensible gases present. The terminal temperature difference is defined as the difference between the vapor saturation temperature and the coolant exit temperature. For design purposes 5°F is recommended in calculating the mass flow rates.

Most of the information available in the literature dealing with "drop" direct contact condensers is directed toward condensation of steam or the condensation of a vapor on its own liquid. Typical of these is the work of Isachenko and Kushmirev(14) who utilized the solution of the temperature distribution for a sphere of constant radius initially at a temperature T_o and exposed to a fluid at T_{SAT} to generate an expression for the change in radius due to condensation, and then they applied a one parameter distribution function to account for drops of varying initial radius to obtain condensation heat transfer in a spray. This assumption of constant radius in obtaining the transient temperature distribution was also applied by Ford and Lekic(15) in studying experimentally condensation of steam on a single water drop and was shown to approximate well the behavior for most of the transient due to the fact that h_{fg} is large and thus the actual change in radius is small. However, for late in the process when the driving force is small the theory deviated from the results.

Several references are available on experimental measurements of direct contact condensation of steam including the work of Weinberg(16), Isachenko and Solodov(17), Brown(18), and MacNair, E. J.(19). The above deal with jet or spray condensers including the effects of the presence of noncondensible gases.

References 16-18 deal with gravity induced flow as in a barometric condenser. Reference 19 reports on a pipe line condenser where water spray is injected into a horizontal pipe with the condensing vapor in turbulent flow. Oliker(20) presents current design formulas for steam-condenser-deaerators used as feedwater heaters in steam power plants in the U.S.S.R.

Direct Contact Condensers of the drop-jet type have been considered for systems of immiscible liquids. Reference 6 discussed earlier, using a single tray, evaluated the tray as a condenser for the Aeroclor-steam system described in Section II-A-1. Values based on the nozzle area indicated heat transfer coefficients up to 100,000 Btu/hr ft^2 °F which increased with the superficial vapor velocity. These coefficients corresponded to volume coefficients up to 400,000 Btu/hr^3 of froth °F. Reference 6 preferred the packed bed condenser since closer approach temperatures were obtained. Coons(21), in 1953, also reported high heat transfer coefficients for direct contact condensation of water and of organics in spray contactors.

Other references of interest include the work of Johns(22), Bhagade et al(23), Sampson and Springer(24), Fair(1), two patents(25), (26), and the work of Miyazaki et al(27). The work of Chojnowski(28) is also of interest in dealing with a statistical variation of drops within a spray as is that of Tribus(29).

It should be mentioned, that the basic models for condensation of one fluid on an immiscible drop of another, let alone sprays, have not as yet been formulated. This is clearly seen by examining the works of References 11, 12 and 15. With the exception of very small condensation the models for drops are inadequate to describe the heat transfer process. The data for steam, however, and the Aeroclor-steam experiments of Reference 6 are sufficiently attractive to stimulate further work.

II-A-3 Bubble Type Direct Contact Condensers

Bubble type direct contact condensers include all those systems where the condensing vapor is injected directly into a continuous pool or stream of cold liquid. This type of device has been of interest as an open feedwater heater and as a vapor suppression system associated with nuclear reactors(30)-(33). They have also become of interest as compact condensers for sea water distillation.(34), (35) The several types of designs, as shown in Figure 7, differ basically in the behavior of the continuous phase.

In References 30-33 the cold continuous phase is primarily a pool of water into which an injection nozzle is inserted. Depending on the nozzle length and the per cent of non condensible gases present up to 99 per cent condensation efficiency for steam can be obtained with tubes extending less than 20 cm into the pool. B.R. Harris(36) has carried out similar experiments condensing organic vapors in a pool of water. He develops a means of calculating the number of dip tubes and water requirements of a so called blowdown drum in order to obtain a vibration free apparatus for complete condensation of an organic vapor.

Reference 34 deals with pentane bubbles condensing in pentane and in water and clearly shows the advantage of the use of the high conductivity fluid for the continuous phase. For this system, a simple column, Figure 8, volumetric heat transfer coefficients up to 27,000 Btu/hr ft^3 °F were achieved with counter current flow and 99% condensation. This corresponded to initial bubble radii of 0.25 cm with close initial packing. The counterflow arrangement aided heat transfer in that the important parameter in bubble systems is relative velocity between the bubbles and the continuous phase. These heat transfer results were obtained with the driving temperature difference of up to 3.6°C. Smaller initial radius bubbles could have yielded higher heat transfer coefficients although probably not as great as in a turbulent flow pipe exchanger.

Direct injection of vapor into liquid flowing turbulently in a tube offers an effective condensation device. Large surface area is maintained due to the turbulent shear. Bankoff and Mason(37) and Grassmann and Wyss(38) were able to achieve volumetric heat transfer rates of nearly 400,000 Btu/hr ft^3 °F in such devices while condensing steam. Similar results although somewhat lower 100,000-200,000 Btu/hr ft^3 °F were achieved by Lackey(35) when using steam and an organic liquid phase.

Poll and Smith (39) achieved high heat transfer in a froth Contact Heat Exchanger. Miyazaki et al(27) obtained excellent results in a supersonic nozzle with a central water stream. Heat transfer coefficients as high as 450,000 Btu/hr ft^2 °F based on interfacial area were reported. Examples of possible designs are shown in Figure 7.

Little other literature is available that deal with equipment design although there are many papers dealing with the collapse, and condensation of single bubbles. More recently trains of bubbles have received attention; however, much theoretical work has yet to be accomplished. The basic papers having to do with bubble condensation of immiscible fluids are primarily due to Sideman and co-workers. These are included as References 40-49. Other pertinent papers are included in References 50-55.

II-B Superheated Vapor

When the vapor to be condensed is superheated, the coolant must remove the sensible heat within the vapor as well as the heat of vaporization.(1) For this type of duty there is a definite advantage to a counterflow system. The basic mechanisms of liquid film (packed bed), drop and bubble systems are all applicable; however, changes in design are necessary to insure complete or nearly complete condensation of the vapor and avoidance of loss of working fluid with any non-condensible gases that may be present. Typical equipment systems might be the counter current designs discussed under previous sections.

The heat transfer in the superheat regime is governed by liquid-gas heat transfer relations. These are discussed by Fair(1) (60), Sideman(61) and Jacobs(62) among others for a wide variety of equipment designs for all three mechanisms. The heat transfer coefficients attainable for removal of sensible heat are notably smaller than with changes of phase and are nominally controlled by the gas side heat transfer. Typically the heat transfer coefficients obtained for removal of sensible heat may vary from 100 to 2000 Btu/hr ft^3 °F. These values are several orders of magnitude below those obtainable for condensation. It can thus be seen that for even 5-10% of the total heat load superheat can lead to significant increases in the size of the condenser-cooler.

III RECOMMENDED SYSTEMS AND FURTHER WORK

The literature survey covered three basic mechanisms for direct contact condensation. These mechanisms were condensation on a film, condensation on a drop and condensation of a vapor bubble. All three mechanisms indicated volumetric heat transfer coefficient of over 100,000 Btu/hr ft^3 °F were possible with steam as the condensing vapor. Limited information available indicated that equally large values might be possible for other fluid vapors but little basic theory is available to ascertain approximate values. (The results of Moalem and Sideman(33) may well have been restricted by initial bubble size to 27,000 Btu/hr ft^3 °F). Thus, some theoretical work must progress on all three mechanisms although crude designs are possible for all three.

In order to assess the relative capability of film type (packed bed) condensers it is proposed to extend the theory of Tamir and Rachmilev(11) to account for a second film of the condensed fluid on a film of liquid on a sphere. This model will follow that on Murty and Sastri(12) but deal with two immiscible fluids. Values of the heat transfer coefficients obtainable will be calculated for pentane on water, isobutane on water, R-113 on water and R-114 on water as well as water on water. Using a ratio of the first three to the last, volumetric heat transfer coefficients for packed beds will be obtained for each fluid system by multiplying them times values in the literature for water condensing on water. Thus, it will be possible to compare costs and sizes with other systems.

The design of drop type condensers requires the development of a theoretical model for the static condensation of an immiscible fluid on a non-circulating liquid drop. This type of model is an extension of the work of Ford and Lekic(15) who worked with steam and neglected the resistance of the forming immiscible layer. Although for their case of steam, where the heat capacity of the drop was small compared with the enthalpy of phase change, the neglect of this added resistance to heat flow is small, this would not be the case with an organic fluid condensing on water. (See Reference 11). Such a model is being developed and will be applied to a spray following the statistical modelling of References 14 and 18 as well as the earlier work of Reference 63. This model should be complete by June 1977.

The effect of a binary vapor, water plus working fluid for both of the above models will require further investigation.

The condensation or collapse of bubbles within a continuous liquid phase has been treated reasonably well by Sideman and co-workers however, further experimental work is necessary to check his work with pentane vapor and water. Indeed the effects of a condensing binary vapor has not yet been treated. However, the results of Reference 33 indicate that volumetric heat transfer coefficients of 27,000 Btu/hr ft^3 °F at least should be attainable. Thus, although not necessarily the optimum design, sufficient information is available to design a rather complete direct contact binary geothermal cycle. Work will proceed now on gaining sufficient information to optimize the cost and obtain comparison with other systems including the turbulent flow pipe condenser. Additional experimental data is being accumulated by Mr. Heimir Fannar at the University of Strathclyde to accomplish these tasks.

Final recommendations for direct contact condensers will follow after completion of the above tasks. As design models are completed they will be incorporated into the University of Utah Computer Program Dirgeo.

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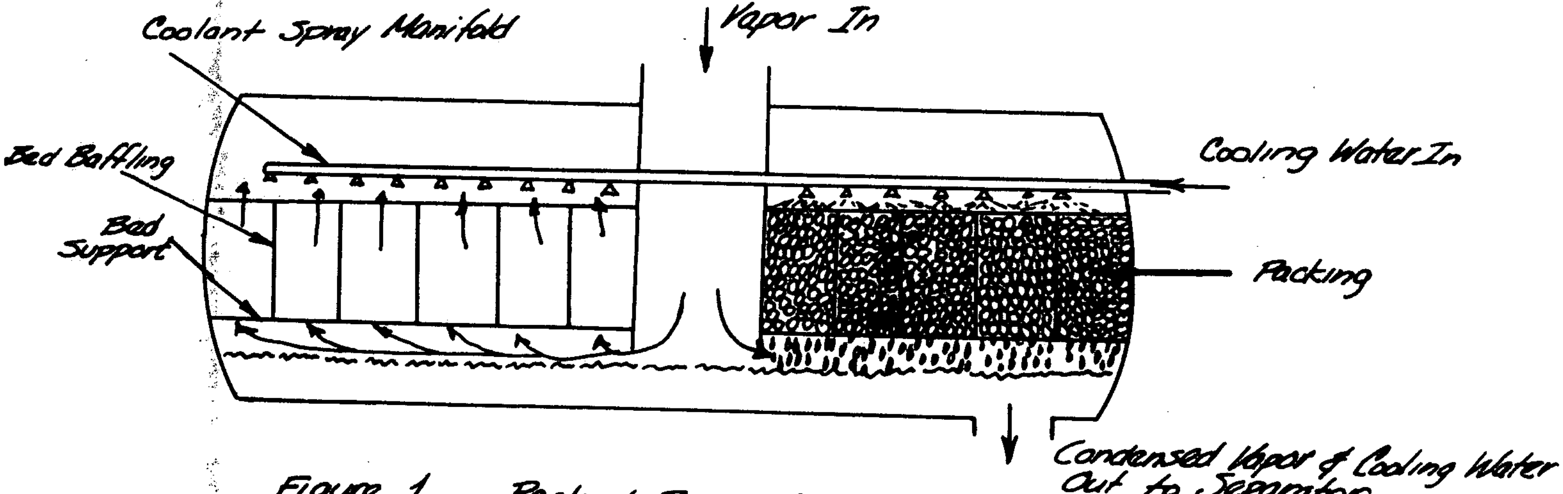


Figure 1 Packed Bed Type Direct Contact Condenser

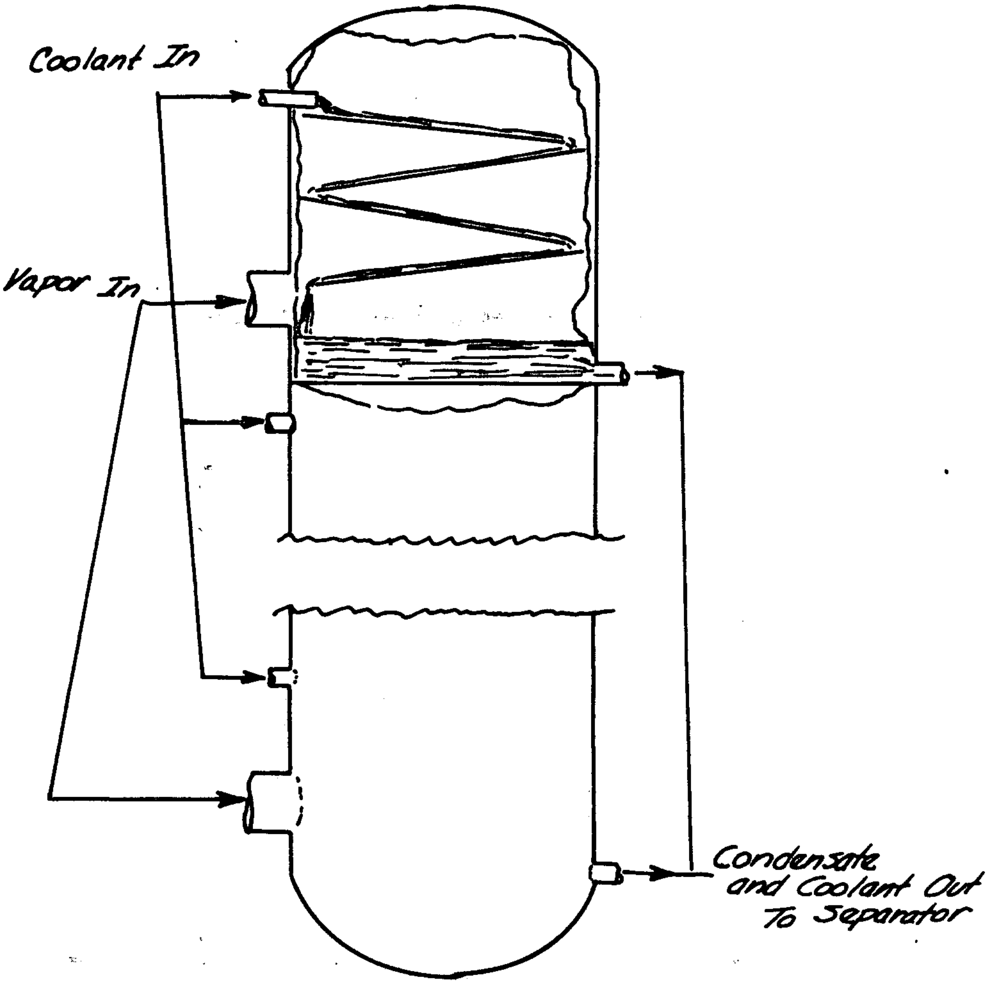
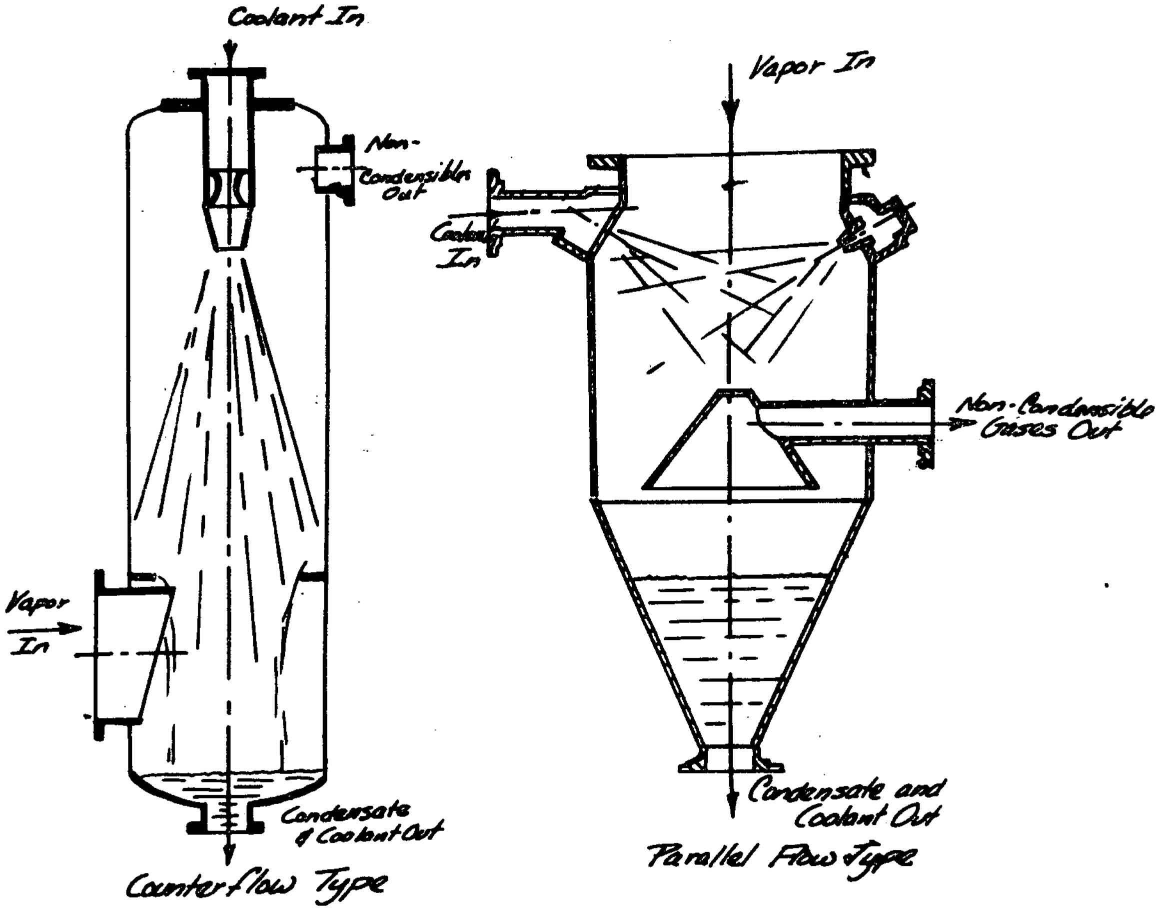


Figure 2 Film Type Direct Contact Condenser



Counterflow Type

Parallel Flow Type

Figure 3 Two Designs of Barometric Condensers

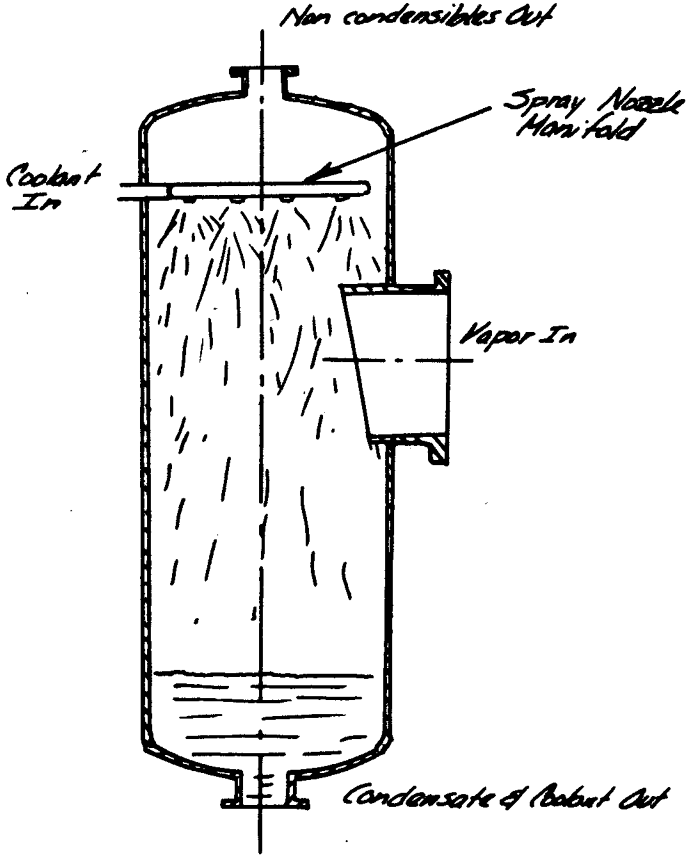


Figure 4 Simple Spray Tower

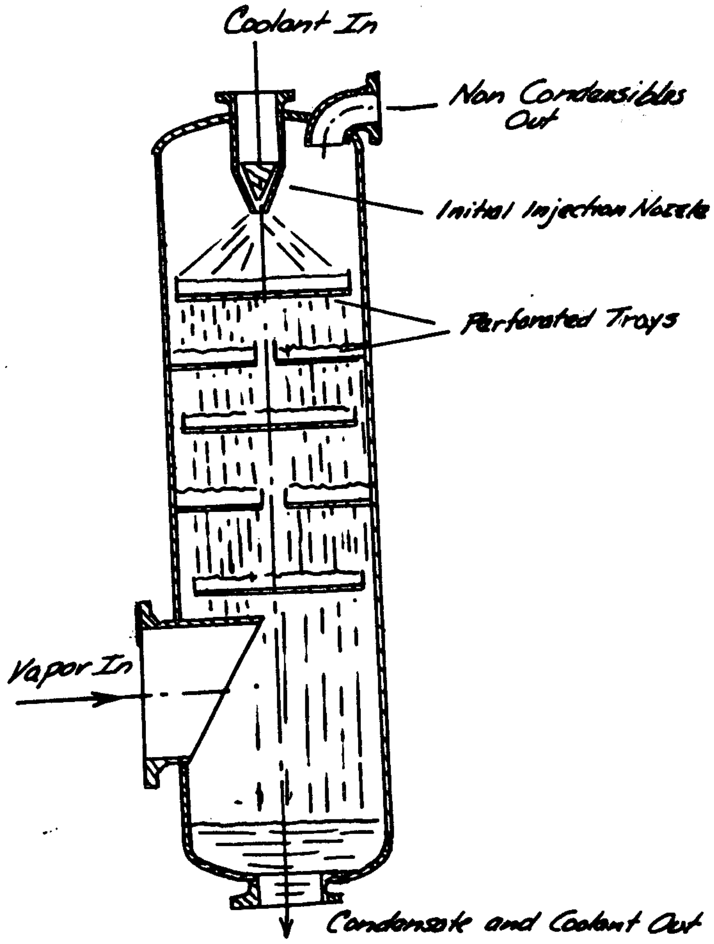


Figure 5 Jet Type Condenser
(Shown Counter flow)

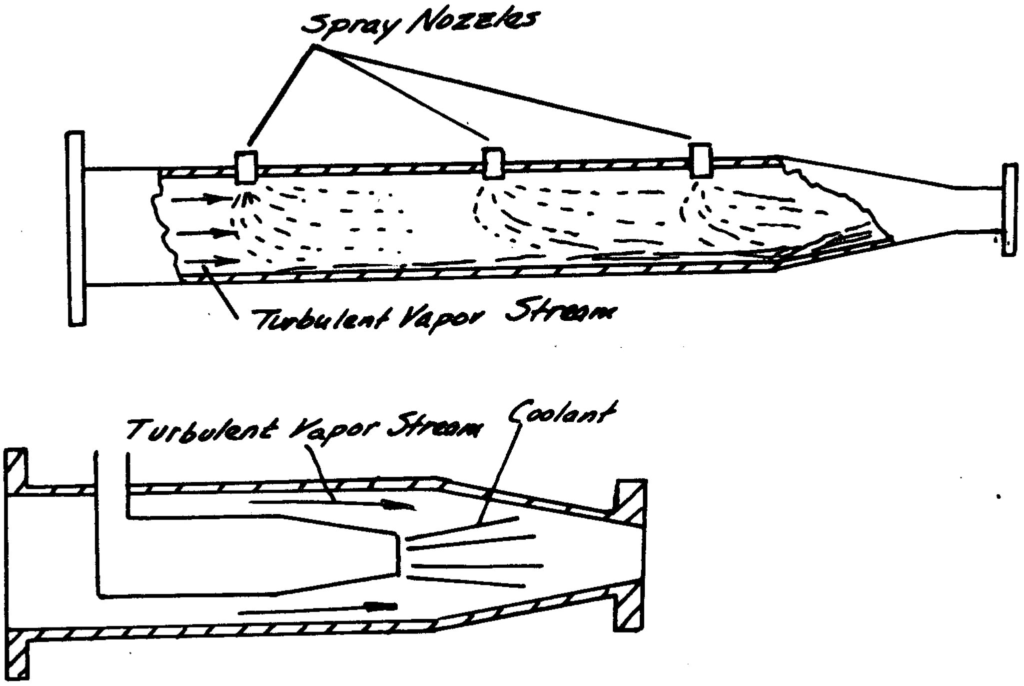
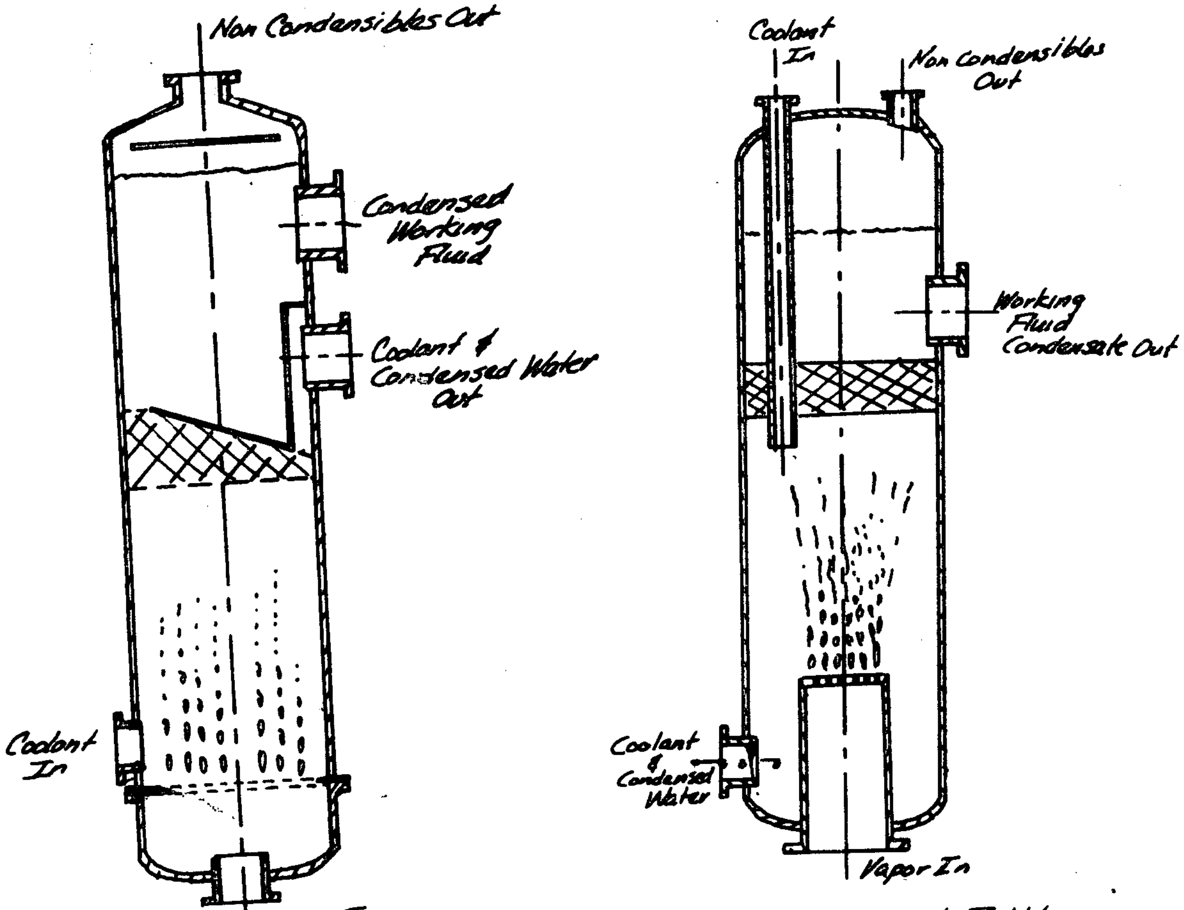
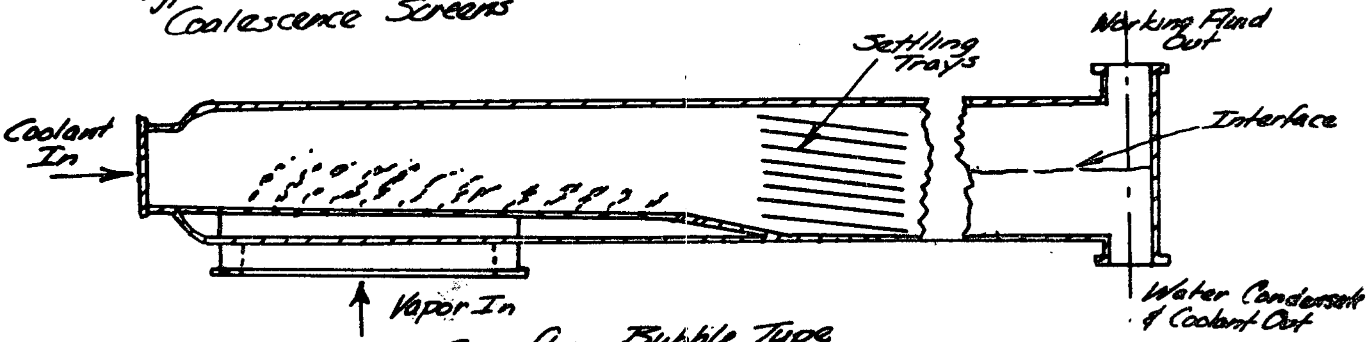


Figure 6 Pipe Flow Condensers



Parallel Flow Bubble Type Condenser With Coalescence Screens

Countercurrent Bubble Type Condenser with Coalescence Screens



Crossflow Bubble Type Condenser with Settler

Figure 7 Some Bubble Type Direct Contact Condensers

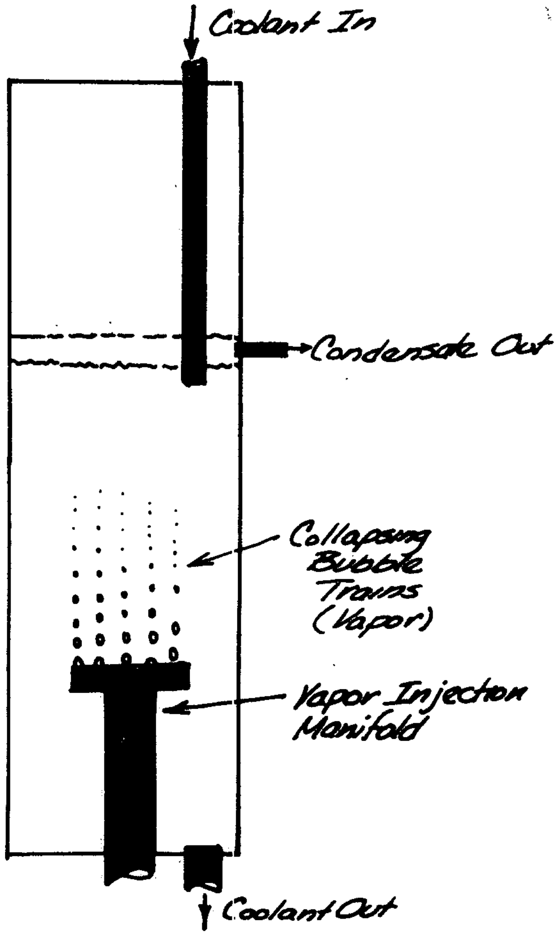


Figure 8 Vapor Bubble Condenser for Pentane in Water (Ref 33)