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DIRECT CONTACT CONDENSATION WITH TWO IMMISCIBLE FLUIDS

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Daryl Lee Lackey
(M.S. Thesis)

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DIRECT CONTACT CONDENSATION WITH TWO IMMISCIBLE FLUIDS

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June 29, 1962

ABSTRACT

The theory, design techniques, and relative economics are presented for three basically different direct-contact condensation processes involving fluids whose condensed phases are immiscible. The specific system developed for this study used Aroclor 1248 (Monsanto Chemical Corporation) and steam. The processes investigated were (a) the injection and (b) induction of steam into a high-velocity stream of Aroclor in the throat section of a Venturi, and (c) bubbling of steam into a low-velocity stream of Aroclor, using a packed tower to artificially increase the surface of contact.

The induction, injection, pressure drop, and heat-transfer characteristics of a Venturi in direct-contact condensation service were experimentally investigated, and empirical correlations for the performance of the unit are included.

The performance of a direct-injection device was also experimentally determined, and correlations obtained.

Finally, the theoretical development of relationships predicting the performance of a packed tower in direct-contact condensation service is discussed.

I. INTRODUCTION

The literature contains essentially nothing on direct-contact heat transfer (condensation) involving immiscible fluids. Vener suggests that a Venturi might be an excellent device for direct-contact heat transfer,[1] but he does not say that it has been done. Shao-chio Hu has published an article on the design of a packed tower for use as a direct-contact gasoline condenser.[2] Hu's work is discussed in detail later in this paper (Sec. IV) and it can easily be shown that his design technique is not theoretically correct.

This absence of published information is really not too surprising. The technique of condensing a vapor with one fluid that is immiscible with a condensed fluid is obviously of common use in industry, and it can be postulated that those processes for which the mechanical details of direct-contact condensation have been solved show enough economic advantage over more conventional equipment that they are kept secret.

If the problem of direct-contact condensation is considered from a processing standpoint, it is easily seen that there are only three basic processes that can be used. First, one fluid can be induced, or injected, into a high-velocity (and highly turbulent) stream of the second fluid. For example, the first fluid can be injected into the throat section of a Venturi through which the second fluid is flowing. The second basic process is to use a device that artificially increases the contact surface between the two fluids; for example, a packed tower. The third process is to inject one fluid into another at relatively low velocities; for example, by using a sieve tray tower.

The primary purpose of this particular work is to compare the relative economics of the three basic processes listed above. The three mechanical techniques actually compared are a modified Venturi, a packed tower, and a bubble-cap tray tower. Since nothing in the literature allows us to reliably predict the performances of either a Venturi or a bubble-cap tray in this service, it was necessary to

develop the required design information experimentally. This was not so in the packed-tower case because there sufficient information and theoretical analyses exist for a reliable design.

A secondary purpose of this work is to ascertain the most economical direct-contact condensation step as part of a new sea-water conversion process that has been proposed by Professor C. R. Wilke of the University of California. Very briefly, this process consists of a series of evaporation steps operating at successively lower pressures. A hot mixture of sea water and Aroclor is fed to the evaporators. At the end of the last evaporator, the Aroclor and sea water are separated, and the Aroclor is fed to a series of condensers functioning at successively higher pressures. The water vapor from the evaporators is condensed to reheat the Aroclor. At the end of the condenser series, the hot Aroclor is separated from the product water. It is then reheated in a furnace to compensate for the sensible heat lost in the waste sea water, the product water, and the heat losses from the system. The Aroclor is then mixed with fresh sea water and returned to the evaporator series.

II. THE EXPERIMENTAL VENTURI

A. Theoretical Discussion

Since this is a venture into an area not previously investigated, the theoretical discussion here is based on fundamental engineering concepts. The first portion of the discussion deals with design considerations of the experimental Venturi. The second section includes a discussion of the cavitation phenomenon, and the derivation of equations relating the performance of the Venturi to the pertinent variables.

1. Design of the Experimental Unit

The experimental unit can be divided into three sections for the purpose of discussion: (a) a convergent section that accelerates the Aroclor to some velocity, (b) a throat section through which steam is introduced into the fast stream of Aroclor, and finally (c) a diverging section to recover the velocity head of the Aroclor-water-steam mixture as a pressure head. From the standpoint of heat transfer, this diverging section or "diffuser" provides the volume in which heat transfer takes place. Also, by virtue of its pressure-recovery characteristics, the diffuser increases heat transfer rates by increasing the temperature driving force.

The first or convergent section offers no problem in design. The behavior of such sections is well known. It is generally accepted that with reasonable design, frictional effects associated with accelerating a fluid with a converging section can be maintained below 5% of the velocity head developed.

The second or throat section of the unit must be modified from that usually found in Venturis. To illustrate this, consider the physical situation shown in Fig. 1(a). For the calculation, assume that the Aroclor has a throat velocity of 50 fps, no steam flow, that the throat's static pressure with no steam flow is zero psia, and that the available steam pressure is 5 psig. The maximum driving force for steam flow is then

$$\frac{(19.7 \text{ psia})(144 \text{ in}^2/\text{ft}^2)}{85 \text{ lb/ft}^3} = 33 \text{ ft-lb/lb of Aroclor}$$

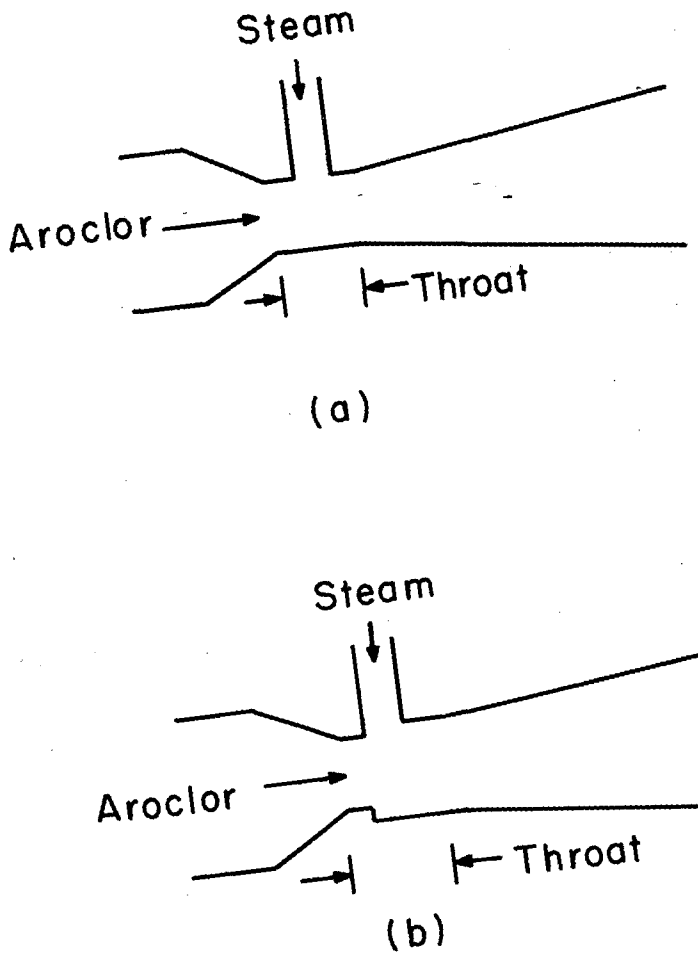

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Fig. 1. Venturi schematics.

This driving force for steam flow can be reduced to zero if the Aroclor is sufficiently accelerated in the portion of throat which immediately follows the steam entry. The required increase in Aroclor velocity is

$$\frac{V^2}{2g} = \frac{V_i^2}{2g} + 33 = \frac{(50)^2}{64} + 33 = 72 \text{ fps}$$

and

$$V = [(72)(2g)]^{1/2} = 68 \text{ fps}.$$

If it is assumed that this increase in Aroclor velocity is caused by the introduction of steam, the volumetric ratio of steam to Aroclor becomes

$$\frac{68 - 50}{50} = \frac{18 \text{ ft}^3 \text{ (steam)}}{50 \text{ ft}^3 \text{ (Aroclor)}} .$$

On a weight basis, this in turn becomes, assuming a specific steam volume of 25 ft^3/lb,

$$\frac{18 \text{ ft}^3 \times 1/25 \text{ lb/ft}^3}{50 \text{ ft}^3 \times 86 \text{ lb/ft}^3} = 0.000167 \frac{\text{lb (steam)}}{\text{lb (Aroclor)}} .$$

This rather crude approach, then, clearly establishes the need to expand the throat section at the steam inlet; i.e., as shown in Fig. 1 (b).

To design an optimum diffuser from purely theoretical considerations is virtually impossible. The difficulty lies in the extremely complex nature of a two-phase flow situation in which the vapor-phase volumetric flow rate is rapidly changing. A total divergence angle of 7 deg was arbitrarily used in the experimental unit. At relatively low steam-to-Aroclor ratios, this seems reasonably close to the optimum because the friction-loss coefficient as a function of the divergence angle doesn't vary greatly as the angle varies roughly from 5 to 10 deg.[3] At higher steam-to-Aroclor ratios, the arbitrary selection of 7 deg becomes progressively more unreliable.

2. Theoretical Performance

(a) Fluid flow characteristics. In considering the performance of the Venturi as a fluid flow device, a simple force balance will provide some idea of the pertinent variables and their relationship. The physical situation and variables are as shown in Fig. 2. A force balance in the "x" direction is

$$\Sigma F_x = \Sigma \text{ (momentum rate)}_x$$

$$P_T A_T + \cos 7 \text{ deg} \int P_2 \, dA - P_d A_d$$
$$= \frac{W_d}{g} V_d Q_d - \frac{W_A}{g} V_A Q_A - \cos 45 \text{ deg} \frac{W_s}{g} V_s Q_s \quad .$$

We have as an approximation, $\cos 7 \text{ deg} \int P_2 d A \approx 0$; also, $A_d \gg A_T$, and therefore $V_d \approx 0$. If we assume that the difference between the available steam pressure P_c, and the throat pressure P_T, is converted into a steam velocity head,

$$P_T = P_c - V_s^2/(2g) \, W_s .$$

When we substitute $F_A \equiv$ Aroclor mass flow rate $= Q_A W_A$, and also $F_S \equiv$ steam mass flow rate $= Q_s W_s$, into the force balance, we obtain

$$a_1 P_c - a_2 P_d = a_3 F_A^2 + a_4 (F_s^2 / W_s) ,$$

where the a's are constants.

W_s is a function of the steam properties and the pressure at the throat. The throat pressure is also a function of the Aroclor flow rate. If we assume W_s to be a simple power function of F_A, say $W_s = b F_A^x$, the force balance above reduces to

$$F_S^2 \equiv (C_1 P_c + C_2 P_d + C_3 F_A^2) F_A^x ,$$

where the C's are constants. Obviously, this equation is only an approximation because we have made several assumptions in arriving at it.

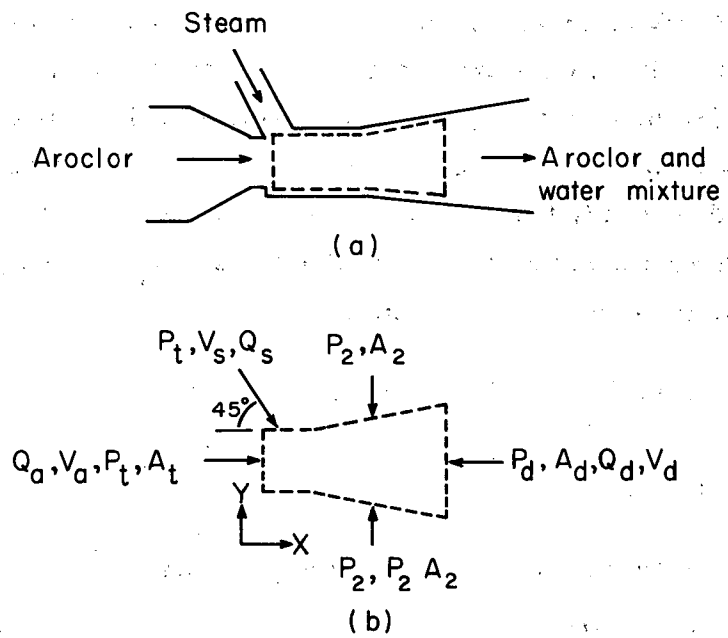

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Fig. 2. Force balance diagram: (a) location of free-body section, and (b) fluid free-body section.
Legend: A = area, P = pressure, Q = volume flow rate, V = velocity, and W = fluid unit weight;
(subscripts) $_a$ = Aroclor, $_d$ = discharge, $_s$ = steam, $_t$ = throat, and $_2$ = sidewall.

A relatively rigorous treatment of the condensation interface has been developed by P. Chiarulli and R. F. Dressler.[4] Their specific purpose was to develop equations describing the direct-contact condensation of steam in water. The condensation zone of these authors is idealized as an interface that separates the vapor and liquid and has a friction, heat removal, and cold-liquid injection mechanism at this interface. Using this model Chiarulli and Dressler then applied mass, momentum and energy balances to both sides of the interface. In the equations below, the subscript v denotes the initial vapor state, L the initial liquid state, and W the sidewall; an absence of subscript denotes the final liquid state. The standard symbols represent velocity (U), pressure (p), specific volume (v), temperature (T), enthalpy (H) mass flow rate (m), and area (A). The total mass of cold fluid injected per unit time is m_W, the frictional force at the wall is F_W, and the heat removed per unit time is h_W. Using these notations, we have as the mass balance,

$$A(u/v) = A_V(U_V/v_V) + A_L(U_L/v_L) + m_W , \tag{1}$$

or

$$m = m_V + m_L + m_W. \tag{2}$$

The momentum balance is then given as

$$A_p + mU = (A_V P_V + m_V U_V) + (A_L P_L + m_L U_L) + m_W U_V - F_W, \tag{3}$$

and the energy balance as

$$m(H + 1/2\, U^2) = m_V(H_V + 1/2 U_V^{\ 2}) + m_L(H_L + 1/2 U_L^{\ 2})$$

$$+ m_W H_W + 1/2 U_W^{\ 2}) - h_W. \tag{4}$$

Equations (3) and (4) are then rewritten to

$$A_P + v(m^2/A) = (A_V P_V + m_V U_V) + (A_L P_L + m_L U_L) + m_W U_W - F_W, \tag{5}$$

and

$$H(P, V) + 1/2\, m^2 V^2/A^2$$

$$= (H_V + 1/2 U_V^2)\frac{m_V}{m} + (H_L + 1/2 U_L^2)\frac{m_L}{m} + (H_W + 1/2 U_W^2)\frac{m_W}{m} - \frac{h_W}{m} \tag{6}$$

The equation of state for the liquid is

$$v = v(p, T).$$

The following assumptions may then be made:

(a) Since $v_V \gg v$, and m is not too large compared with m_V, the v terms in Eqs. (5) and (6) can be neglected.

(b) The enthalpy function, $H(p, t)$, and the equation-of-state function $v(p,t)$, are essentially independent of p for liquids. For the liquid, these functions are then evaluated at the saturation pressure and as a result the functions reduce to

$$H = H(p_s, T) = H_s(T),$$

and

$$v = v(P_s, T) = v_s(T).$$

(c) For water, C_P doesn't vary widely with temperature, so that

$$H = H_s(T) = C_p T + C_0 .$$

These assumptions are substituted into Eqs. (5), (6) and (7) to yield

$$p = [(A_V P_V + m_V U_V) + (A_L P_L + m_L U_L) + m_W U_W - F_W]/A,$$

$$T = [(H_V + 1/2 U_V^2)(m_V/m) + (H_L + 1/2 U_L^2)(m_L/m) + (H_W + 1/2 U_W^2)$$

$$(m_W/m) - (h_W/m) - C_0]\, C_p ,$$

and $v = v_s(T)$. These equations are in turn solved for P, T, and v.

(b) Heat transfer characteristics. J. M. Burgers and A. Ghaffari have developed an analysis of the speed of condensation of steam in water as part of an overall analysis of steam-driven water jets.[5] Their solution is summarized below.

The unidimensional unsteady state heat-conduction equation was solved for the boundary conditions of distance from surface ($y = 0$), time ($t = 0$), and temperature ($T = T'$, where T' is the initial water temperature). We have also the conditions of $y = 0$, $t > 0$, and $T = T_s$, where T_s is surface temperature. The heat-conduction equation of Burgers and Ghaffari is then

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial y^2} .$$

With the above boundary conditions, the approximate solution becomes

$$T = T' + (T_s - T')(1 - \mathrm{erf} \frac{y}{2(2t)^{1/2}}) .$$

The heat flow rate to the interior is therefore

$$q = -k \left(\frac{\partial T}{\partial y}\right)_0 = PC_p (T_s - T') \left(\frac{a}{\pi t}\right)^{1/2}$$

and the heat transferred in time t is

$$Q = (2/\sqrt{\pi})\, PC_p (T_s - T') \sqrt{at} = 3.08 \sqrt{t}\ \mathrm{cal/cm^2} \text{ for water.}$$

The remainder of their analysis involves assuming values for contact time, steam-to-water weight ratio, steam velocity, water temperature, and steam enthalpy. The required amount of surface contact area is then calculated. The example presented by these authors was for a contact time of 0.1 sec, a steam-to-water ratio of 0.5, a steam velocity of 1.003 m/sec, a steam enthalpy of 639.4 kcal/kg, and an initial water temperature of 20° C. The calculated surface-to-volume ratio for the water was 34.4 cm^2/cm^3. This corresponds to drops with a radius of 1 mm or 1,000 microns.

For the Venturi, our real interest is in developing a theoretical basis for a volumetric heat-transfer coeffficient based on an apparent-temperature driving force. This can easily be done, but a more rigorous approach to the problem than that of Burgers and Ghaffari is indicated. A reasonable physical model of the Venturi results if we assume that steam is the continuous medium in the "throat," the mixing chamber where the steam contacts the Aroclor. We then assumed that the Aroclor stream from the Aroclor nozzle immediately breaks into droplets on entry to the chamber. If a very short section of the chamber is considered, then the pressure within the section would not vary appreciably, and therefore heat would be transferred from isothermal steam to the surface of the Aroclor drops. This can be seen as an unsteady-state situation because the surface temperatures of the drops are then a function of time, among other things. Derivation of this function required solution of the unsteady-steady conduction-heat transfer equation for drops. This equation is

$$\frac{1\partial T}{\alpha \partial t} = \frac{2\partial T}{r\partial r} + \frac{\partial^2 T}{\partial r^2} .$$

The appropriate boundary conditions are

(a) $T = T_0$ (initial Aroclor temp), at time $t = 0$, radius $r > 0$;

(b) $T = T_1$ (steam temp), at $t = \infty$, $r > 0$;

(c) T = finite, at $r = 0$ $t > 0$;

and

(d) $\left(\frac{\partial T}{\partial r}\right)_{r=0} = -\frac{h}{k}(T_s - T_1)$, $t > 0$ (T_s = surface temp).

The solution to this equation and its boundary conditions, as given by Mickley, Sherwood, and Reed is[6]

$$T - T_1 = \sum_n (2/a_n)^{1/2} [\exp(-\alpha a_n^2 t)] \frac{A_n \sin a_n r}{r} ,$$

where

$$A_n = (T_0 - T_1) \frac{(2a_n \pi)^{1/2}}{r_0} \left(\frac{\sin a_n r_0}{a_n^2} - r_0 \frac{\cos a_n r_0}{a_n} \right),$$

and a_n represents values satisfying

$$\tan a_n r_0 = \frac{a_n r_0}{k - r_0 h} .$$

In order to use these equations and to continue the solution to achieve a volumetric heat transfer coefficient, and other terms, we must assume values for a number of the variables. Assume that the initial Aroclor temperature is 180 °F, and the steam temperature is 220 °F. Assume that the Aroclor drops are rather coarse, say 1/64-in. in diameter. Also, let us assume for our purpose here a very short contact time of 0.00167 sec. This time corresponds to a travel distance of 1 inch for a 50-fps Aroclor velocity. A reasonable value of the heat-transfer coefficient from the steam to the surface of the Aroclor drop is chosen to be 2000 Btu/hr-ft^2-°F. (McAdams et al. have reported values of U ranging from 574 to 2300 for steam to water in a falling-film condenser.[7]) With these assumed conditions and the equation above, the surface temperature of the Aroclor drop at the end of 0.00167 sec is found to be 196 °F.

The surface-to-volume ratio for the drops is

$$\frac{S}{V} = \frac{3}{r_0} = \frac{3}{6.56 \times 10^{-4}} = 4.58 \times 10^3 \text{ ft}^2/\text{ft}^3 .$$

For an Aroclor flow of 25 lb/min in 0.00167 sec, the surface area (SA) is then

$$SA = 4.58 \times 10^3 \times \frac{25 \text{ lb/min}}{87 \text{ lb/ft}^3} \times \frac{0.00167}{60} = 0.037 \text{ ft}^2 .$$

The actual log-mean-temperature driving force (LMTD) is

$$LMTD = \frac{(220-180) - (220-196)}{\ln (220-180)/(220-196)} = 31 \text{ °F} .$$

The heat transfer rate Q (for the experimental Venturi) is then

$$Q = (2000)(0.037)(31) = 2300 \text{ Btu/hr} .$$

The "apparent" temperature T of the Aroclor at the end of 0.00167 sec becomes

$$T = 180 + \frac{2300 \text{ Btu/hr}}{0.3 \text{ Btu/lb-}^\circ\text{F} \times 1500 \text{ lb/hr}} = 180 + 5 = 185\,^\circ\text{F}.$$

The apparent-temperature driving force is therefore

$$(\text{LMTD})_a = \frac{(220-180) - (220-185)}{\ell n\,(220-180)(220-185)} \approx 38\,^\circ\text{F}.$$

The volume of the section of the experimental Venturi between the end of the Aroclor nozzle and a point 1 inch inside the mixing chamber is approximately

$$V = (\pi/4)(1/16)(1/144)(1/12) = 2.8 \times 10^{-5} \text{ ft}^3.$$

The apparent volumetric heat-transfer coefficient becomes therefore

$$U_V = \frac{Q}{(\text{LMTD})_a\, V} = \frac{2300}{38 \times 2.8 \times 10^{-5}} = 2.3 \times 10^6 \text{ Btu/hr-ft}^3\text{-}^\circ\text{F}.$$

Most certainly, even though the assumptions on which this coefficient is based are reasonable they are still subject to considerable error. The real significance of our calculation is that the order of magnitude of the volumetric heat transfer coefficient is several million Btu/hr-ft^3-°F.

(c) Cavitation. By its very nature, the process described above requires that the Venturi operate as a cavitated unit. The phenomenon of cavitation is normally characterized by serious losses in mechanical efficiency, serious vibration problems, and rapid pitting and destruction of those parts of the unit in contact with the fluid.

There are two potential sources of cavitation in the unit. The first is in the unit's diffuser and is unavoidable: it results from the introduction of steam into the throat of the Venturi. The second source, however, is avoidable. This is cavitation caused by operating the Aroclor nozzle at velocities high enough to reduce the nozzle

Static pressure to the vapor pressure of the water in the Aroclor.

Whatever the source, the cavitation can be briefly described as follows. Bubbles of steam formed at the steam inlet are rapidly swept into the diffuser. These steam bubbles collapse from two causes. First, heat is transferred from the steam to the Arolcor, in which case the steam bubbles will collapse relatively slowly. But also, many of the bubbles are swept into a region of high pressure and collapse suddenly. The fluid rushes in to fill the void at the point of collapse, momentarily raising the pressure at this point to a very high value. Should the point of collapse be at a boundary wall, the wall's surface may be stressed locally beyond its elastic limit, resulting in fatigue and eventual destruction of the wall.

B. Experimental Equipment

A schematic diagram of the experimental equipment is shown in Fig. 3. A brief description of each item follows.

The Aroclor feed tank was an insulated standard 55-gal steel drum, fitted with a top-entering agitator which was a model VH-1 CWS, 1/4-hp, direct-driven 1750-rpm Eastern mixer. The tank was also equipped with three 3750-watt Chromalox heaters. The voltage supply to these heaters was infinitely adjustable, so that the heat input rate could be set anywhere between zero and the maximum.

The Aroclor feed pump was an all-iron Eastern model 3J horizontal centrifugal pump. A performance curve was run for this pump in Aroclor service. The total discharge head at no flow was 108 ft. It was 65 ft at a pumping rate of 4 gpm.

The Aroclor feed rate rotometer was a Fischer and Porter series 1700 Flowrator, size 6, model 10A—1735A. The float was a BSVT-64 (316 stainless steel) the tube number was B6-35-10/77. Calibration of this unit indicated a flow of 26 lb/min of Aroclor at a reading of 40% of full scale.

Details of the Venturi are shown in Fig. 4. The Aroclor inlet pressure was measured just before the start of the Aroclor nozzle

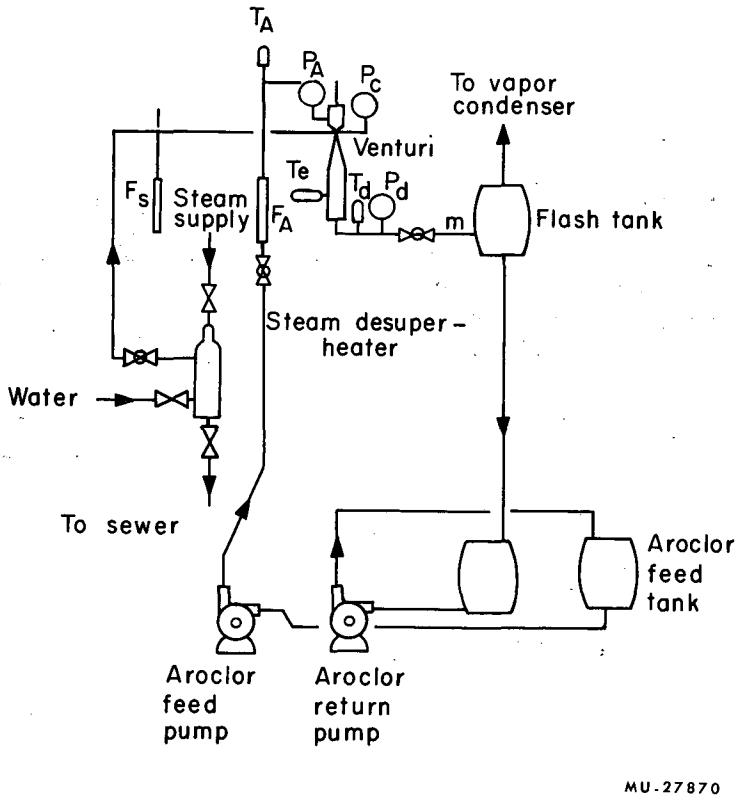


Fig. 3. Schematic diagram of the experimental equipment.

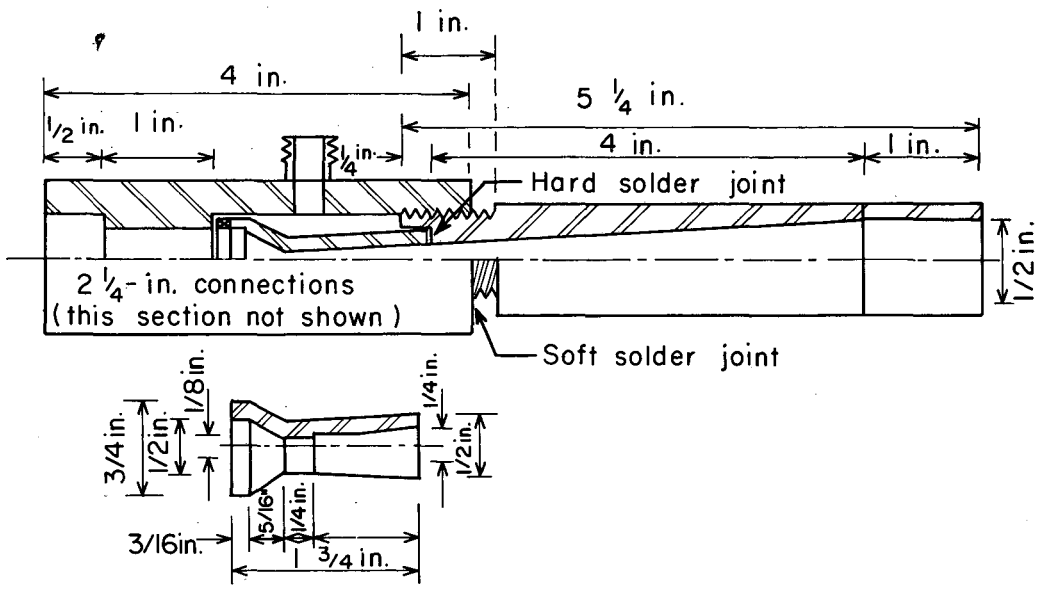


Fig. 4. Details of yellow-brass experimental Venturi. Gaskets used were Garlock No. 7710.

with a U. S. Gauge Company range 0 = 100 psi bourdon-type pressure gauge. The steam chest pressure was measured with a Jas. P. Marsh Company compound gauge ranging from -30 in. of mercury to + 15 psig. The discharge pressure was measured with a U. S. Gauge Company 0-15 psi gauge. All temperatures were measured with standard glass mercury thermomenters with a range of 0-300 °F in 2- °F divisions. The Aroclor inlet temperature thermometer was placed in a small steel thermowell.

The steam desuperheater (see Fig. 3) was constructed of a 1-ft 4-in.-section of 4-in. steel pipe. The steam inlet was a 1-in. pipe that extended to within 2 in. of the bottom of the unit. The steam outlet was a 1/2-in. connection, located 4 in. below the top of the unit. The unit was fitted with two 1/2-in. connections at the bottom for a drain and a water inlet. A Crane Company No. 610 brass water gauge was installed on the side of the unit to give an indication of the water level within.

The flash tank was a small steel drum of about 30 gal capacity. The Aroclor return drum was a standard 55-gal steel drum. The Aroclor return pump was a small laboratory model horizontal centrifugal pump.

The steam-orifice meter was constructed from a brass plate and two solder-type fittings. A 1/8-in. hole was drilled in the plate, the plate was brazed in place between the two fittings. Pressure taps were drilled in fittings in locations corresponding to that of flange taps.

The pressure differential across the orifice was measured with a 14-in. mercury manometer, calibrated by adjusting the steam flow until the desired pressure differential across the orifice was obtained. The steam flow was then totally condensed in a bucket containing 20 pounds of cold water, and the water temperature was measured after a finite time interval. The steam flow rate was calculated from these measurements. Six different such measurements were made, and the steam flow rates were calculated and plotted against the orifice pressure differential on log-log graph paper to give a calibration plot.

A calibration of the Aroclor feed-rate rotometer had been previously developed, and therefore only a spot check of this calibration curve was made, done by weighing the amount of Aroclor flow in a finite time interval and then checking this weight flow rate and the rotometer scale reading with that shown on the calibration curve.

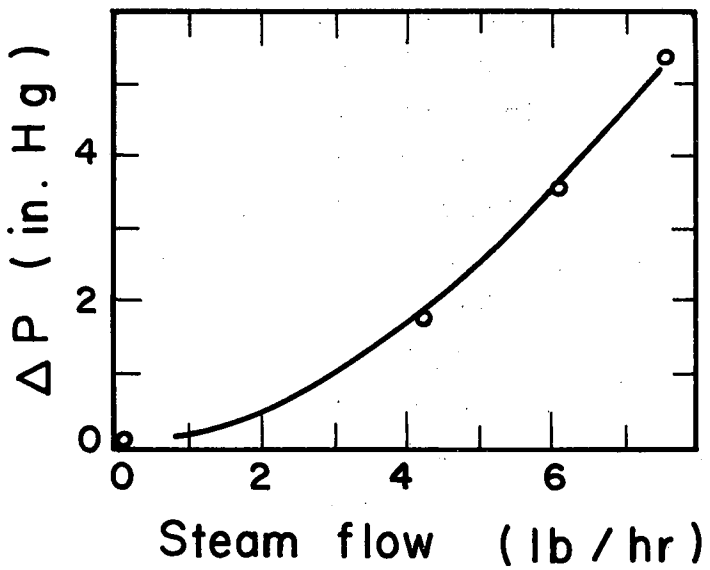
During the preliminary checkout of the equipment, steam was fed to the Venturi with no Aroclor in the unit. This test was made to ensure that there was no major pressure drop in the steam supply system to the Venturi mixing chamber . Figure 5 is a plot of this data and shows that there was no appreciable resistance to flow in the steam supply system.

C. Experimental Procedure

At the start of each run, all the Aroclor in the system was transferred to the Aroclor return tank. Any water that had accumulated anywhere in the system was drained off after which the Aroclor was returned to the feed tank and heated to the desired temperature. The voltage supply to the tank heaters was then reduced and the hot Aroclor was circulated throughout the entire unit to bring the various components to an even temperature.

Once the entire unit was hot, the Aroclor return pump was stopped and the steam supply to the desuperheater was turned on. The water level in the desuperheater was reduced to a minimum. The name "desuperheater" turned out to be a misnomer. The steam supply was so wet that this item actually functioned as a "knock-out drum." It was necessary to watch the water level in the desuperheater quite closely to avoid feeding water to the Venturi rather than steam.

When the entire unit was at the proper temperature and the steam supply system was readied, the standard procedure was to open the Venturi discharge valve wide and then set the Aroclor flow rate to a desired value. The following was then measured: the Aroclor inlet temperature and inlet pressure, the steam inlet pressure (in this case,



MU-27872

Fig. 5. Pressure loss characteristics of Venturi steam inlet.

this was the pressure at the Venturi throat), and the Venturi discharge temperature and pressure. The discharge pressure was then incrementally increased, and the Aroclor flow rate was readjusted to the desired value for each increment. The data taken at each increment were the same as before. Operation in this manner yielded information on the Venturi's performance under no-steam feed conditions. It also provided a base for evaluating the true Aroclor temperature-differential when steam was added to the unit.

The experiments in which steam was added to the unit were set up exactly like the no-steam flow runs. The steam feed to the unit was then varied until the desired steam inlet pressure was reached. The same data as described above were taken, and in addition, the steam inlet pressure at the Venturi, and steam-orifice-meter pressure differential. The same procedure was followed as outlined above for incrementally increasing the discharge pressure. The exception was that with a steam feed to the unit, both Aroclor feed rate and steam feed rate required readjustment after each increase in discharge pressure.

D. Results and Discussion

1. Operability and Stability

The experimental apparatus proved to be a very simple and easily manipulated unit. Examination of the equipment flowsheet (Fig. 3) shows that potentially a serious difficulty might exist in adjusting and maintaining flow rates, because of the requirement of a throttle valve on the Aroclor flow and another on the Venturi discharge. However, this problem did not arise. Usually, with the unit operating it was sufficient to adjust the discharge valve until the desired pressure was reached. After that, a slight trim of the Aroclor and steam valves was all that was required to restore the previous Aroclor flow and steam inlet pressure. Also, the system appeared to be quite stable. Once a desired set of operating conditions had been attained, these conditions showed very little tendency to drift.

A final operational feature of interest was that whenever steam was fed to the unit, a high-frequency but low-amplitude noise was heard. The frequency was slightly less than a hum, and although the vibrations were physically evident, they did not affect the experiment, even though the apparatus was not rigidly supported. These vibrations could be damped by adding roughly 5% of air to the steam.

2. Cavitational Effects

The noise mentioned above was undoubtedly caused by the rapid collapse of the steam, or in short, cavitation. To observe the effect of this cavitation, the experimental unit was cut in two and examined. The photographs (Figs. 6, 7, and 8) are a series of progressively magnified views of one of the half-sections. The bulk of the unit was in "as new" condition except for the markings inside within one inch of the Aroclor outlet nozzle (the steam-injection area). Examination of these dark areas showed that there was some pitting and much discoloration. The pits were apparently quite random with no discernible pattern. Also, the pits were not deep enough to measure. The Venturi had been operated roughly 50 hours before it was cut up. Therefore, even though the pitting of the experimental unit was of little consequence, it is quite likely that such a unit in continuous service would have a useful life measured in months rather than the usual years.

3. Correlation of Induction Characteristics

Figures 9, 10 and 11 are plots of the raw data taken with the unit. The Aroclor flow rate is the abscissa, and the steam flow rate is the ordinate. The parameters are steam supply pressure at the Venturi (called P_c), the Aroclor inlet temperature, and the Venturi discharge pressure.

These curves show that the unit behaved as expected. When the discharge pressure of the Venturi was at 0 psig, the Aroclor did not fill the unit and therefore we could expect the steam flow rate to be relatively independent of the Aroclor flow rate, as indicated by the data.

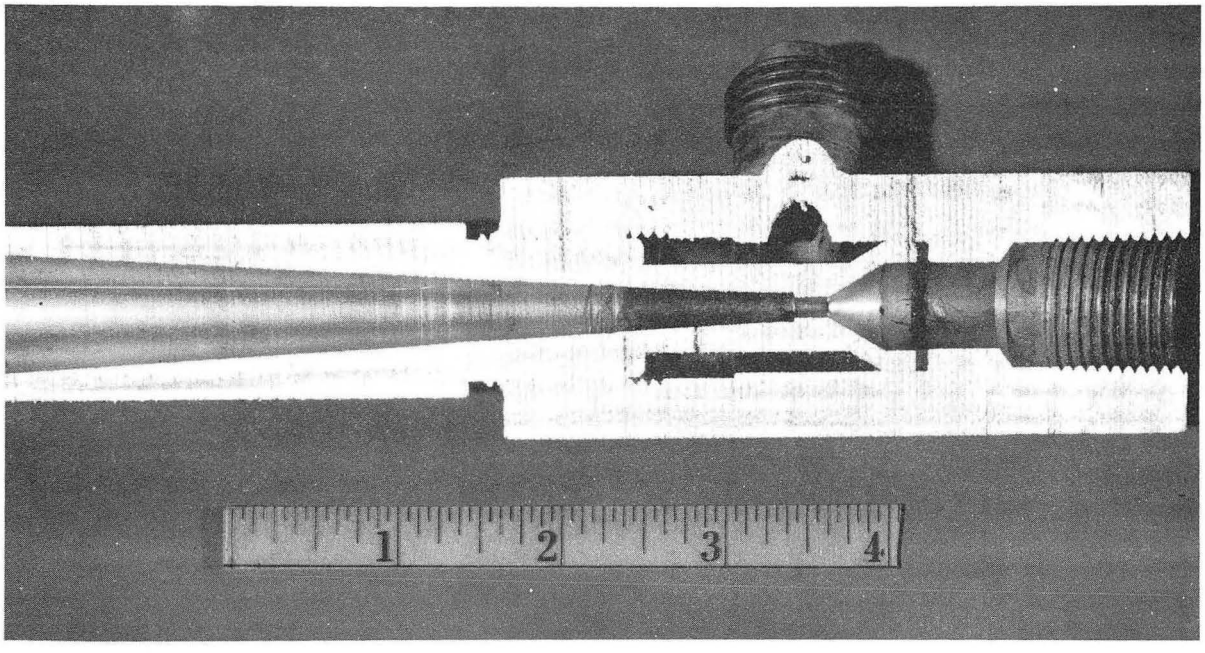


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Fig. 6. Half-section of the experimental unit.

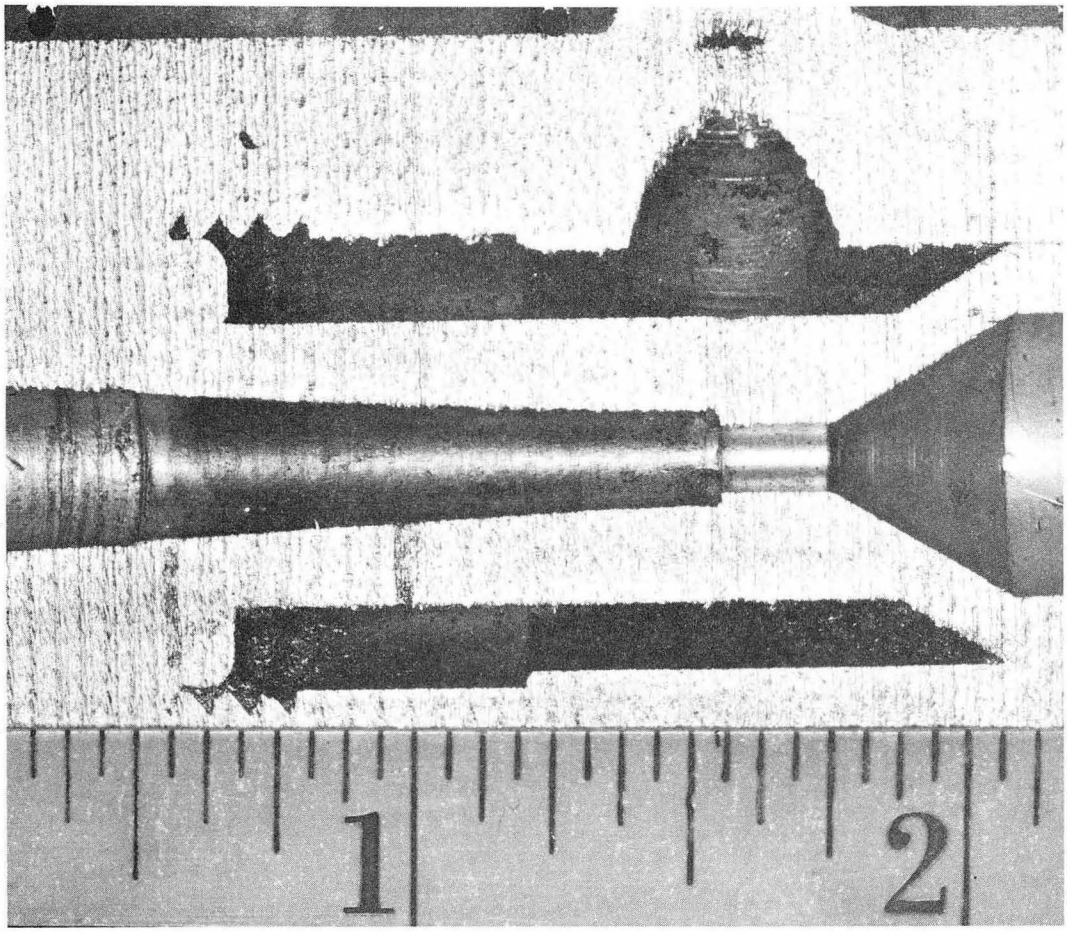

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Fig. 7. Close up view of cavitated area.

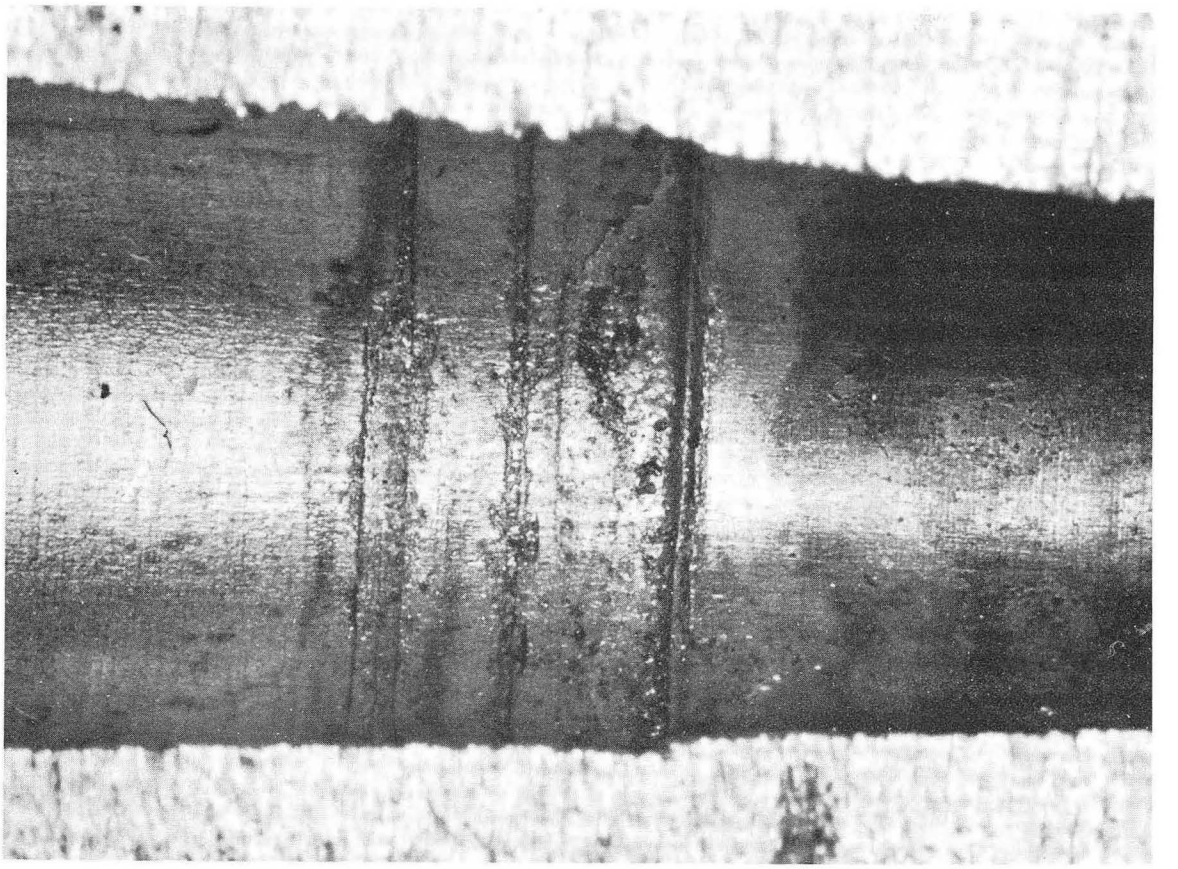

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Fig. 8. Detail showing pitting and discoloration caused by cavitation in the most affected area.

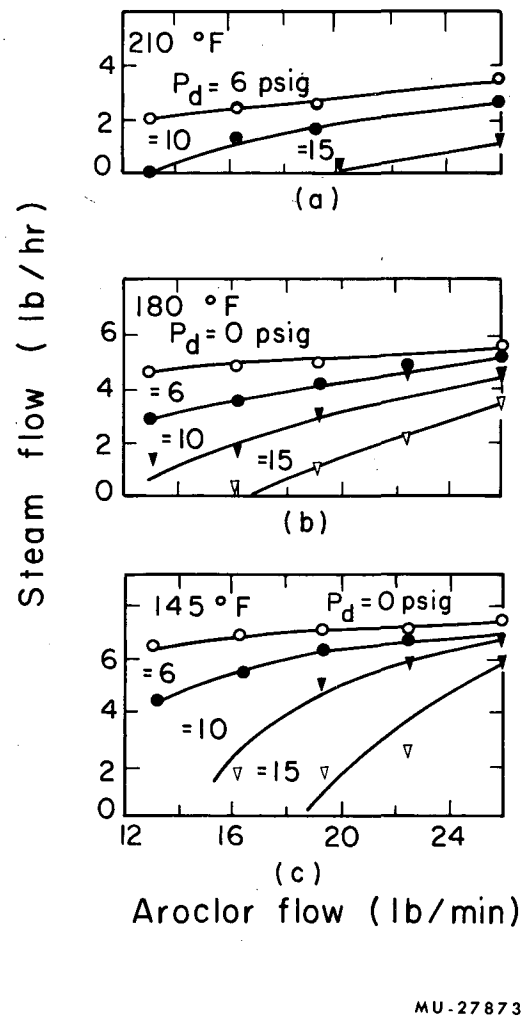

Fig. 9. Venturi operating characteristics at 6 psig steam inlet pressure. Aroclor inlet temperatures were (a) 210°F, (b) 180° F, and (c) 145° F.

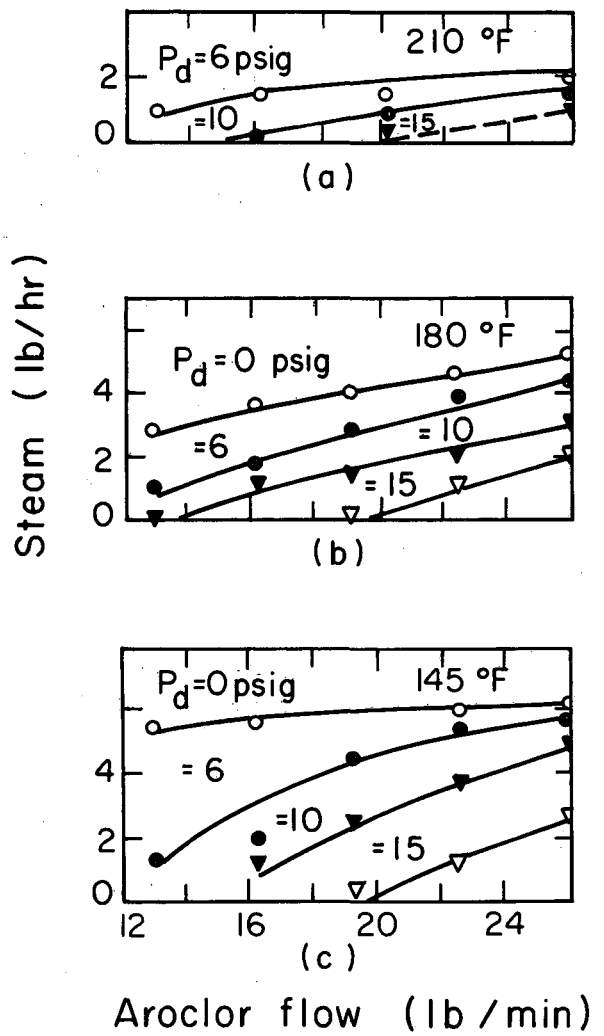

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Fig. 10. Venturi operating characteristics at 3 psig steam inlet pressure. Aroclor inlet temperatures were (a) 210° F, (b) 180° F, and (c) 145° F.

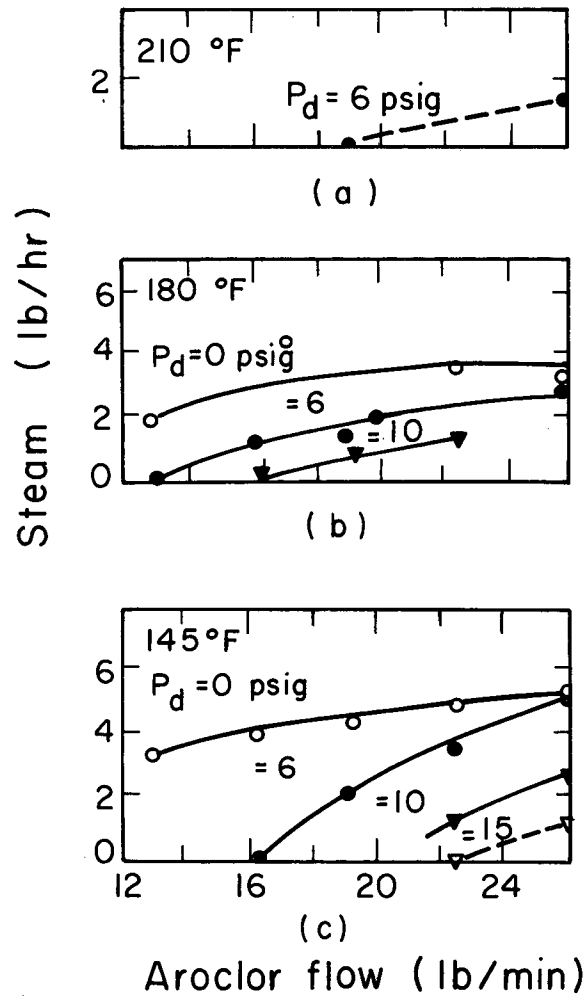

Fig. 11. Venturi operating characteristics with 0 psig steam inlet pressure. Aroclor inlet temperatures were (a) 210° F, (b) 180° F, and (c) 145° F.

Similarly, at a discharge pressure of 15 psig the Aroclor should certainly fill the diffuser, and therefore the steam flow rate would be a strong function of the Aroclor flow rate. Again, this is what the data indicated. As the discharge pressure was increased from 0 psig, then, one expected the steam flow to become an increasingly stronger function of the Aroclor flow rate. This, in fact is what the data shows.

The outstanding feature of these nine curves (Figs. 9 through 11) is the pronounced effect they show of the Aroclor inlet temperature; as the temperature was increased, the steam flow rate dropped drastically. Part of this was attributed to cavitation of the Aroclor flow nozzle; however, it is unlikely that this is the total cause of the efficiency loss.

The approach to correlating the data was to obtain an empirical equation that best fitted the data, rather than forcing a similarity to a theoretical equation. This empirical equation was found to be

$$F_s = (0.56 + 0.04\ P_c - 0.012\ P_d)\ F_A^{0.70} \quad , \qquad (1)$$

where F_s is the steam flow rate in lbs/hr, P_c is the steam pressure in psig, P_d is the discharge pressure in psig, and F_A is the Aroclor flow rate in lbs/min. This equation closely resembles that developed from the simplified force balance, and it describes most of the data taken at an Aroclor inlet temperature of 140 °F. It does not describe all the data. It was found by trial and error that the criterion for the use of the equation was the dimensionless parameter

$$\left(\frac{P_d - P_c}{P_c}\right)\left(\frac{F_{A\,(max)}}{F_A}\right)^{1.5} \leq 0.50 \ . \qquad (2)$$

Note that if the ratio is less than or equal to 0.50, the equation applies. It is postulated that this ratio has the same significance as the Reynolds number in fluid flow calculations.

For operation at higher Aroclor temperatures, it was found that the data correlated reasonably well into the form

$$F_{s(cav)} = F_s f, \tag{3}$$

where

$$f = (1.16 - 0.057\ P_v) - (1.86)(P_d - P_c)(P_v - 2.8)^{0.9} \times 10^{-3}, \tag{4}$$

where P_v is the vapor pressure of water (in psia) at the temperature of the inlet Aroclor. It is not too surprising to find that P_v was the strongest variable in this empirical equation. Even though all the water was removed that would separate by gravity settling, a considerable number of water droplets remained suspended in the Aroclor. One spot check discovered that the Aroclor was 1% water! Also, it was not surprising to find that as the vapor pressure was increased, the unit finally reached a point at which it was no longer an induction device. To illustrate this, let $P_d - P_c = 0$, and let $f = 0$. Then solving for P_v yields $P_v = 20$ psia. Therefore, if we have $P_v = 20$ psia, and to get a value of $f > 0$, $P_d - P_c$ must be negative; or in other words, the steam-supply pressure must exceed the Venturi discharge pressure.

Figure 12 compares steam flow rates calculated from the empirical equations against those measured. Obviously, the equation for operation of the Aroclor flow nozzle without cavitation more adequately describes the situation than does the equation derived for cavitation of the flow nozzle. In either case, the vast majority of the calculated points falls within the accuracy range of the steam meter.

The Aroclor pressure-drop characteristics of the Venturi seemed quite high, both with and without a steam feed to the unit (see Fig. 13). However, the measured Aroclor pressure drop across the unit with no-steam flow corresponded very closely to the theoretical pressure drop. For example, at the maximal Aroclor flow rate of 26 lb/min and a discharge pressure of 0 psig, the measured pressure drop was 25 psi and the theoretical pressure drop was 23 psi. The Aroclor pressure drop across the unit with steam flow appeared to be primarily a function of the Aroclor flow rate and the discharge pressure. It is reasonable to expect that the increase in the Aroclor pressure drop from no-steam flow to a steam flow is a function of the steam flow rate.

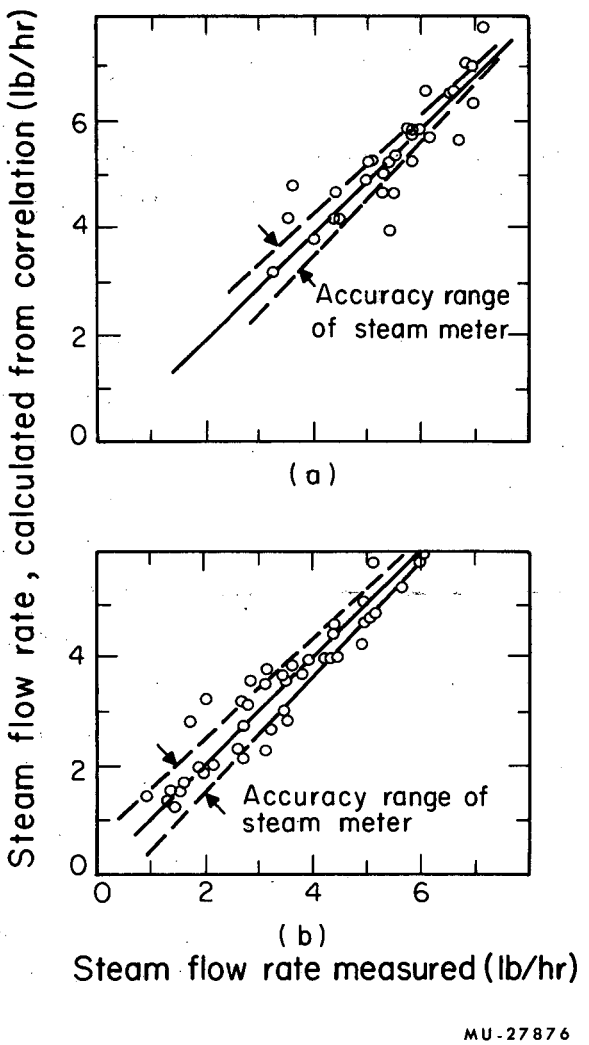

Fig. 12. Comparison of steam flow rates calculated from correlation with those measured experimentally. Operation of Aroclor flow nozzle was in (a) not cavitated, and in (b) with cavitation.

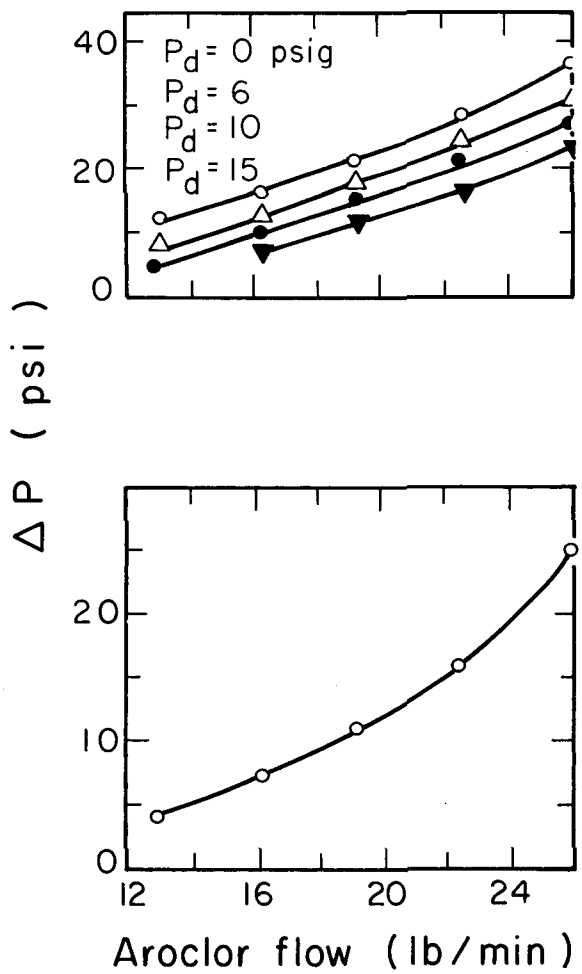

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Fig. 13. Venturi pressure-drop characteristics. The Aroclor inlet temperature in both cases was 140° F, but in (a) steam was supplied at 6 psig, while in (b) no steam was supplied to the unit.

However, Fig. 14 indicates that there is no such reasonable relationship between these variables. A close examination of Fig. 13(a) shows that the Aroclor pressure drop with a steam feed to the unit is almost linear with Aroclor flow rate. Empirically then, this relation is

$$\Delta P = 1.77(F_A - A), \tag{5}$$

where

$$A = 11.2 + 0.75\,P_d. \tag{6}$$

Another item of interest is the volumetric ratio of steam to Aroclor at the higher steam flow rates. For example, consider the data taken at 26 lb/min of Aroclor at 140 °F, 0 psig steam pressure, and 0 psig discharge pressure. The weight ratio of steam to Aroclor is not particularly impressive:

$$\frac{5.5 \text{ lb/hr (steam)}}{26 \times 60 \text{ lb/hr (Aroclor)}} = 3.5 \times 10^{-3} \ \frac{\text{lb(steam)}}{\text{lb(Aroclor)}}.$$

However, on a volume basis, this ratio becomes

$$\frac{3.5 \times 25 \text{ ft}^3/\text{lb (steam)} \times 10^{-3}}{1/87 \text{ ft}^3/\text{lb (Aroclor)}} = 7.6 \ \frac{\text{ft}^3\text{(steam)}}{\text{ft}^3\text{ (Aroclor)}}$$

These two ratios point up the most troublesome problem of the process; that of the extreme volumes of steam involved to obtain a reasonable Aroclor temperature increase.

4. Heat Transfer Characteristics

The volumetric heat transfer coefficients are shown in tabular form in the data tables (I-VII). The experiments were originally planned with the intention that the first group would define the steam induction and injection characteristics of the Venturi, and that the second would define the volumetric heat transfer characteristics. Unfortunately, the available steam supply pressure was not high enough to allow operation at measurable conditions in which the volumetric heat

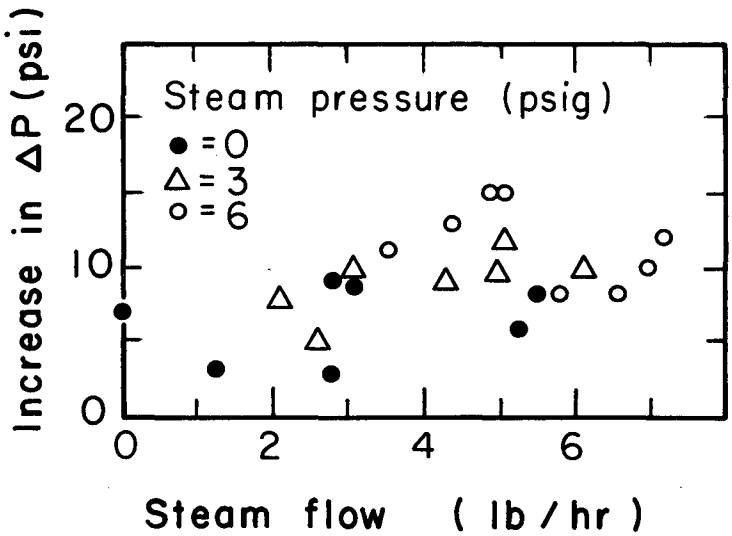

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Fig. 14. Increased Aroclor pressure drop as a function of steam flow rate. The Aroclor flow rate for all three steam pressures is 26 lb/min.

transfer capacity of the Venturi was exceeded; this condition was satisfied only in those runs made at an Aroclor inlet temperature of 210 °F and a discharge pressure of 0 psig.

It was not possible under these conditions to measure the Aroclor temperature-rise accurately enough to be meaningful. More accurate temperature-sensing elements would not have solved the problem, because in the diffuser they would have had to measure a liquid temperature very accurately in a liquid-vapor mixture. Since the primary purpose of this particular project has been to develop a cost comparison ov various methods of direct contact condensation, this discrepancy in the true effective diffuser volume is not of major concern. The small amount of additional volume involved could easily have been added to a minimum Venturi in the form of a short tailpipe. Therefore, each of the coefficients shown in the table is a minimum coefficient, because the volume upon which they are based is in excess of that actually required. Even so, the calculated coefficients are quite large, predominantly in the range of 150,000 to 4000,000 Btu/hr-ft^3 - °F.

The photographs of the Venturi half-section (Figs. 6 through 8) show pits and discoloration of the Venturi's diffuser sidewalls in only the first inch, indicating that at least the major portion of the condensation occurred in this small volume. The remainder of the diffuser was in "as new" condition. The ratio of the total diffuser volume to this smaller volume is roughly 20 to 1, which indicates that the actual volumetric heat transfer coefficients are at least three million Btu/hr-ft^3 - °F. This then confirms the theoretical prediction of coefficients in the millions of Btu/hr-ft^3 - °F.

Table I. Venturi data Aroclor flow rate, 26 lb/min.

Pressure at Venturi-Aroclor inlet (psig)	Pressure at steam inlet to Venturi (psig)	Pressure at Venturi discharge (psig)	Aroclor temperature at inlet (°F)	Temperature at Venturi discharge (°F)	Steam flow rate (lb/hr)	F_s (Calc'd)	ΔT Venturi (°F) (Meas'd)	ΔT Venturi (°F) (Calc'd)	U_v (Btu/hr-ft^3-°F)
25	-11.3	0	140		0				
26	-10.8	5			0				
25	-10.8	10			0				
31	- 4.7	15			0				
33	0	0	140	150	5.5	5.5	10	12.6	164,000
33	0	6	140	150	5.3	4.8	10	12.1	134,000
34	0	10	140	146	2.8		6	6.4	67,500
34	0	15	140	143	1.2		3	2.8	25,600
35	3	0	144	157	6.1	6.6	13	14	185,000
35	3	6	144	156	5.8	5.9	12	13.3	149,000
35	3	10	144	155	5.0	5.4	11	11.5	121,000
36	3	15	144	150	2.6		6	6	56,400
37	6	0	141	157	7.2	7.8	16	16.5	203,000
37	6	6	141	157	7.0	7.1	16	16	167,000
38	6	10	142	158	6.6	6.6	16	15.2	150,000
39	6	15	143	156	5.8	6.0	13	13.3	122,000
23	-12.3	0	177		0				
23	-11.3	5			0				
25	- 9.3	10			0				
28	- 3.4	15			0				
32	0	0	182	188	3.1	3.8	6	6.8	222,000
32	0	5	182	188	2.8	3.1	6	6.1	164,000
32	0	10	182	182	0		0	--	--
35	3	0	171	185	5.1	4.8	14	11.2	260,000
35	3	6	177	186	4.3	4.0	9	9.4	189,000
35	3	10	179	185	3.1	3.5	6	6.8	125,000
36	3	15	180	182	2.1	3.5	2	4.5	

(cont.)

Table I. (cont.)

Pressure at Venturi-Aroclor inlet (psig)	Pressure at steam inlet to Venturi (psig)	Pressure at Venturi discharge (psig)	Aroclor temperature at inlet (°F)	Temperature at Venturi discharge (°F)	Steam flow rate (lb/hr)	F_s (Calc'd)	ΔT Venturi (°F)		U_v (Btu/hr-ft^3-°F)
							(Meas'd)	(Calc'd)	
37	6.25	0	180	193	5.1	5.8	13	11.2	308,000
38	6.25	5	181	194	4.9	5.0	13	10.8	225,000
38	6.25	10	182	194	4.4	4.4	12	9.7	180,000
39	6.25	15	182	191	3.6	3.8	9	7.9	139,000
26	-6.9	0	208						
26	-6.9	6							
26	-6.9	10							
27	-6.1	12							
28	-3.9	15							
32	0	0	210	211	2.1	1.9	1	(4.5)	
35	0	6	211	212	1.4	1.2	1	(3.0)	
33	0	10	211		0		0	0	
34	3	0	211	212	3.2	2.6	1	(6.9)	
36	3	6	211	214	1.9	1.8	3	4.1	306,000
34	3	10	211	213	1.4	1.5	2	3.0	169,000
34	3	15	211	211	0.9		0	2.0	82,000
39	6.50	6	210	217	3.5	2.8	7	7.5	422,000
39	7	10	210	216	2.7	2.1	6	5.8	238,000
39	7	12	210	214	1.9	1.8	4	4.1	
39	7	15	210	213	1.2	1.3	3	2.6	86,000

Table II. Venturi data; Aroclor flow rate, 22-1/2 lb/min.

Pressure at Venturi-Aroclor inlet (psig)	Pressure at steam inlet to Venturi (psig)	Pressure at Venturi discharge (psig)	Aroclor temperature at inlet (°F)	Temperature at Venturi discharge (°F)	Steam flow rate (lb/hr) ΔP_0 (in./Hg)	Steam flow rate (lb/hr) (lb/hr)	F_s (Calc'd)	ΔT Venturi (°F) (Meas'd)	ΔT Venturi (°F) (Calc'd)	U_v (Btu/hr-ft^3-°F)
16	-11.8	0	145							
19	- 8.3	6								
23	- 4.4	10								
29	0	15								
25	0	0	142	153	2.00	5.0	5.0	11	13.2	149,000
25	0	6	142	150	1.05	3.5	4.3	8	9.3	90,000
26	0	10	142	144	0.15	1.2		2	3.2	28,000
28	0	15	142	143	0.05	0		1	0	
28	3	0	142	156	2.60	5.8	6.0	14	15.4	167,000
28	3	6	142	156	2.30	5.4	5.4	14	14.3	137,000
29	3	10	142	151	1.10	3.6	4.9	9	9.5	84,000
29	3	15	142	144	0.10	0.9		2	2.4	19,000
29	6	0	144	160	3.44	6.9	7.1	16	18.3	193,000
31	6	6	144	160	3.20	6.5	6.5	16	17.2	161,000
32	6	10	144	158	2.55	5.7	6.0	14	15.1	131,000
33	6	15	143	149	0.50	2.3		6	6.1	44,400
17	- 8.8	0	180							
17	- 8.8	6								
20	- 4.9	10								
25	0	15								
24	0	0	180	186	1.05	3.5	3.5	6	8.8	232,000
23	0	6	179	181	0.30	1.7	2.8	2	4.3	80,000
25	0	10	175	177	0.15	1.2		2	3.0	46,400
25	0	15	177	178	0.05	0		1	0	
27	3	0	173	184	1.6	4.4	4.4	11	11.1	223,000
27	3	6	174	183	1.2	3.8	3.7	9	9.6	160,000
27	3	10	174	179	0.4	2.0	3.2	5	5.1	73,000
28	3	15	174	176	0.10	0.9		2	2.3	28,500
30	6	0	172	186	2.10	5.6	5.3	14	14.2	257,000
31	6	6	173	185	1.90	4.9	4.6	12	12.4	185,000
31	6	10	172	184	1.60	4.4	4.0	12	11.1	149,000
32	6	15	172	178	0.40	2.0		6	5.0	58,300

Table III. Venturi data: Aroclor flow rate, 19-1/4 lb/min.

Pressure at Venturi-Aroclor inlet (psig)	Pressure at steam inlet to Venturi (psig)	Pressure at Venturi discharge (psig)	Aroclor temperature at inlet (°F)	Temperature at Venturi discharge (°F)	Steam flow rate (lb/hr) ΔP_0 (in./Hg)	Steam flow rate (lb/hr) (lb/hr)	F_s (Calc'd)	ΔT Venturi (°F) (Meas'd)	ΔT Venturi (°F) (Calc'd)	U_v (Btu/hr-ft^3-°F)
11	-10.8	0	145							
16	- 4.9	6								
20	- 1.2	10								
25	3 ½	15								
19	0	0	145	158	1.65	4.5	4.3	13	14	145,000
20	0	6	145	151	0.45	2.2		6	6.8	58,000
21	0	10	145	145	0	0		0	0	
21	3	0	145	161	2.60	5.8	5.4	16	18	178,000
22	3	6	145	158	1.60	4.4	4.8	13	13.6	115,000
24	3	10	145	152	0.55	2.4		7	7.4	57,000
24	3	15	145	145	0	0		0	0	
21	6	0	146	165	3.65	7.0	6.3	19	21.8	208,000
24	6	6	146	164	2.95	6.2	5.8	18	19.2	160,000
25	6	10	145	160	2.05	5.1	5.4	15	15.8	120,000
26	6	15	145	151	0.30	1.7		6	5.3	35,000
10	- 8.1	0	172							
14	- 4.9	6								
18	- 0.98	10								
23	4	15								
18	0	0	174	183	1.05	3.5	3.0	9	10.4	204,000
20	0	6	174	177	.20	1.4		3	4.1	60,000
20	0	10	174	176	.10	0.9		2	2.7	34,000
22	0	15	174	174	0	0		0	0	
21	3	0	175	187	1.25	3.9	3.9	12	11.6	215,000
21	3	6	176	184	.65	2.7	3.2	8	8	116,000
21	3	10	176	180	.20	1.4		4	4.1	52,000
22	3	15	176	176	0	0		0	0	

(cont.)

Table III. (cont.)

Pressure at Venturi-Aroclor inlet (psig)	Pressure at steam inlet to Venturi (psig)	Pressure at Venturi discharge (psig)	Aroclor temperature at inlet (°F)	Temperature at Venturi discharge (°F)	Steam flow rate (lb/hr)		F_s	ΔT Venturi (°F)		U_v
					ΔP_0 (in./Hg)	(lb/hr)	(Calc'd)	(Meas'd)	(Calc'd)	(Btu/hr-ft^3-°F)
22	6	0	176	192	1.95	5.0	4.7	16	14.8	262,000
23	6	6	176	190	1.40	4.2	4.0	14	12.5	172,000
24	6	10	177	187	.70	2.8	3.6	10	8.3	102,000
23	6	15	187	180	.10	0.9		2	2.7	28,000
10	-7.4	0	212							
13	-3.9	6								
17 ½	-1.5	10								
22	1	15								
18	0	0	211	211	0.20	1.4	1.5	0	(4.0)	
19	0	6	211	211	0	0		0	0	
21	3	0	211	212	0.85	3.1	2.2	1	(9.0)	
21	3	6	212	213	0.20	1.4	1.4	1	4.0	
21	3	10	212	212	0.10	0.9		0	2.6	
22	3	15	212	212	0	0		0	0	
24	7	7	214	222	0.60	2.6	2.2	8	7.5	418,000
25	7	10	214	219	0.25	1.6	1.7	5	4.6	171,000
25	7	12	214	217	0.10	0.9	1.4	3	2.6	
25	7	15	214	214	0	0		0	0	

Table IV. Venturi data: Aroclor flow rate, 16.2 lb/min

Pressure at Venturi-Aroclor inlet (psig)	Pressure at steam inlet to Venturi (psig)	Pressure at Venturi discharge (psig)	Aroclor temperature at inlet (°F)	Temperature at Venturi discharge (°F)	Steam flow rate (lb/hr) ΔP_0 (in./Hg)	Steam flow rate (lb/hr) (lb/hr)	F_s (Calc'd)	ΔT Venturi (°F) (Meas'd)	ΔT Venturi (°F) (Calc'd)	U_v (Btu/hr-ft^3-°F)
7	-7.9	0	145							
14	-1.0	6								
17	2.5	10								
23	7.5	15								
14	0	0	144	157	1.3	4.0	3.9	13	14.7	127,000
14	0	6	144	145	0	0		1	0	
15	3	0	144	163	2.35	5.5	4.8	19	20.2	171,000
16	3	6	144	152	0.35	1.90		8	7.0	47,500
17	3	10	144	146	0.10	0.90		2	3.3	20,400
22	3	15	144	144	0	0		0	0	
17	6	0	143	167	3.40	6.7	5.6	24	24.7	196,000
18	6	6	144	164	2.20	5.3	5.1	20	19.5	135,000
20	6	10	143	149	0.25	1.6		6	5.9	34,600
23	6	15	143	143	0	0		0	0	
4	-7.9	0	180							
11	-1.5	6								
15	1.5	10								
20	6.7	15								
11	0	0	180	189	0.65	2.70	2.7	9	9.5	193,000
12	0	6	181	183	0.15	1.20		2	4.2	59,000
15	0	10	181	181	0	0		0	0	
15	3	0	181	192	1.10	3.60	3.5	9	12.7	232,000
15	3	6	181	186	0.30	1.70		5	6.0	78,000
15	3	10	182	183	0.10	1.20		1	3.2	49,500
20	3	15	182	182	0	0		0	0	
18	6	0	182	198	1.90	4.9	4.2	16	17.2	305,000
17	6	6	182	196	1.05	3.5	3.6	14	12.3	165,000
18	6	10	182	188	0.25	1.50		6	5.3	58,000
19	6	15	182	184	(trace)	(0.8)		2		
6	-6.9	0	212							
10	-1.5	6								
15	2	10								
20	7	15								
12	0	0	213	212	0.20	1.4		-1	(4.8)	
12	0	6	213	212				-1	0	
14	3	0	210	211	0.75	2.9	1.9	1	(10)	
15	3	6	209	211	0.20	1.4		2	4.8	
15	3	10	209	209	0	0		0	0	
18	6	0	208	211	1.25	3.8	2.0	3	(13)	
18	6	6	208	216	0.55	2.4	1.5	8	8.3	257,000
19	6	10	207	210	0.20	1.4		3	4.8	104,000
20	6	15	207	207	0	0		0	0	

Table V. Venturi data: Aroclor flow rate, 13 lb/min

Pressure at Venturi-Aroclor inlet (psig)	Pressure at steam inlet to Venturi (psig)	Pressure at Venturi discharge (psig)	Aroclor temperature at inlet (°F)	Temperature at Venturi discharge (°F)	Steam flow rate (lb/hr) ΔP_0 (in./Hg)	Steam flow rate (lb/hr) (lb/hr)	F_s (Calc'd)	ΔT Venturi (°F) (Meas'd)	ΔT Venturi (°F) (Calc'd)
4	-5.4	0	146						
10	1	6							
15	4.8	10							
20	10.2	15							
8	0	0	144	159	0.95	3.3	3.3	14	15.2
10	0	6	144	144	0	0		0	0
11	3	0	146	168	2.25	5.4	4.1	22	24.8
11	3	6	146	151	0.15	1.2		5	5.5
15	3	10	146	146	0	0		0	0
12	6	0	147	175	3.05	6.3	4.8	28	29
14	6	6	146	167	0.155	4.3	4.4	21	19.8
15	6	10	146	146	0	0		0	0
2	-5.4	0	180						
9	2	6							
13	5	10							
18	10	15							
8	0	0	184	190	0.35	1.9		6	8.3
9	0	6	184	184	0	0		0	0
10	3	0	188	197	0.75	2.8		9	12.2
10	3	6	184	187	0.10	0.9		3	3.9
13	3	10	184	184	0	0		0	0
13	6	0	183	199	1.80	4.7		16	20
13	6	6	182	197	0.80	3.0		15	13.2
14	6	10	182	185	0.15	1.2		3	5.2
18	6	15	182	182	0	0		0	0
3	-4.9	0	208						
8	0	5							
13	5	10							
17.5	10.5	15							
6	0	0	208	210	0.10	0.90		2	(3.8)
8	0	6	209	209	0			0	0
11	3	0	209	211	0.50	2.3		2	(9.9)
10	3	6	210	211	0.10	0.90		1	3.9
13	6.5	0	212	212	1.5	4.3		0	(18.8)
14	6.8	5	214	216	0.6	2.55		2	(11.2)
15	7.0	10	2.4						

III. DIRECT INJECTION

A. Theoretical Discussion

The experimental Venturi we have considered in the preceding sections can also be regarded as a direct-injection device operating in the extremely turbulent flow region. However, it isn't necessary to inject steam in Aroclor under extremely turbulent conditions; therefore, this section deals with the expected performance of direct injection into the laminar flow region.

As would be expected, the mechanical energy requirements of such a device was low. From a mechanical energy loss standpoint, the ideal situation would have been to design a unit in which the Aroclor and steam velocities were essentially independent of one another. This would have required relatively low steam velocities and, since the volume ratio of steam to Aroclor can be quite high, extremely low Aroclor velocities. Under these conditions, the pressure drop across the unit would be determined by the Aroclor flow rate, and within limits would be independent of the steam flow rate. Also, the steam pressure drop would of necessity be identical to that of the Aroclor, except for entry losses.

In the laminar flow region the pressure drop can be predicted from the familiar Fanning equation

$$F = \frac{f V^2 L}{2 gD} ,$$

where $f = 64/Re$, and $Re = \frac{D\rho V}{\mu}$; and we have $V = C_1 F_A$, where F_A is the Aroclor flow rate.

Combining these quantities yields (for any single unit),

$$F = C_2 F_A .$$

Therefore, if the experimental system meets the criteria above, the data should show

$$\Delta_{P(steam)} = \Delta_{P(Aroclor)} = (\text{constant})(F_A) + \text{any gravity head} + \text{difference in entry losses.}$$

The theoretical heat transfer characteristics of the direct-injection device would follow those of our experimental Venturi. The contact between the steam bubbles and the Aroclor then becomes a problem of convection and unsteady-state condition, just as it was for the Venturi. However, if the Venturi analysis is examined closely, one finds that there are two prime variables: the surface area of contact and the condensing-film heat-transfer coefficient. Therefore, we can expect that in a low-velocity direct-injection device, the steam to Aroclor ratio would be a major variable. This ratio should define the maximum Aroclor temperature rise possible for total condensation in a fixed device. Also, by the same reasoning, for a given Aroclor flow, the volumetric heat-transfer coefficient should be almost directly proportional to the steam flow.

B. Experimental Equipment

The basic equipment used in the Venturi experiments was also used in the direct-injection experiments. The chief modification was the removal of the Venturi itself, and the installation of the equipment schematized in Fig. 15.

C. Experimental Procedure

The experimental procedure, so far as operation of the feed tank and other auxiliary equipment is concerned, was identical to that described in the section on the Venturi (Sec. II-B). The only difference between these experiments and those with the Venturi was that for a run, the discharge pressure and steam flow rate were maintained constant, and the Aroclor flow rate was varied. The dependent variables were the Aroclor inlet pressure, the steam inlet pressure, and the Aroclor temperature increase.

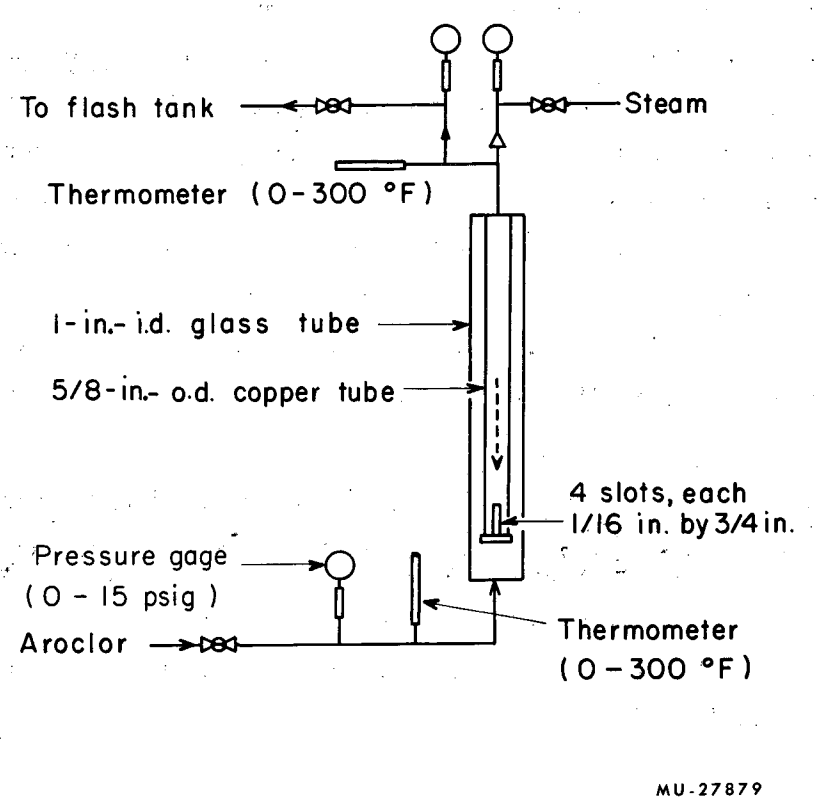

Fig. 15. Schematic diagram of direct-injection equipment. Pressure gauge (lower right) is equipped with a Marshalltown throttler (typical).

D. Results and Discussion

1. Operability and Stability

The direct injector was an exceedingly difficult device to operate. The vibration from the collapse of the steam bubbles was so violent that it was necessary to install Marshalltown throttlers on the pressure gauges to dampen them enough to allow reading. Also, the unit was not particularly stable. Constant manipulation was required to maintain the desired operating conditions.

2. Heat Transfer Characteristics

Figure 16 is a plot of the temperature increase of Aroclor against the Aroclor flow rate, for four different steam flow rates. The dotted curves show the temperature increases for complete condensation of the steam. Inspection of these curves indicates that a temperature increase of approximately 28 °F is the maximum possible with total condensation of the steam. We may conclude that a constant pressure, the ratio of Aroclor flow rate to steam flow rate, is a constant also for total condensation.

Figure 17 plots the volumetric heat transfer coefficient against the steam flow rate. The heat transfer coefficient is that for the maximum Aroclor temperature increase, consistent with total steam condensation. The linear relationship indicated that

$$U_v = 9.200 \ F_s,$$

where $F_s \equiv$ steam flow in lb/hr, and $U_v \equiv$ heat transfer coefficient (volumetric average) = Btu/hr-ft^3-°F, might well be expected under the conditions specified. The steam bubble-size issuing from the injector should be generally independent of steam flow rate (within limits of flow discussed in this paper). Also, at relatively low steam and Aroclor flows, the steam-bubble velocity is caused by the difference in the density of the Aroclor and the steam, and is therefore independent of steam flow rate. We then conclude that the surface area for heat

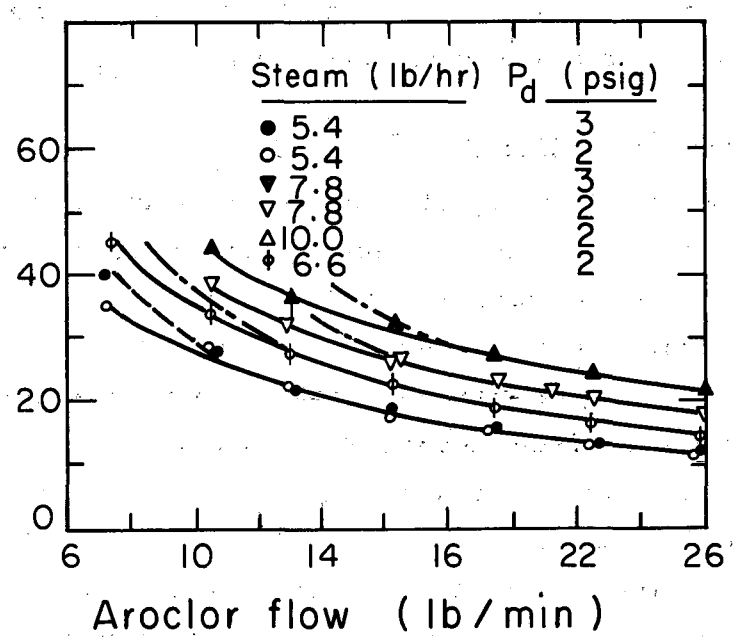

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Fig. 16. Direct-injection Aroclor temperature increases; Note: dotted curves show ΔT calculated from a material and heat balance.

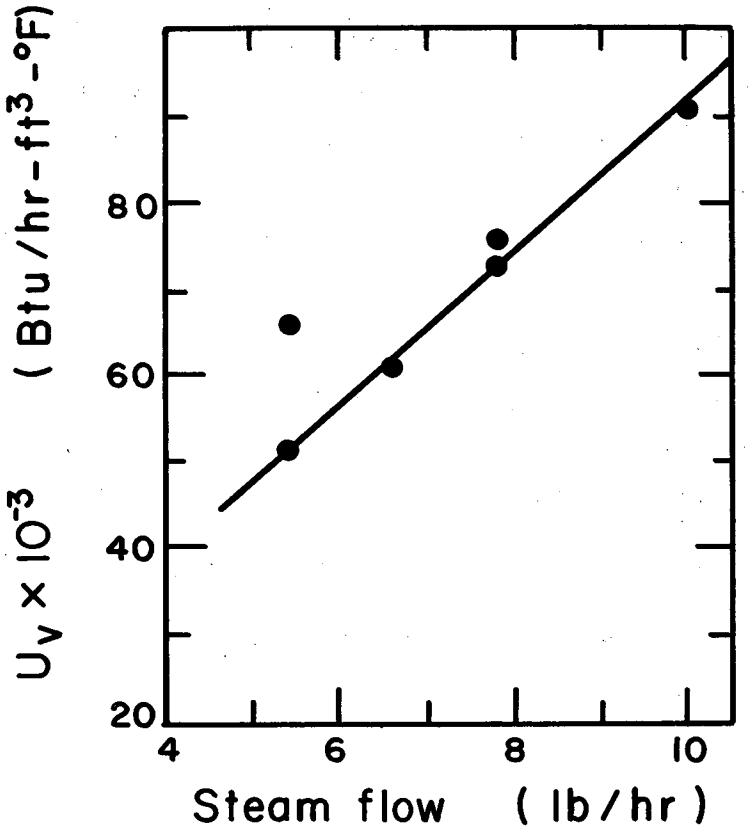

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Fig. 17. Direct-injection heat transfer coefficient.

transfer is directly proportional to the steam flow rate. If the condensation film coefficient for heat transfer is constant, then the volumetric heat-transfer coefficient is directly proportional to the steam flow rate.

From the above reasoning, it was presumed that as the steam flow rate is increased beyond the maximum that will condense, the U_v (Btu/hr-ft^3-°F) increases. The data (Tables VI and VII) indicate that this is true. However, sufficient data to develop a dependable correlation for these conditions were not taken. The point, not being of interest to this study, was therefore not pursued further.

3. Pressure Drop Characteristics

The Aroclor pressure drops at various Aroclor flow rates and steam flow rates are shown in Fig. 18. The pressure drops plotted are corrected and include 18 inches of gravity head. Correction was necessary because the experimental device had a large pressure drop between the Aroclor pressure gauge and the inlet to the glass tube. Rather than rebuild the device, it was decided to run it at no steam flow, and then to measure the Aroclor pressure at the steam inlet with the steam pressure gauge. The difference in these gauge readings, minus the gravity head, represents the frictional loss between the Aroclor pressure gauge and the steam inlet. This loss was measured at all the Aroclor flow rates used in the experiments.

The Aroclor pressure-drop characteristics of the device were as predicted in the theoretical discussion (see Sec. III-A). The pressure drop was linear with the Aroclor flow rate, and was essentially independent of the steam flow rate. The relationship between the Aroclor flow rate and the pressure drop was found to be approximately

$$\Delta P = 0.05\ F_A + 1.4,$$

where ΔP is in psi, and F_A is in lb (Aroclor)/min.

The steam pressure drops at various Aroclor flow rates and steam flow rates are shown in Fig. 19. This relationship is approximately $\Delta P = 0.05$, and $F_A + 1.0$.

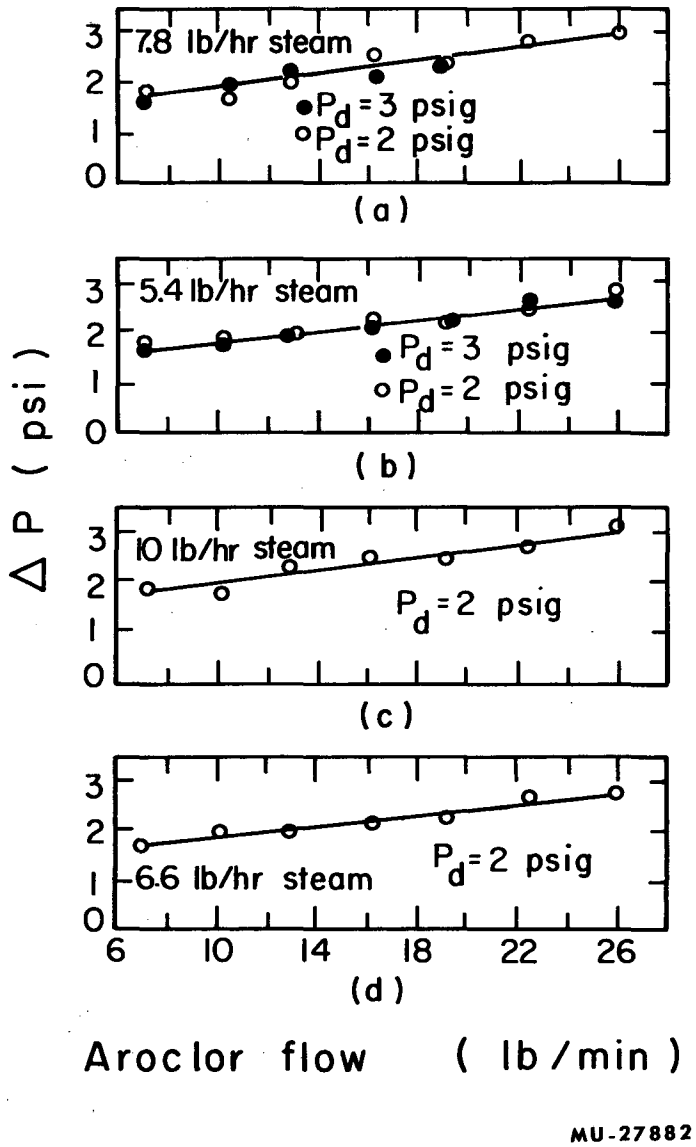

Fig. 18. Direct-injection steam pressure drop.

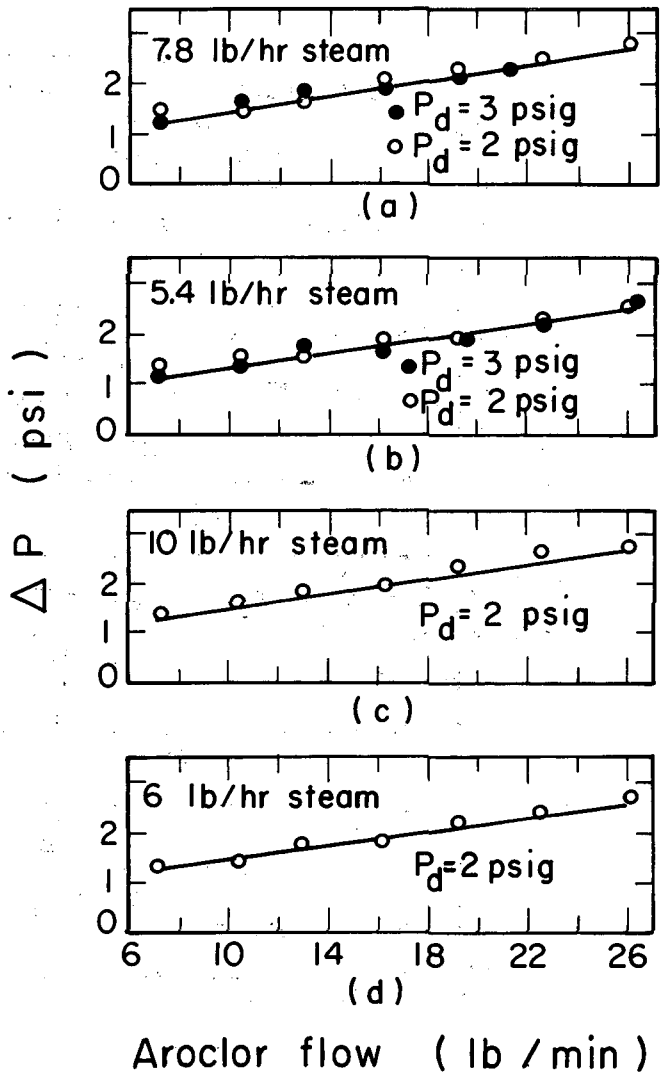

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Fig. 19. Direct-injection Aroclor pressure drop.

Table VI. Direct injection (discharge pressure = 3.0 psig)

Aroclor flow (lb/min)	Aroclor inlet pressure (psig)	Corrected Aroclor pressure (psig)	Steam inlet pressure (psig)	Steam flow (lb/hr)	Aroclor temperature (°F)		Aroclor temp rise (°F)		Aroclor pressure drop (psi)		U_v (Btu/hr-ft^3-°F)
					(Inlet)	(Exit)	(Meas'd)	(Calc'd)	(Total)	(Total less gravity head)	
26	9.0	5.8	4.9	0	160	160			2.8	1.9	
22.5	7.9	5.6	4.7						2.6	1.7	
19.25	7.2	5.2	4.3						2.2	1.3	
16.2	6.4	5.0	4.1						2.0	1.1	
13	5.8	4.8	3.9						1.8	0.9	
10.5	5.4	4.7	3.8						1.7	0.8	
7.2	4.9	4.5	3.6						1.5	0.6	
26	8.9	5.7	5.7	6.6	161	177	16	14	2.7	1.8	52,000
22.5	8.0	5.7	5.4		161	178	17	16	2.7	1.8	53,000
19.25	7.3	5.3	5.1		162	181	19	19	2.3	1.4	56,000
16.2	6.6	5.2	4.8		162	185	23	23	2.2	1.3	58,000
13	6.0	5.0	4.7		162	190	28	28	2.0	1.1	61,000
10.5	5.7	5.0	4.4		164	197	33	36	2.0	1.1	67,000
7.2	5.1	4.7	4.3		164	209	45	51	1.7	0.8	85,000
26	8.8	5.6	5.6	5.4	160	173	13	12	2.6	1.7	41,000
22.5	7.9	5.6	5.2		160	175	15	13.4	2.6	1.7	42,000
19.25	7.2	5.2	4.9		161	177	16	15.4	2.2	1.3	43,000
16.2	6.6	5.2	4.7		161	180	19	18.5	2.2	1.3	45,000
13	6.0	5.0	4.7		162	184	22	25	2.0	1.1	47,000
10.5	5.5	4.8	4.3		164	192	28	29.5	1.8	0.9	51,000
7.2	5.0	4.6	4.2		165	205	40	42	1.6	0.7	52,000
21.2	7.7		5.4	7.8	162	183	21	21			
19.25	7.3	5.3	5.2		162	185	23	22.5	2.3	1.4	68,000
16.2	6.6	5.2	4.9		163	190	27	27	2.2	1.3	73,000
13	6.3	5.3	4.8		164	195	31	33	2.3	1.4	75,000
10.5	5.7	5.0	4.6		166	206	40	42	2.0	1.1	101,000
7.2	5.1	4.7	4.2		167	212	45	60	1.7	0.8	100,000

Table VII. Direct injection (discharge pressure 2.0 psig)

Aroclor flow (lb/min)	Aroclor inlet pressure (psig)	Corrected Aroclor pressure (psig)	Steam inlet pressure (psig)	Steam flow (lb/hr)	Aroclor temperature (°F)		Aroclor temp rise (°F)		Aroclor pressure drop (psi)		U_v (Btu/hr-ft^3-°F)
					(Inlet)	(Exit)	(Meas'd)	(Calc'd)	(Total)	(Total less gravity head)	
26	7.1	4.3	3.4	0	160	160			2.3	1.4	
22.5	6.75	4.3	3.4						2.3	1.4	
19.25	6.4	4.3	3.4						2.3	1.4	
16.2	5.4	4.2	3.3						2.2	1.3	
13	4.8	3.9	3.0						1.9	1.0	
10.5	4.6	3.8	2.9		160	181	21	21.4	1.8	0.9	
7.2	4.0	3.7	2.8						1.7	0.8	
26	7.9	5.1	4.7	10	160	181	21	21.4	3.1	2.2	86,000
22.5	7.1	4.7	4.6		160	184	24	24.5	2.7	1.8	87,600
19.25	6.6	4.5	4.3		160	187	27	27.5	2.5	1.6	91,400
16.2	5.7	4.5	4.0		160	192	32	34	2.5	1.6	98,000
13	5.2	4.3	3.8		162	198	26	43	2.3	1.4	102,000
10.5	4.6	3.8	3.6		164	208	44	54	1.8	0.9	127,000
7.2	4.2	3.9	3.4		165	212	47	77	1.9	1.0	116,000
26	7.8	5.0	4.8	7.8	162	181	19	18	3.0	2.1	67,000
22.5	7.2	4.8	4.5		162	181	19	20	2.8	1.9	68,000
19.25	6.4	4.3	4.3		163	186	23	24	2.3	1.4	70,000
16.2	5.8	4.6	4.0		164	190	26	28	2.6	1.7	76,000
13	5.0	4.1	3.7		166	198	32	35	2.1	1.2	89,000
10.5	4.5	3.7	3.4		167	205	38	45	1.7	0.8	100,000
7.2	4.2	3.9	3.4		169	211	42	63	1.9	1.0	99,000
26	7.6	4.8	4.6	5.4	166	178	12	11.8	2.8	1.9	47,000
22.5	6.9	4.5	4.3		166	180	14	13.4	2.5	1.6	49,000
19.25	6.1	4.3	3.9		167	182	15	15.4	2.3	1.4	51,000
16.2	5.5	4.3	3.8		168	185	17	18.5	2.3	1.4	50,000
13	4.9	4.0	3.6		169	191	22	23	2.0	1.1	57,000
10.5	4.5	3.9	3.5		170	198	28	29.5	1.9	1.0	66,000
7.2	4.1	3.8	3.3		172	207	35	42	1.8	0.9	76,000

These empirical equations are listed as "approximately" because there seemed to be a very slight dependence of pressure drop on the steam flow rate. This apparent dependence has been ignored, because the accuracy was such that it was within the experimental error. The difference of 1.4 and 1.0 at zero Aroclor flow is easily explained by the 8-in. gravity head difference between the Aroclor pressure gauge and the steam inlet. Therefore, the pressure-drop characteristics of the direct-injection device were as expected.

IV. THE PACKED TOWER

A. Theoretical Discussion

Shao-chio Hu, in an article describing packed tower direct-contact gasoline condensers, included the details of his design technique.[2] The system he was working with used a vapor stream composed primarily of gasoline with some steam and a small amount of noncondensables. The coolant was water. Very briefly, his design technique was the following:

(a) Calculation of the system's heat and material balances.

(b) Calculation of the tower diameter, using the curve of Sherwood et al:[9]

$$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2} \text{ vs } \frac{U_0^{\,2}}{g_c}\,\frac{a}{F^3}\,\frac{\rho_G}{\rho_L}\,\mu^{0.2}$$

For his own tower diameter, Hu designed a diameter just slightly larger than that for flooding.

(c) Calculation of HTU (height of transfer unit in ft) from the equation of Sherwood and Holloway,[10]

$$H_L = \frac{1}{a}\left(\frac{L}{\mu}\right)^n \left(\frac{\mu}{\rho_L D_L}\right)^s .$$

The diffusivity D_L was calculated using Wilke's equation[11]

$$D_L = \frac{4.0\times 10^{-7}\, T_L}{\mu\,(V_s^{\,1/3} - k_1)} .$$

(d) Calculation of the liquid mass-transfer coefficient from

$$k_L\, a = \frac{1}{H_L \rho_L} .$$

(e) Calculation of the number of transfer units from

$$\frac{haV}{L} = \frac{T}{LMTD}, \text{ and } N_t = \frac{haV}{L(Le)c},$$

where Le (Lewis number) = $\left[\frac{k}{(\rho_G D_v D)}\right]^{2/3}$.

Term D_v was calculated from the Arnold equation.

(f) Calculation of tower height from $H = N_t H_L$.

Nevertheless, there are good reasons to doubt the validity of Hu's technique. For example, his assumption that the liquid film is controlling is quite valid at the bottom of the tower when the vapor is rich in gasoline. It is questionable, however, that the liquid film would be controlling at the top of the tower where the vapor is very lean in gasoline. Perhaps his most dubious step is the calculation of the tower height (step f) from a number of transfer units based on the gas properties and the height of a liquid-film transfer unit.

A design technique that has a sound theoretical basis can be developed from analogies between heat and mass transfer, and known mass-transfer characteristics. The approach is to divide the tower into two sections, a desuperheating zone and a condensation zone. In the desuperheating zone, the heat transfer can be calculated by analogy to a mass-transfer situation in which the gas film is controlling. In the condensation zone, one should assume that, once the vapor saturation temperature is reached, the condensation process is controlled by unsteady-state conduction into the liquid.

It is proposed to estimate the coefficient for unsteady-state conduction by analogy to liquid-film controlled liquid-phase mass transfer, and to adapt the relevant factors to the design technique.

In the desuperheating zone, the heat balance on a differential element of tower volume is

$$dq = ha\,(T - t)\,dV = AG\,Cp\,dt,$$

or

$$\frac{haV}{ACpG} = \int \frac{dt}{T - t} \approx \ln \frac{T_1 - t_1}{T_2 - t_2} = \frac{haZ}{CpG}.$$

Since Z equals the tower height,

$$Z = \frac{CpG}{ha} \ln \frac{T - t_1}{T - t_2} \quad . \tag{7}$$

The Chilton-Colburn analogy provides a basis for estimating the heat-transfer coefficient from the mass-transfer coefficient.[12] The relationships are

$$J_H = J_D,$$

$$J_H = (St)_{HT} (Pr)^{2/3} \quad ,$$

and

$$J_D = (St)_{MT} (Sc)^{2/3} \quad ,$$

where

$$(St)_{HT} \equiv \text{Stanton number for heat transfer} \equiv \frac{h}{Cp\,U_0} \quad ,$$

$$Pr = \text{Prandlt number} = \frac{Cp\mu_G}{k} \text{ of } \frac{Cp\mu_L}{k} \quad ,$$

$$(St)_{MT} = \text{Stanton number for mass transfer} = \frac{k_L}{U_0} \text{ or } \frac{k_G}{U_0} \quad ,$$

and

$$Sc \text{ (Schmidt number)} = \frac{\mu_L}{P_L D_L} \left(\text{or } \frac{\mu_G}{P_G D_G} \right).$$

If we assume that the effective surface area of the packing for mass transfer and heat transfer are equal, then the Chilton-Colburn equations can be solved for the heat transfer coefficient (this is a conservative assumption, because the effective area for heat transfer is generally thought to be greater than that for mass transfer):

$$ha = k_G a\, Cp \left[\frac{\left(\frac{\mu_G}{P_G D_G} \right)}{\left(\frac{Cp_G \mu_G}{k_G} \right)} \right]^{2/3} \quad ,$$

and we have

$$HTU_{HT} = \frac{CpG}{ha}, \text{ and } HTU_{MT} = \frac{G}{kgaP} \quad ;$$

so

$$\frac{HTU_{HT}}{HTU_{MT}} = (Pr/Sc)^{2/3}. \tag{8}$$

The problem is now one of evaluating the height HTU_{MT} of a mass transfer unit. The height of the gas film transfer unit can be estimated for the steam-Aroclor system from the data of Fellinger for the ammonia-water system,[13] using Wilke's technique.[14] Very briefly, the derivation of this technique is as follows:

$$HTU_G :: Sc^{1/2},$$

$$HTU_G :: Re^{0.4},^{15}$$

$$a_v :: h_0 \text{ when } a_v = \frac{ft^2 \text{ (surface effective)}}{ft^3 \text{ (packing)}}$$

$$HTU_G :: 1/a_v :: \frac{1}{h_0},$$

where h_0 is the total liquid holdup in packing.

Shulman and associates[16] reported that

$$h_0 = 0.00039\, L^{0.57}\, Z^{0.13}\, \rho^{-0.84} \left(\frac{\sigma}{73}\right)^{0.924-0.262 \text{ Log } L},$$

where L = liquid rate (lb/hr), Z = liquid viscosity (cP), ρ = liquid density, and σ = liquid surface tension.

When all of the above is combined, the result is (for $Z < 12$ Cp),

$$\frac{(HTU_G)_1}{(HTU_G)_2} = \left(\frac{Sc_1}{Sc_2}\right)_G^{1/2} \left(\frac{\mu_2}{\mu_1}\right)_G^{0.4} \left(\frac{Z_1}{Z_2}\right)_L^{0.13} \left(\frac{\rho_1}{\rho_2}\right)_L^{.84} \left(\frac{\sigma_1}{\sigma_2}\right)_L^{0.924-0.262 \log L}, \tag{9}$$

for identical liquor and gas rates from one system to another for a given packing size.

The desuperheating design technique then is to calculate the tower diameter as Hu did, consult Fellinger's curves for an HTU for the packing size selected and the liquid and gas flow rates, then to convert this HTU to the Aroclor-steam system using Eq. (9) above and then calculate HTU for (a) heat transfer from Eq. (8), and (b) the height of the desuperheating zone from Eq. (7).

In the condensation zone, the mass-transfer mechanism corresponding to the heat-transfer mechanism is that of liquid film controlling. The mass-transfer equation is (for a short contact time)

$$\frac{\partial C}{\partial \theta} = D \frac{\partial^2 C}{\partial X^2} ,$$

with boundary conditions

$$x = 0, \qquad \theta > 0, \qquad C = C_i ;$$

$$x = \infty, \qquad \theta > 0, \qquad C = C_0 ;$$

$$x > 0, \qquad \theta = 0, \qquad C = C_0 .$$

Vivian and Peaceman have solved this equation[17] to yield

$$\left(N_A\right)_{av} = 2\,(C_i - C_0)\left(\frac{D}{\pi\theta}\right)^{1/2} = k_{L_{av}}\,(C_i - C_0) ,$$

or

$$\left[K_L\right]_{av} = \left(\frac{4\,D}{\pi\theta}\right)^{1/2} .$$

Starting with the heat-conduction equation, an equation similar to the above can be developed, to wit:

$$\frac{\partial\,(Cp\rho\ T)}{\partial\theta} = \alpha\ \frac{\partial^2\,(Cp\rho\ T)}{\partial X^2} ,$$

where α = thermal diffusivity = $k/Cp\rho$.

The boundary conditions would be the same as above and, if the contact time is quite short, or if $Cp\rho \approx$ constant, the solution will yield

$$\frac{Q}{A} = 2\ Cp\rho\ (T_i - T_0)\left(\frac{\alpha}{\pi\theta}\right)^{1/2} = h(T_i - T_0)$$

or

$$h = Cp\rho\left(\frac{4\alpha}{\pi\theta}\right)^{1/2} .$$

The contact time θ is identical for heat and mass transfer, so

$$h/k_L = Cp\rho\ (\alpha/d)^{1/2}$$

Thus we have, for heat and mass transfers respectively,

$$HTU_{HT} = (LCp_L)/(ha_L), \text{ and } HTU_{MT} = L/(k_L\ a\rho);$$

and therefore,

$$\frac{HTU_{HT}}{HTU_{MT}} = \frac{Cp\rho}{ha}\ k_{La} = \left(\frac{D}{\alpha}\right)^{1/2} . \qquad (10)$$

The problem is again one of estimating the HTU_{MT}. Wilke[14] has developed an extension of the "Penetration theory" first proposed by Higbie,[18] that enables one to estimate the HTU for a new system from data on another system. Very briefly, the derivation of this technique is, starting with

$$k_L = \left(\frac{4D}{\pi\theta}\right)^{1/2} ,$$

for flow down a short wall,

$$\theta = \frac{h}{V_i} \text{ and } V_i = \left(\frac{9\,g\,\Gamma^2}{8\,\mu\rho}\right)^{1/3} \text{(laminar flow);}$$

then

$$k_L = 2\left(\frac{D}{\pi h}\right)^{1/2}\left(\frac{9g\,\Gamma^2}{8\,\mu\rho}\right)^{1/6}$$

and

$$\frac{k_L h}{D} = 2\left(\frac{h}{\pi D}\right)^{1/2}\left(\frac{9g\,\Gamma^2}{8\mu\rho}\right)^{1/6} .$$

This formula can be rearranged into

$$\frac{k_L h}{D} = 2.89\left(\frac{\mu}{\rho D}\right)^{1/2}\left(\frac{\Gamma}{\mu}\right)^{1/3}\left(\frac{g h^3 \rho^2}{\mu^2}\right)^{1/6}$$

Vivian and Peaceman have observed experimentally that Γ/μ enters to the 0.4 power,[17] so that

$$\Gamma = \frac{Q\rho}{\Omega} ,$$

where $Q = ft^3$, and Ω = wetted perimeter (ft) .
Since we also have

$$\Omega :: \frac{a_v V}{h} = \frac{\text{total wetted surface}}{\text{height}} a_v S ,$$

then

$$\frac{\Gamma}{\mu} = \frac{Q\rho}{a_v S \mu} = \frac{L}{a_v \mu} .$$

Let us assume h :: dp; then

$$\frac{k_L\, dp}{D} = C\left(\frac{\mu}{\rho D}\right)^{1/2}\left(\frac{L}{a_v \mu}\right)^{0.4}\left(\frac{g\, dp^3 \rho^2}{\mu^2}\right)^{1/2}$$

and

$$HTU_L = \frac{L}{[k_L a_v]_{av}} .$$

Combining and rearranging, we obtain

$$HTU_L = C\left(\frac{L}{a_v \mu}\right)^{0.6}\left(\frac{\mu}{\rho D}\right)^{-0.5}\left(\frac{g \rho^2}{\mu^2\, dp^3}\right)^{-1/6} .$$

If this is set up as a ratio for two systems, then

$$\frac{HTU_{L(1)}}{HTU_{L(2)}} = \left(\frac{a_{v(2)}}{a_{v(1)}}\right)^{0.6}\left(\frac{\mu_1}{\mu_2}\right)^{0.233}\left(\frac{\rho_2}{\rho_1}\right)^{0.833}\left(\frac{D_2}{D_1}\right)^{0.5} .$$

if the relation of Shulman et al.[16] is introduced for a_v, then

results (for $\mu < 12$ Cp) become

$$\frac{HTU_{L(1)}}{HTU_{L(2)}} = \left(\frac{\mu_1}{\mu_2}\right)^{0.155} \left(\frac{D_2}{D_1}\right)^{0.5} \left(\frac{\rho_2}{\rho_1}\right)^{0.333} \left(\frac{\sigma_2}{\sigma_1}\right)^{0.555-0.152 \log L} \quad . \quad (11)$$

The design technique then is to consult the curves of Sherwood and Holloway[10] for an HTU_L for the O_2-water system, calculate the HTU_L for the Aroclor water system from Eq. (11) calculate HTU_{HT} from Eq. (10) and the height of the condensation zone from Eq. (7) when $HTU_{HT} = (L\ Cp)/h\ a$.

V. ECONOMIC COMPARISONS

A. Introduction

Five processes for a 10-million Btu/hr heat duty are compared here, both on acapital cost and operating cost basis. In all five, Aroclor is heated from 212 °F to 227 °F, using steam available at one atmosphere. These processes are Venturi-in-series operation, Venturi with recirculation, direct injection, packed tower and a conventional surface condenser operation. It was necessary to use multiple-pass operation on the Venturis because the induction characteristics are such that a single-pass unit did not have the required steam capacity. The conventional surface-type unit was included to provide a basis for comparison with the various direct-contact processes.

The capital cost estimates were developed from Cecil Chilton's Cost Engineering in the Process Industries (McGraw-Hill Book Company, Inc., New York, 1960).

B. Outline of Design Techniques

The actual design calculations for the several schemes are quite lengthy and would serve no real purpose in this paper. Therefore only outlines of the calculations are included. The calculation common to all the processes considered is a heat and material balance. Also, all the processes are designed to include a vapor recompression step between the evaporator and the condenser. Details of the operating conditions are shown on the equipment flowsheets.

1. Venturi

There are two ways the Venturi can be used– either in series or in recirculation operation. The calculation techniques are essentially the same however, and so only the series-operation calculations are outlined. The overall approach is to calculate the performance of the small experimental unit and then scale up to the full size requirements through dynamic similarity. The steps of this calculation are to:

(a) Calculate the heat and material balance for the system.

(b) Check the parameter (Eq. 2) to be sure the empirical equations apply.

(c) Calculate the "f" factor using Eq. (4). P_v is taken as the vapor pressure of water at the entering Aroclor temperature.

(d) Calculate the steam feed to the Venturi from Eqs. (1) and (3). Note that the discharge pressure is selected and that the steam pressure is set by the compresser outlet pressure.

(e) Repeat all of the steps above for the second unit in the series. Note that a heat balance on the first unit is required to find the Aroclor inlet temperature to the second unit. This temperature is required to find the P_v for the "f" factor.

(f) The above is continued until the total steam feed to the series of condensers is that required by the overall heat and material balance.

(g) Calculate the Aroclor pressure drop from Eqs. (5) and (6).

(h) Scale up on dynamic similarity basis. For the series operation system, it was found that three units were required. For the recirculation system, it was found that a recirculation rate of 3:1 was required. More detailed information on the operating conditions is shown on the flow sheets. Details of the equipment are shown on the capital estimate sheets (Sec. VI).

2. Direct Injection

A direct-injection device can either be designed as a sieve tray, or as an injection tube, or as a bubble cap (the experimental unit). For economic comparison, a bubble cap tray was selected as the steam-injection device, because the empirical correlations are really only applicable to this type of injection. The design calculation steps were to:

(a) Calculate the heat and material balance for the system.

(b) Calculate the heat duty from (a).

(c) Calculate the LMTD.

(d) Calculate the tower diameter from

$$\frac{\text{Aroclor lb/min}}{26}(1 - (5/8))^2 = \text{diam}^2$$

We must note here that 26 lb/min of Aroclor was the maximum Aroclor flow tested in the experimental unit. The diameter of the full scale unit is in inches.

(e) Calculate $[U_v]_{av}$ from $[U_v]_{av} = 9.200\ F_S$,

where $F_S = \frac{\text{steam flow (lb/hr)}}{D^2}(1-5/8)^2$.

(This technique gives the same steam-bubble concentration in the full scale unit as in the small experimental unit, and therefore U_v is an overall average for total condensation.)

(f) Calculate the required liquor volume and height from

$$V = \frac{Q}{\text{LMTD} \times U_v}\ \text{ft}^3,$$

and $H = V/A$ ft.

(g) Calculate the Aroclor pressure drop from

$$P = 0.05\ F_A + hg$$

where $F_A = \frac{\text{Aroclor flow lb/min}}{D^2}(1-5/8)^2$,

and hg = height of liquid inside unit (psi).

(h) Check steam compressor discharge pressure originally specified, to be sure that the condensing pressure (and therefore temperature), plus the unit's pressure drop, are compatible with the compressor discharge pressure. If they are not the compressor discharge pressure must be adjusted and the calculations repeated.

3. Packed Tower

The design technique for the packed tower is discussed in detail in Sec. IV of this paper.

4. Surface condenser

The design technique for the tubular surface condenser was taken after that of D. Q. Kern.[8] Aroclor was placed on the tube side; steam was on the shell side. Briefly, the steps were:

(a) Assume U_D, calculate the LMTD and estimate the surface required.

(b) Assume an Aroclor velocity, calculate the number of tubes and the number of tube side passes and the tube length from (a).

(c) Correct the LMTD for a multipass unit (use the charts in the Standards of Tubular Exchanger Manufacturers' Association, 3rd ed. (TEMA, New York, c1952).

Note: the LMTD was taken as being between the saturation temperature of the vapor and the Aroclor temperatures, as suggested by McAdams[19].

(d) Calculate the steam film condensing coefficient using McAdams' equation

$$h_0 = \frac{3.100}{D_0^{1/2} \Delta t^{1/2}} ,$$

where $\Delta t = \frac{T_v - t_w}{2}$, and T_v = vapor condensing temp (°F) , then

$$h_{i0} = h_0 \times \frac{\text{o.d. tube}}{\text{i.d. tube}}$$

where t_w = tube wall temp, (°F) and D_0 = tube od (ft).

(e) Calculate the Aroclor film coefficient based on Kern's[8] adaptation of Sieder and Tate's correlation.[20] Plot R_e vs J_H, where

$$J_H = \left(\frac{hi\,D}{k}\right)\left(\frac{Cp\,\mu}{k}\right)^{-1/3}\left(\frac{\mu}{\mu_w}\right)^{-0.14} .$$

(f) Calculate U_{clean} from

$$U_c = \frac{hi_A \times h_{ios}}{hi_A + h_{ios}} .$$

(g) Calculate U_{dirty} from

$$U_D = \frac{Q}{LMTD \times A}$$

(h) Calculate the dirt factor from

$$R_D = \frac{1}{U_D} - \frac{1}{U_C} \quad ,$$

if the factor is reasonable, continue. If it is not, correct the surface and recalculate R_D.

(i) Calculate the Aroclor tube side-pressure drop from the charts already referred to in (c) above.

(j) As a general rule, several units should be designed at various tube side-velocities, and the capital and operating costs compared, to arrive at the optimum unit.

VI. CAPITAL ESTIMATE SUMMARY AND COST SHEETS

Examination of the cost comparison sheet shows that the packed tower is the most attractive of the cases considered. The difference between the fixed capital costs for the packed tower and the direct-injection cases is stated within the accuracy of the estimates. The difference in operating costs between these two cases, however, is significant. This difference is caused primarily by the injection's higher power requirement for the steam compressor. The steam pressure drop in the injector is about 4.5 psi and is about 2/3 Aroclor gravity head. The packed tower steam pressure drop is insignificant by comparison.

The two Venturi cases are less attractive than a conventional surface condenser. The Venturis themselves are quite cheap by comparison to the shell and tube heat exchanger. However, the auxiliaries such as surge tanks, instruments, etc. more than offset this difference. In all fairness to the Venturis, it should be pointed out that the operating conditions picked for the comparison were such that the Venturis were at a disadvantage because of the Aroclor inlet temperature. At a much lower Aroclor inlet temperature, the Venturis might well be the better of the schemes. Lower Aroclor temperatures however, would require operating the system under a vacuum which would cause a number of design and operational problems.

Table VIII. Venturi - series operation.

Item No.	Qty.	Description	Total installed cost
1	3	Venturis, all-bronze; Aroclor inlet 12-in diam; throat, 6-in diam., mixing chamber 8-1/2-in diam; diffuser length, 48 in. (cost for each estimated to be same as 2 Cyclones).	$2,200
2	3	Aroclor feed pumps, all-iron, bronze-fitted; 3100 gpm; at 30-ft TDH, 40-hp motor; foundation and wiring.	11,400
3	2	Surge tanks, 8,000-gal, copper, complete with foundation	20,000
4	1	Steam compressor 10,300 lb/hr; at 10 psi ΔP, 165 (theoritical); hp, centrifugal compressor; complete with foundation, drive, motor and wiring.	42,000
		Subtotal	$75,600
5		Process piping, at 30%.	25,000
6		Instrumentation, at 15%.	11,300
		Subtotal	111,900
		Engineering, at 15%	16,800
		Contingencies at 15%	16,800
		TOTAL	$145,500
			$145,000

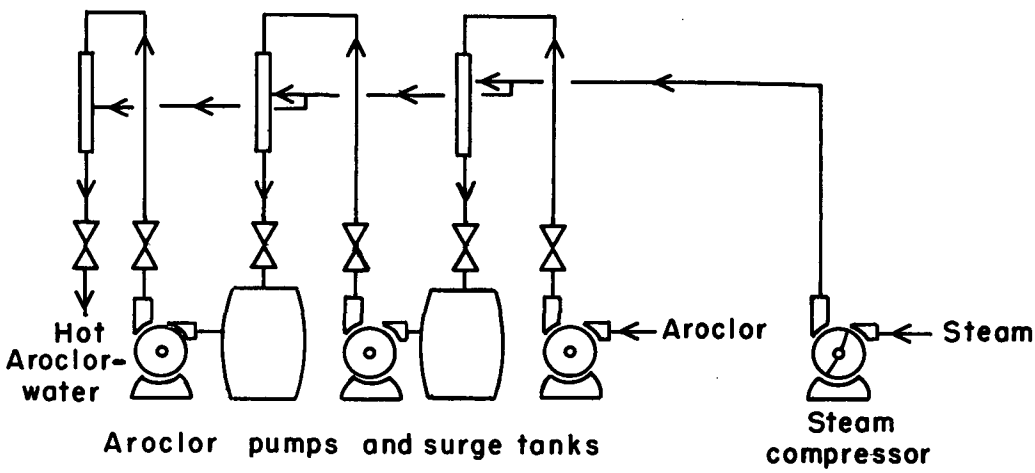

Fig. 20. Flowsheet: modified Venturi equipment, series operation. Operating conditions (basis, 10,300 lb/hr steam):

Stage no.	Aroclor gpm.	Aroclor inlet (°F)	Exit temps (°F)	Pressures inlet	Pressures exit	Steam (psig)
1	3,100	212	222	17	5	10
2	3,100	222	226	17	5	10
3	3,100	226	227	17	5	10

Table IX. Venturis - recirculation

Item No.	Qty.	Description	Total installed cost
1	1	Venturi, all bronze; Aroclor inlet, 24-in diam, throat 12-in. diam; mixing chamber 17-in diam; diffuser, length, 8 ft (cost estimated to be same as 2 Cyclones).	$ 2,000
2	1	Aroclor feed pump, all-iron, bronze-fitted, 3,100 gpm; at 20-ft TDH, 25-hp motor; wiring and foundation.	3,400
3	1	Aroclor recirculation pump, all-iron, bronze-fitted, 12,400 gpm; at 30-ft TDH, 125-hp motor, wiring and foundation.	8,800
4	1	Recirculation tank, 25,000-gal, copper, complete with foundation.	22,000
5	1	Steam compressor, 10,300 lb/hr 10-psi ΔP, 165 theoretical hp; complete unit installed.	42,000
		Subtotal	78,200
		Process piping at 30%	23,400
		Instruments at 5%	3,900
		Subtotal	105,500
		Engineering at 15%	15,800
		Contingencies at 15%	15,800
		TOTAL	$137,100
			$137,000

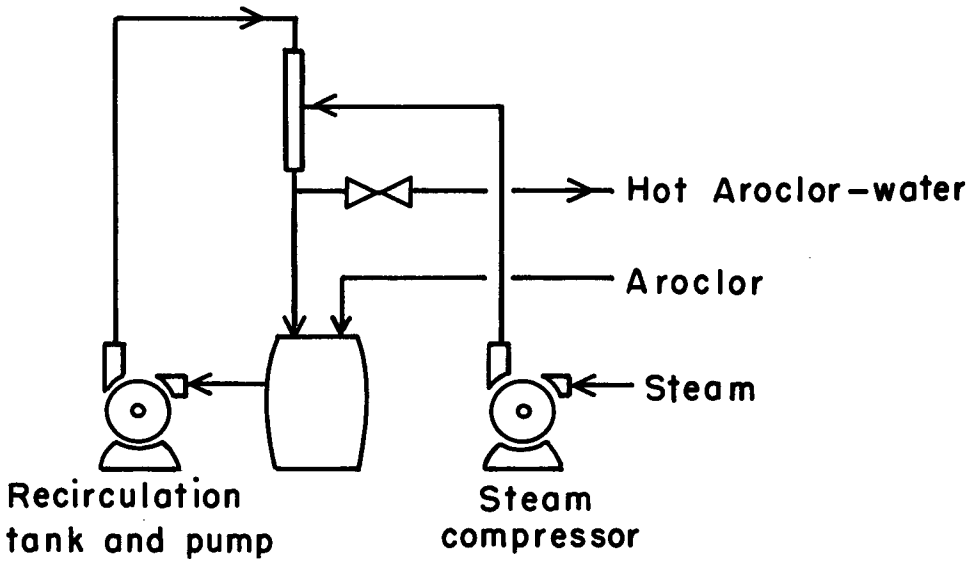

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Fig. 21. Flowsheet: modified Venturi equipment, recirculation operation. Operating conditions (Venturi):
Aroclor feed: 3,100 gpm. at 212°F.
Recirculation: 12,400 gpm. at 223 °F.
Steam: 10,300 lb/hr at 10 psig.
Product: 3,100 + gpm. at 227 °F.
Venturi ΔP: 12 psi.

Table X. Direct injection.

Item No.	Qty.	Description	Total installed cost
1	1	Tower, copper, 30-in diam, 8 ft tall; 1 tray; 5.3 ft of liquid.	$ 2,300
2	1	Aroclor feed pump, all-iron, bronze-fitted, 3,100 gpm; at 15-ft TDH, 20 hp motor; wiring and foundation.	2,800
3	1	Steam comprssor, 10,300-lb/hr; at 10-psi ΔP-165 (theoretical) hp; centrifugal compressor; complete unit, with drive, foundation, etc.	42,000
		Subtotal	47,100
4		Piping at 30%	14,100
5		Instruments at 15%	7,000
		Subtotal	68,200
		Engineering at 15%	10,200
		Contingencies at 15%	10,200
		TOTAL	$ 88,600
			$ 89,000

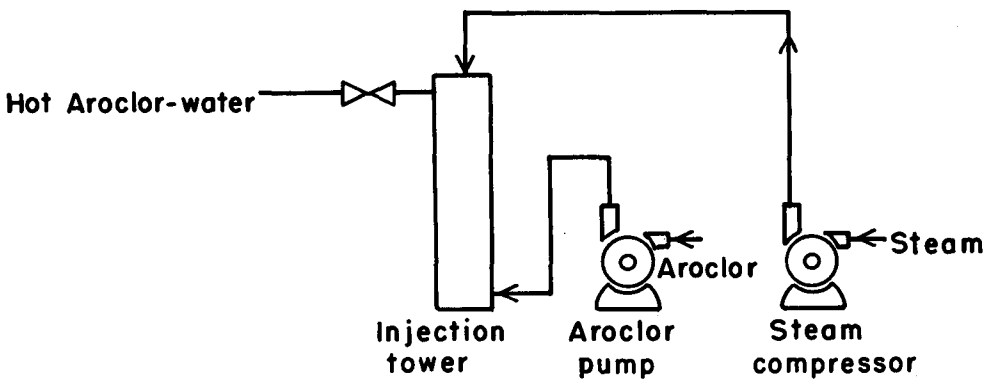

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Fig. 22. Flowsheet: direct-injection equipment. Operating conditions (injection tower):
Aroclor feed: 3,100 gpm. at 212 °F.
Steam feed: 10,300 lb/hr at 10 psig.
Product: 3,100 + gpm. at 227 °F.

Table XI. Packed tower.

Item No.	Qty.	Description	Total installed cost
1	1	Packed tower copper, 10-ft diam×8 ft high, 3-ft packed depth, 250 ft^3 packing; tower complete with foundation, etc	$ 16,000
2	1	Aroclor feed pump, all-iron, bronze-fitted, 3100 gpm; at 15-ft TDH, 20-hp motor, wiring and foundation.	2,800
3	1	Steam compressor, 10,300 lb/hr; at 6-psi ΔP, 90 (theoretical) hp centrifugal compressor; complete unit, drive, foundation etc.	24,000
		Subtotal	42,800
		Piping (same as injection, Table X)	14,100
		Instruments (Same as injection, Table X)	7,000
		Subtotal	63,900
		Engineering at 15%	9,600
		Contingencies at 15%	9,600
		TOTAL	$ 83,100
			$ 83,000

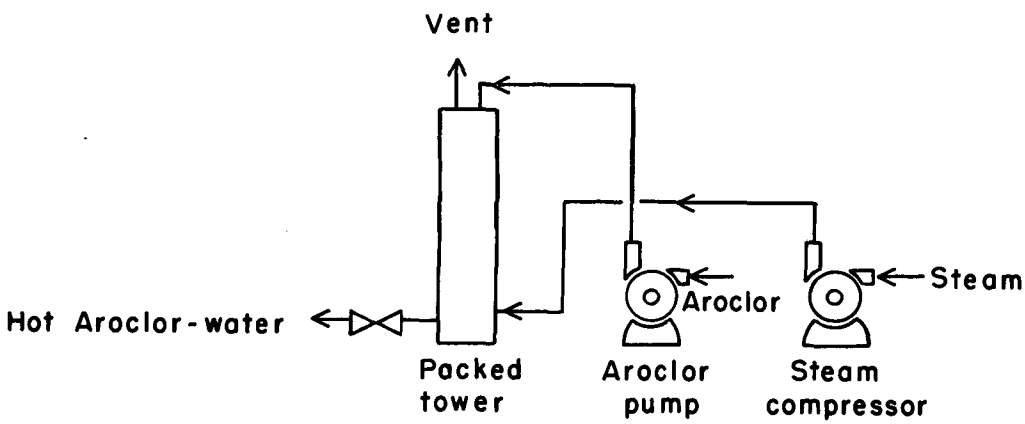

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Fig. 23. Flowsheet: packed tower equipment. Operating conditions (packed tower):
Aroclor feed: 3,100 gpm. at 212 °F.
Steam feed: 10,300 lb/hr at 6 psig.
Product: 3,100 + gpm at 227 °F.

Table XII. Surface condenser.

Item No.	Qty.	Description	Total installed cost
1	1	Shell and tube heat exchanger; steel shell, brass tubes, 2200-ft^2 surface; 1, 128 3/4-in. 16-ga, 12-ft-long tubes for 4 passes tube side, one pass shell side.	$ 18,400
2	1	Aroclor feed pump, all-iron, bronze-fitted, 3,100-gpm; at 65-ft TDH, 75 hp motor, wiring and foundation	6,000
3	1	Steam compressor, 10,300 lb/hr; at 10-psi ΔP; complete unit, drive, foundation, etc.	42,000
		Subtotal	66,400
4		Piping at 20%	13,300
		Instruments at 5%	3,300
		Subtotal	83,000
		Engineering at 15%	12,400
		Contingencies at 15%	12,400
		TOTAL	$ 107,800
			$108,00

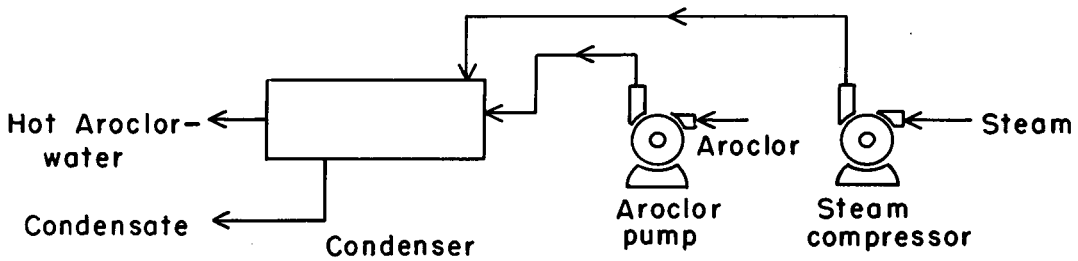

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Fig. 24. Flowsheet: surface condenser equipment. Operating conditions (condenser):
Aroclor feed: 3,100 gpm. at 212 °F.
Steam feed: 10,300 lb/hr at 10 psig.
Product: 3,100 + gpm at 227 °F.

Table XIII. Cost comparison

	A Venturi-series	B Venturi-recirculation	C Direct injection	D Packed tower	E Surface condenser
Electricity @ 1.15¢/kWh[3]	$ 23,000	$ 25,200	$15,800	$ 8,600	$ 19,800
Labor - manufacturing(1/4-man)	5,800	5,800	5,800	5,800	5,800
Supervision - manufacturing (1/4-man)	2,500	2,500	2,500	2,500	2,500
S. S. Tax, Comp. Ins., Pensions	800	800	800	800	800
Repairs - M & E, @ 10% M & E	14,500	13,700	8,900	8,300	10,800
Total direct conversion	$ 46,600	$ 48,000	$33,800	$ 26,000	$ 39,700
Depreciation - 12 yr. -Stn. Line	$ 12,100	$ 11,400	$ 7,400	$ 6,900	$ 9,000
Controllable - F. I. E. @ 20% D. C.	9,300	9,600	6,700	5,200	9,900
Noncontrollable - F. I. E. @ 2% of capital	2,900	2,700	1,800	1,700	2,200
Total indirect conversion	$ 24,300	$ 23,700	$ 15,900	$ 3,800	$ 21,100
Total operating cost	$ 70,900	$ 71,700	$ 49,700	$ 39,800	$ 60,800
Fixed capital	$145,000	$137,000	$ 89,000	$ 83,000	$ 108,000

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NOMENCLATURE

A	Cross-sectional area (ft^2).
a	Surface per unit volume (ft^2/ft^3).
b	Constant
c	Concentration ($lb\text{-}mols/ft^3$)
Cp	Specific heat (Btu/lb-°F)
D	Diameter (ft).
D_L, D_V	Diffusivity (ft^2/hr).
dp	Diameter of particle (ft).
F	Flow rate (generally lb./hr unless otherwise noted).
G_m	Gas mass-flow rate ($lb\text{-}mols/hr.\ ft^2$).
G	Gas mass-flow rate, ($lb/hr\text{-}ft^2$).
g_c	Gravitational conversion factor
H	Height (ft).
h	Heat transfer coefficient, ($Btu/hr\text{-}ft^2\text{-}°F$).
h_0	Total liquid holdup in column.
HTU	Height of a transfer unit (ft).
j	"j" factor in Chilton Colburn Analogy (j_d = mass transfer; j_h = heat transfer).
k_L	Liquid film mass-transfer coefficient, ($lb\text{-}mols/ft^2\text{-}hr$ unit concentration).
kg	Gas film mass-transfer coefficient ($lb\text{-}mols/ft^2\text{-}hr\text{-}atm$).
k	Thermal conductivity ($Btu/hr\text{-}ft^2\text{-}°F/ft$).
L_m	Liquid mass-flow rate ($lb\ mols/hr\text{-}ft^2$).
L	Liquid mass-flow rate ($lb/hr\text{-}ft^2$).
LMTD	Log mean temperature driving force (°F).
NTU	Number of transfer units.
N	Mass transfer flux ($lb\text{-}mols/ft^2\text{-}hr$).
P	Pressure (psi).
Q	Heat flow (Btu/hr), or volumetric flow rate (ft^3/hr).
r	Radius (ft).
S	Surface area (ft^2).

T	Temperature (°F).
t	Time (hr).
U_0	Velocity (ft/hr).
U	Overall heat transfer coefficient (Btu/hr-ft^2-°F).
x, y	Distance along axes (ft).
V	Volume, (ft^3).
W	Fluid unit weight (lb/ft^3).
Z	Tower height (ft, generally, unless otherwise noted).

Greek Letters

α	Thermal diffusivity.
μ	Viscosity, (lb/ft-hr).
ρ	Density (lb/ft^3).
σ	Surface tension.
θ	Time (hr).
Δ	Differential; i.e., Δp is pressure loss.

Subscripts

A	Aroclor.
c	Steam inlet chamber.
d	Discharge.
G	Gas.
HT	Heat Transfer.
L	Liquid.
MT	Mass transfer.
o	Orifice.
S	Steam.
V	Volumetric, i.e., $U_V \equiv$ (Btu/hr-ft^3-°F).
v	Vapor; i.e., P_v is vapor pressure.
t	Throat (in Fig. 2)
2	sidewall.

REFERENCES

1. Ray Vener, Chem. Eng. 63, No. 8, 175 (1956).
2. Shao-chio Hu, The Refining Engineer, C-12, 722 (Nov. 1956).
3. J. K. Vennard, Elementary Fluid Mechanics, 3rd ed. (John Wiley & Sons, Inc., New York, 1954).
4. P. Chiarulli and R. F. Dressler, J. Appl. Phys. 28, 990 (1957).
5. J. M. Burgers and A. Ghaffari, On the Application of Steam-Driven Water Jets for Propulsion Purposes, J. Res. Nat. Bur. Std. 60, No. 2 (1958).
6. H. S. Mickley, T. K. Sherwood and C. E. Reed, Applied Mathematics in Chemical Engineering (McGraw-Hill Book Company, Inc., New York, 1957).
7. W. H. McAdams, T. B. Drew, and G. S. Bays, Jr., Trans. Amer. Soc. Mech. Engrs. 62, 627 (1940).
8. D. Q. Kern, Process Heat Transfer (McGraw-Hill Book Company, Inc., New York, 1950).
9. T. K. Sherwood, J. H. Shipley and Clark Holloway, Ind. Eng. Chem. 30, 765 (1938).
10. T. K. Sherwood and C. Holloway, Trans. Am. Inst. Chem. Engrs. 36, 39 (1940).
11. C. R. Wilke, Chem. Eng. Progr. 45, 218 (1949).
12. T. H. Chilton and A. P. Colburn, Ind. Eng. Chem. 26, 1183 (1934).
13. L. L. Fellinger, (Sc.D. Thesis), Massachusetts Institute of Technology, 1941 (unpublished).
14. C. R. Wilke, (University of California, Berkeley) private communication.
15. C. R. Wilke and O. A. Hougen, Trans. Am. Inst. Chem. Engrs. 41, 455 (1945).
16. H. L. Shulman, C. F. Ullrich, A. Z. Prouex, J. O. Zimmerman, Am. Inst. Chem. Engrs. J, 1, 253 (1955).

17. J. E. Vivian and D. W. Peaceman, A. I. Ch. E. J. 437, (1956).

18. R. Higbie, Trans. Am. St. Chem. Engrs. 31, 365 (1935).

19. W. H. McAdams, Heat Transmission, 2nd ed. (McGraw-Hill Book Company, Inc., New York, 1942).

20. E. N. Sieder and G. E. Tate, Ind. Eng. Chem. 28, 1429 (1936).

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