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Distillation of Binary Mixtures with Capillary Porous Plates

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ABSTRACT

Distillation of liquid mixtures using capillary porous plates is a new process which depends upon the use of the intermolecular interactions between solids and liquids to alter the normal vapor–liquid equilibrium of a given mixture. Distillation of different binary mixtures, namely ethanol–water, ethanol–benzene, and acetone–ethanol systems, of different compositions was experimentally studied in a continuous distillation column equipped with four, five, or six porous sintered stainless steel fractionating plates of 13.5 μm pore diameter as well as six normal sieve plates. The results showed that the main factors affecting the separation efficiency in a given porous plate are the polarization of the pure liquids and the polarization difference between the mixture components. For the ethanol–water system, the results showed that while no separation was achieved in a distillation column with conventional stages, the azeotropic point of this system was broken in the distillation column with porous plates. A distillate of about 94 mol% ethanol was obtained for a feed of the azeotropic composition, i.e., 89.7 mol% ethanol. For the ethanol–benzene system, the azeotropic point was shifted from 40 mol% ethanol to about 30 mol% ethanol. For the acetone–ethanol system, there was no significant difference between the results obtained with normal stages and those with the porous plates. These results are in agreement with the developed theory.

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Key Words. Kelvin equation; Capillarity; Distillation; Polarizability; Surface forces; VLE

INTRODUCTION

Distillation is the most widely used technique for the separation of liquid mixtures in the chemical process industry and typically consumes a third or more of the total energy used in a chemical plant (1). Distillation alone accounts for approximately 3% of the gross national energy consumption. In addition, distillation has a low thermal efficiency, a typical thermodynamic efficiency being about 10% (2). Further, conventional distillation designs provide even lower thermal efficiencies for systems with azeotropes, such as the ethanol–water mixture, where the thermal efficiency is only about 2%. For such systems, separation beyond the azeotropic point cannot be achieved with conventional distillation and another separation step is needed to break the azeotropic point. This step usually involves extractive or azeotropic distillation and requires the addition of a second liquid to alter the vapor–liquid equilibrium of the system by enhancing the relative volatility of one of the components relative to the other. However, the added liquid must subsequently be removed in another distillation column, which reduces the thermal efficiency of the separation process. With the increase in energy costs and the realization of the exhaustibility of the fossil fuels, distillation designs with higher thermodynamic efficiencies are being explored.

Distillation in porous media is a new method (3) that utilizes the surface forces of the solids and the consequent intermolecular interactions between the solid and liquids, which in turn alter the intermolecular interactions among the solution components, thus altering the vapor–liquid equilibrium (VLE). Due to the porous solid–liquid interactions, a layer with different physicochemical properties from those in the bulk phases may be created next to the solid surface. Another interaction, in principle, that is responsible for alteration of the VLE in a porous material is the interface curvature, as given by the well-known Kelvin equation (4–6):

$$\ln\left(\frac{p_{v,0}^{r}}{p_{v,0}^{\infty}}\right) = -\frac{2\sigma_0 \tilde{V}_{l,0}}{rRT} \tag{1}$$

The pioneering work of Yeh et al. (3, 7, 9) proved the feasibility of using microporous media to alter the VLE of a given binary solution. Yeh et al. (3, 7) reported the results of some experimental studies involving distillation of different liquid mixtures including some azeotropic mixtures by the use of macroporous fractionating plates of sintered stainless steel which were

found to have altered the VLE of these liquid mixtures and resulted in high separation efficiencies. Yeh et al. (7) also studied the VLE of ethanol–water mixtures held inside a porous sintered stainless steel plate at 50°C. In this experiment they found that the azeotropic composition had been elevated from 90.0 mol% at the temperature of the study (50°C) to 99.0 mol%. They attributed these results to the strong polar interactions between the water molecules and the pore surface of the porous plate. Yeh et al. (8) also developed an approximate semiempirical theory to predict the vapor pressure inside the capillary plate. Abu Al-Rub and Datta (9, 10) developed a theory to study the vapor pressure of pure liquids as well as the VLE of binary mixtures in porous plates. They showed that the main factors affecting the vapor pressure of pure components and the VLE of a binary mixture are 1) the polarization of the pure liquids, 2) the relative polarization difference of the mixture components, and 3) the polarization of the porous solid. They also developed an accurate theoretical approach to predict the vapor pressure as well as VLE in porous plates.

The objective of this study is to investigate the practical feasibility and the factors affecting the efficiency of continuous distillation with capillary porous sintered stainless steel fractionating plates of 13.5 μm pore diameter for different binary mixtures. The mixtures studied are the ethanol–water system which can be considered as a polar–highly polar components mixture, the acetone–ethanol system which consists of polar components of similar polarization, and the benzene–ethanol system which can be considered a nonpolar–polar mixture.

THEORY

The criterion for VLE in the presence of external fields, such as those exerted by a juxtapositioned solid surface, is found to be (10)

$$y_i p = \gamma_i x_i p_{iv}, \qquad i = 1, 2, \ldots, n \tag{2}$$

which is of a form equivalent to that in the absence of external fields, when Eq. (2) reduces to

$$y_i p_0 = \gamma_{i,0} x_i p_{iv,0} \tag{3}$$

However, the vapor pressure, the total pressure, and the activity coefficients are *all* affected by the presence of fields.

The solid–liquid interactions for the case of liquids in porous plates are discussed in detail based on a molecular approach by Abu Al-Rub and Datta (9). The type and the strength of these interactions depend mainly on the nature of the solid and the liquids. The most common interactions are the van der Waals interactions which may be divided into three main categories:

1) permanent dipole–dipole, or orientation, interactions, which are the dominant interactions for polar–polar systems; 2) dipole–induced dipole, or induction, interactions, which are dominant if one of the materials is polar while the other is nonpolar; and 3) nonpolar, or dispersion, interactions, which are dominant if both materials are nonpolar.

The change in the activity coefficients can be explained on the basis of the fact that in the presence of external fields, the deviation from ideality is due to two contributions: 1) the short-range intermolecular interactions (intrinsic contribution) and 2) the long-range intermolecular interactions (external contribution). Abu Al-Rub and Datta (10), thus, showed that

$$\gamma_i = \gamma_{i,0}\gamma_{i,F} \tag{4}$$

where $\gamma_{i,F}$ is the activity coefficient due to the presence of external force fields. Thus, from an experimental measurement of the activity coefficients in the absence and in the presence of external fields, the long-range interactions contribution can be obtained. Note that $\gamma_{i,0}$ and $\gamma_{i,F}$ may individually be less than or greater than unity, depending upon positive (unlike molecules are attracted less than like molecules) or negative (unlike molecules are attracted more than like molecules) deviations from ideality.

The relative volatility is

$$\alpha_{ij} \equiv \frac{y_i/x_i}{y_j/x_j} = \frac{\gamma_i p_{iv}}{\gamma_j p_{jv}} \tag{5}$$

Abu Al-Rub and Datta (10) developed an approximate approach to predict the VLE of a binary mixture in capillary porous plates using the normal VLE data and the polarizability of the pure components as well as a characteristic constant of the porous capillary plates. They showed that with neglecting the effect of curvature, dispersion effects, and assuming equal contribution of long-range in the activity coefficients, the relative volatility in capillary porous plates is given by

$$\ln \frac{\alpha_{12}}{\alpha_{12,0}} \cong \kappa_s \left(\frac{\tilde{P}_{11}}{\tilde{V}_{11}} - \frac{\tilde{P}_{21}}{\tilde{V}_{21}} \right) \tag{6}$$

The molar polarization of a liquid can be related to its dielectric constant by the Onsager–Kirkwood equation (9, 11–13):

$$\frac{\tilde{P}_{il}}{\tilde{V}_{il}} = \frac{(2\epsilon_{ir} + 1)(\epsilon_{ir} - 1)}{9\epsilon_{ir}} \tag{7}$$

Thus, this approximate approach could predict the VLE within 1% for systems with close values of $\tilde{P}_{11}$ and $\tilde{P}_{21}$ in any porous plate, e.g., acetone–ethanol system, and for any system in a nonpolar porous plate, e.g., ethanol–water

system in porous carbon and Teflon plates. However, for systems with quite different values of $\tilde{P}_{11}$ and $\tilde{P}_{21}$ in porous plates, e.g., ethanol–water system in capillary porous sintered stainless steel plates, this approach could predict the VLE within 2% at a low concentration of the more polar component and within 7% at a high concentration. Thus, for such systems, this approximate approach should be used only to give a rough estimate.

EXPERIMENTAL APPARATUS AND PROCEDURE

To experimentally study the feasibility of using capillary porous fractionating plates for distillation to achieve better or, in general, different separation from conventional distillation, the separation of different types of mixtures was conducted using a Scott Model 9079 (obtained from Scott-Engineering Sciences, a division of A-T-O, Inc.) distillation column as shown in Fig. 1, which can be used for plate- or packed-column distillation. As a plate column, it consists of six sieve plate sections, each assembled from a 5-inch-long, 3-

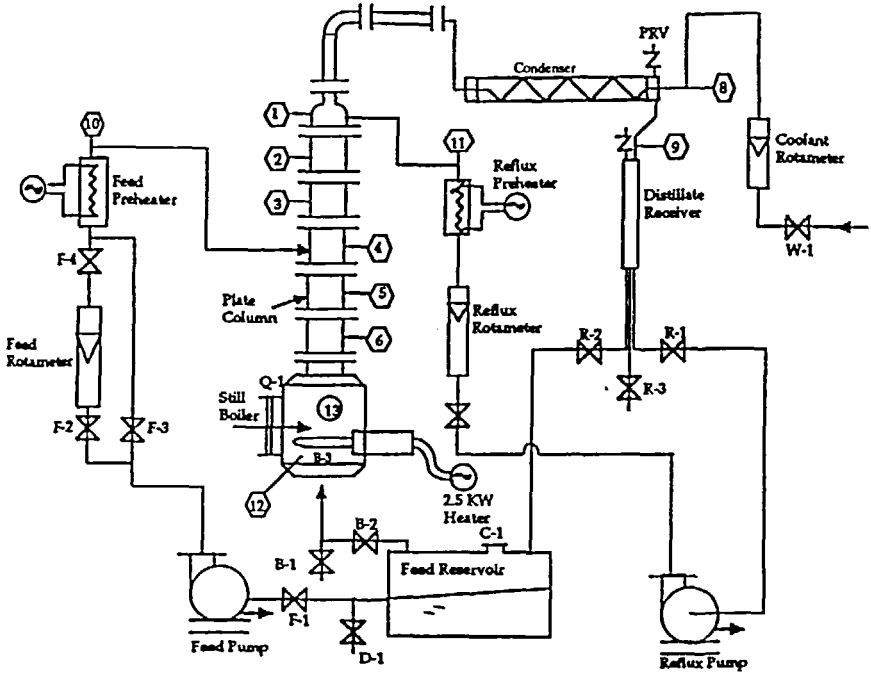

FIG. 1 Scott Model 9079 distillation column used.

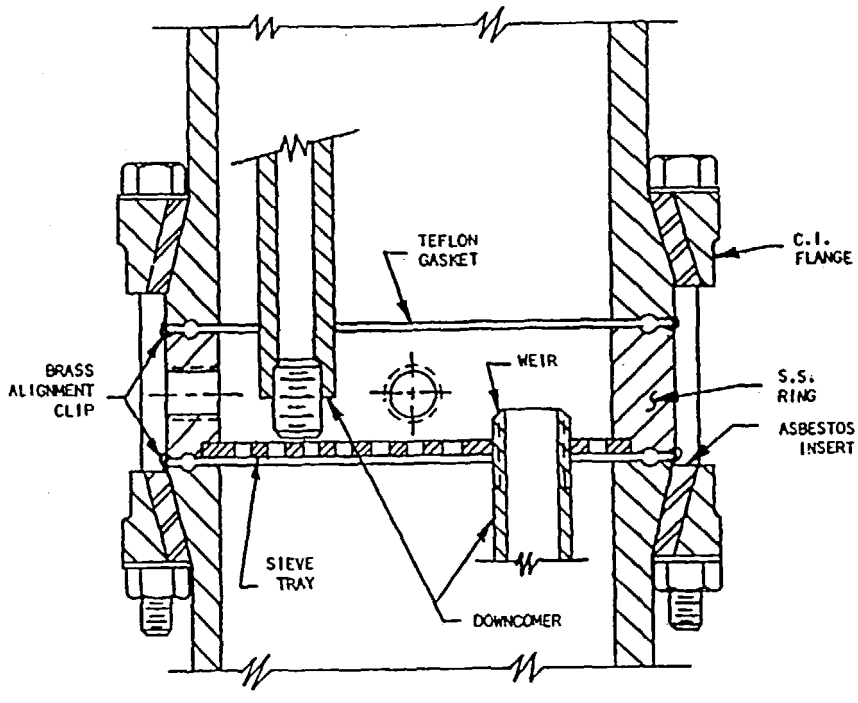

FIG. 2 Plate column assembly (14).

inch I.D. glass pipe section, a stainless steel process ring with four connections, and appropriate rubberized asbestos gasketed flanges, and bolts. Each section contains process fittings for feed, pressure measurement, liquid/vapor sampling, and weir-downcomer adjustment. The diameter of each plate is 3.1 inches with a thickness of 1/8 inch.

The plate column was assembled as follows: Starting with two 6-inch Pyrex glass pipe sections, two cast iron flanges with molded asbestos splitting inserts, two Teflon gaskets, a stainless steel process ring and sieve, or a porous stainless steel plate, the two sections were assembled as shown in the exploded view (Fig. 2). The downcomer was inserted into a weir, and the weir was threaded into the plate. In a similar manner, other sections can be assembled.

The weirs/downcomers were aligned as follows: Beginning with the bottom plate, the plate was rotated until the weir was approximately equidistant between the thermocouple port and the quick-disconnect coupling as shown in Fig. 3. This procedure was repeated for each succeeding section with the alignment for each weir being 180° out-of-phase as one proceeded up the

column. A detailed description of this apparatus and assembly procedures can be found elsewhere (14).

The plate column, when assembled, is approximately 30 inches in height, bolted to the boiler at its bottom and to the vapor feed line at its upper end by means of a bell reducing coupling section and a flexible Teflon expansion joint. On each plate the weir and downcomer are readily accessible for adjustment purposes. In distillation with capillary porous plates, the sieve plates were replaced by porous plates of similar size. This column allows the effects of vaporization, condensation, and vapor–liquid mixing to be viewed and studied under the conditions of dynamic operation. Experiments with porous sintered stainless steel plates of 13.5 μm pore diameter, with and without downcomers, and with normal sieve plates were conducted to compare the "efficiency" of the porous plates in distillation. The porous sintered stainless steel plates used have the following specifications: manufacturer, Technetics Corporation; product number, FM 1104; plate thickness, 1/8 in.; area density, 1.04 lb/ft^2; median pore diameter: 13.5 μm; pore size range, 7–72 μm; tensile strength, 6000 psia; surface area, 39,000 in.^{2}/lb; and thermal conductivity, 0.24 Btu·ft/h·ft^2·°F.

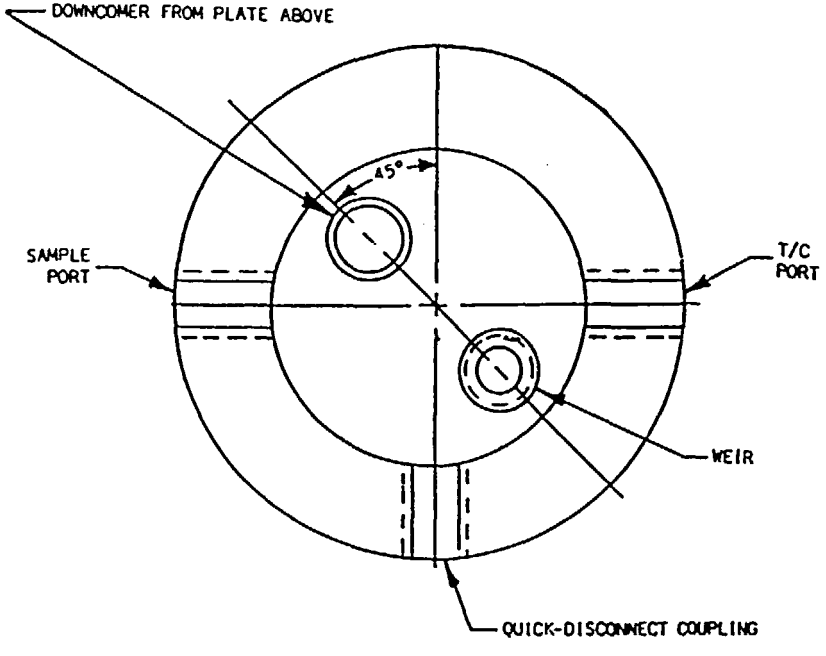

FIG. 3 Plate plan view (14).

The porous plates were prepared by machining them from a larger sheet of the same material. These plates were air blown to remove any dust and then washed in a beaker containing acetone for 24 hours. Next, the plates were dried in a vacuum and then immersed in boiling distilled water for 8 hours twice, using fresh water each time. The plates were then tested for cleanliness by using fresh distilled water and observing their ability to be wetted completely and instantly by water.

After the column was assembled, 8 gallons of the mixture to be distilled was charged into the feed reservoir, and the heating cycle and the flow of water through the condenser were begun. The system would heat up and begin boiling within 15 minutes. The temperature was monitored as distillate began to collect in plates over the boiler. Steady state was obtained within 45 minutes. As the distillate collected in the distillate receiver, the reflux, in the case of normal stages, was adjusted to attain the required reflux ratio. Pressure relief valves are located at the top of the distillate receiver and on the shell side of the condenser. These were set to open at approximately 1.0 psig. If for any reason the liquid level in the boiler were to drop below the electrical heating coils, a thermal-overload switch set to respond at 240°F would interrupt the line power. Samples of the distillate were taken every 15 minutes for 5 hours. The samples were analyzed in a Perkin-Elmer AutoSystem Gas Chromatograph using a 6 ft, 1/8 in. Porapak R column under isothermal conditions at 170°C. Calibration was done for each mixture used, and the accuracy of analysis was estimated to be 1%. Each sample was analyzed five times, and the average value was taken as the composition of that sample.

Three different liquid systems were studied: 1) ethanol–water (distilled water, 200 proof ethanol obtained from Midwest Grain Product), 2) acetone–ethanol (99.7 acetone purity obtained from Fisher), and 3) ethanol–benzene (benzene was obtained from Fisher) systems. These systems were chosen 1) because of the wide range of polarization among the constituents, ranging from nonpolar to highly polar, so that the effect of the liquid "nature" on the separation efficiency could be studied; and 2) because of the importance of some of these systems in industry, e.g., the ethanol–water system. The first system may be considered to be a polar–highly polar mixture since the relative permittivities of the pure components at 25°C are 24.55 and 78.50, respectively. This system has an azeotropic point at about 90 mol% ethanol. The second system can be considered to be a polar–polar mixture with similar polarization of the pure components; the relative permittivities of the pure components at 25°C are 20.75 and 24.55, respectively. The last system can be considered to be a polar–nonpolar mixture since the relative permittivities of the pure components at 25°C are 24.55 and 2.28, respectively (15). This system has an azeotropic point at about 40 mol% ethanol.

For the ethanol–water and ethanol–benzene systems, the feed composition chosen was that corresponding to the azeotropic composition. This choice of the feed composition allowed a quick conclusion regarding the feasibility of this method for breaking the azeotrope. At the azeotropic composition, of course, the liquid and the vapor have identical compositions and no further separation can be achieved through ordinary distillation. Thus, if distillation in porous media is effective in breaking the azeotrope, we would expect the distillate composition to be higher or lower than the feed composition. However, if this process is not effective, then we expect the distillate composition to be the same as the feed composition.

In the case of distillation with capillary porous plates, it is essential to have a liquid film immobilized within the porous plates. Thus, to ensure that the vapor–liquid was immobilized within the porous plate, the pressure differential of the rising vapor between two plates in the vapor phase should not exceed the capillary pressure calculated by the Laplace–Young equation. If this happens, then the vapor will blow through the capillary passages, thus producing no perceptible effect of the external force field. The heating rate was controlled to ensure that the pressure differential of the vapor was less than the capillary pressure.

RESULTS AND DISCUSSION

Ethanol–Water System

The VLEs for the ethanol–water system at 50°C under normal and in porous sintered stainless steel plate of 13.5 μm pore diameter are shown in Fig. 4 (16). As is evident from this figure, the azeotropic point was found to shift from 89.7 mol% ethanol to >99 mol% ethanol. This means that an ethanol concentration in the distillate of 99 mol% can, in principle, be achieved with an adequate number of stages.

The experiment to separate the ethanol–water mixture by a multistage distillation column was conducted under four different column configurations: 1) with four porous sintered stainless steel plates, 2) with five porous sintered stainless steel plates, 3) with six porous sintered stainless steel plates, and 4) with six normal stages. Unfortunately, a larger number of plates could not be utilized in the current column. Moreover, for the case of six sintered stainless steel plates, the experiment was conducted with and without the use of downcomers, and no significant difference in the vapor composition was obtained. The results for a feed composition of 89.7 mol% ethanol under the first and fourth column configuration are shown in Table 1 and in Fig. 5. As can be seen from Fig. 5, the distillate composition in the porous plates obtained at steady state was about 93 ± 0.1 mol% ethanol, which is considerably different from that of the feed. However, as expected, there was no change

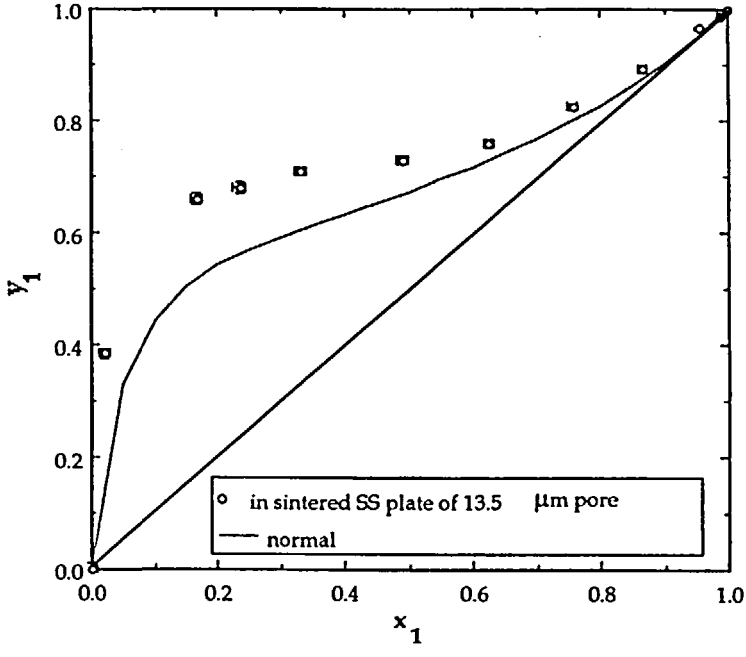

FIG. 4 x_1–y_1 diagram (isothermal) for ethanol–water system at 50°C.

TABLE 1
Distillation of Ethanol–Water System

Mol% ethanol in the feed	Mol% ethanol in the distillate
a. In Four Porous Sintered S.S. Plates of 13.5 μm Pore Diameter with Distillate Flow Rate of 20 mL/min	
55.2	78.3
72.4	86.3
81.0	89.7
83.5	90.8
89.7	93.1
b. In Six Normal Stages with Total Reflux	
62.0	*78.2*
69.0	*80.0*
84.0	*84.4*
89.7	*89.7*

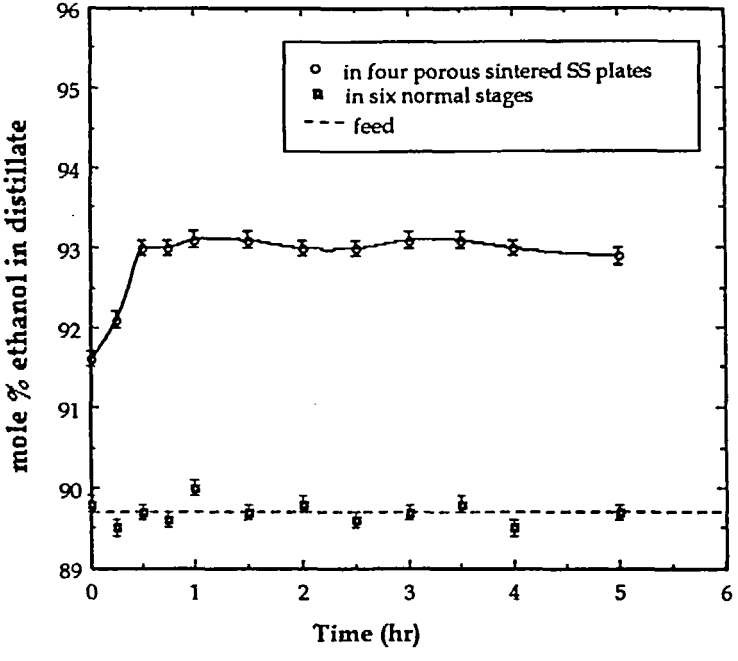

FIG. 5 Continuous distillation of ethanol–water system in four stainless steel plates of 13.5 μm pore diameter and in six normal stages with a distillate flow rate of 20 mL/min and with total reflux for the normal stages.

in the distillate composition in the six normal stages. These results thus prove, beyond doubt, the feasibility of this process for separating the ethanol–water system with azeotropic feed composition using sintered stainless steel plates in a multistage distillation process. The results of the experiment conducted for about 11 hours were similar to those conducted for 5 hours. Moreover, the composition after 90 minutes of starting the experiment was the same as that after 11 hours.

Effect of the Downcomers

Experiments with the microporous stainless steel plates were conducted with and without downcomers. The objective of these experiments was to determine whether the use of downcomers will "decrease" the efficiency of the distillation with capillary porous plates due to the presence of weirs. The results obtained showed that there was no effect of the downcomers on the "efficiency" of separation, i.e., under the same operating conditions, the

distillate composition for both cases, with and without downcomers, was similar. Moreover, the use of downcomers avoided some of the problems encountered when the column was operated without downcomers. These problems will be discussed later. Thus, the experiments were conducted with downcomers.

Effect of the Number of Stages

The effect of the number of stages, within the limitations of the apparatus used, on the distillate composition for the ethanol–water system was studied for the azeotropic feed composition. For the case of normal stages, as expected, there was no effect of the number of stages on the distillate composition, and the feed, bottom product, and distillate had identical compositions. For the case of distillation in porous plates, the results showed that the distillate composition increased from 93 mol% ethanol to about 94 mol% ethanol for a feed of 89.7 mol% ethanol when the number of stages was increased from four to six. The following explanation of contact and separation in porous plates has been suggested by Yeh et al. (3). A vapor produced by boiling the liquid mixture in the reboiler still is brought into contact with the bottom side of the porous plate where it is condensed in the pores of the porous plate. The condensate formed is transmitted through the pores where it is evaporated under the influence of the force field of the solid. The vapor is then transmitted through passages to the top side of the plate where it comes in contact with any free liquid on the top of the plate, thus condensing and evaporating again. The heat required for evaporating the condensate in the pores is obtained by the transfer of the latent heat of condensation and of the sensible heat of the vapor mixture through the plate. Consequently, based on this explanation, for each porous plate the vapor and liquid are in contact twice; in the pores of the porous plate and on the top of the porous plate, which may be considered as a "normal" stage. Thus, in effect the capillary plates can be considered as one normal stage and one capillary porous stage. The existence of the normal stage could possibly result in decreasing the distillate composition for mixtures around azeotropic composition. However, this problem can be avoided in practice by controlling the rate of vaporization of the liquid and the condensation of the vapor in such a way that equilibrium is achieved only in the porous plates and there is no free liquid on the top of the plate.

Effect of the Distillate Flow Rate

Experiments of distillation in capillary porous plates were conducted with distillate liquid flow rates ranging from 10 to 22 mL/min. The distillate flow rate was controlled by controlling the heating rate of the reboiler. The results

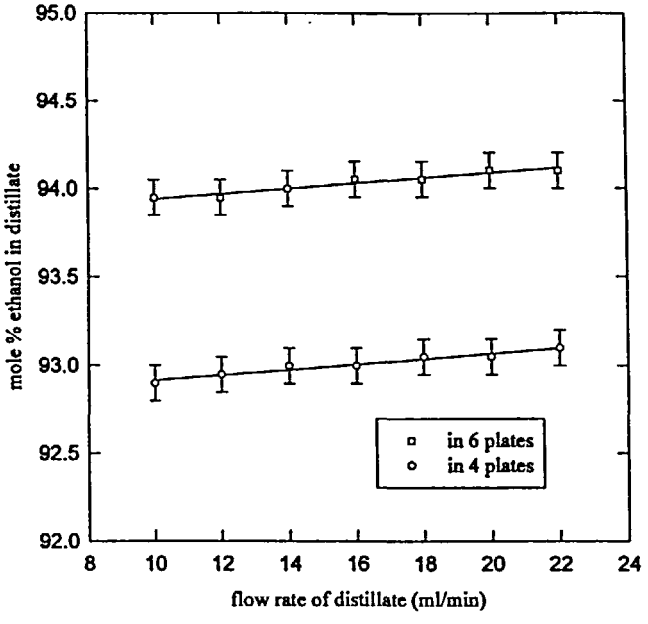

FIG. 6 Effect of distillate flow rate on the distillate composition in stainless steel plates of 13.5 μm pore diameter.

are shown in Fig. 6. As can be seen from these results, the effect of the distillate flow rate on the distillate composition is not significant. Although Fig. 6 shows a minor increase in the distillate composition with an increase in the flow rate, this increase is not significant and is within experimental error. When experiments were conducted without downcomers at higher distillate flow rates (>22 mL/min), two problems were encountered due to the high vapor rate in the column: 1) flooding on the top of the plates so that the experiment had to be stopped, and 2) pressure buildup in the reboiler since the flux of the vapor through the pores of the capillary plates was limited by transport considerations. This also resulted in a stoppage of the experiment. Thus, a safe maximum distillate flow rate was found to be about 20 mL of liquid/min, which is equivalent to a flux of 0.41 mL liquid/cm^2·min through the porous plates. This flow rate was used in all experiments, although this problem was not encountered when downcomers were used.

The pressure drop across the capillary plate was measured for different flow rates for the case of six sintered stainless steel plates with downcomers. The results are shown in Fig. 7. This figure shows that the pressure drop

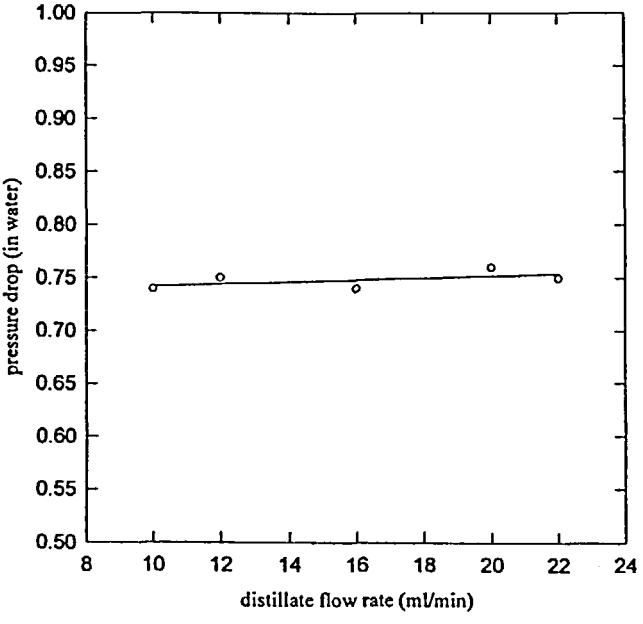

FIG. 7 Pressure drop across capillary plate vs distillate flow rate.

across the capillary plate was about 0.75 in water. This pressure drop was due to the static pressure of liquid above the plate as well as to some heat losses from the column to the surroundings. The results obtained showed that the pressure drop across the capillary plate was relatively independent of the distillate flow rate.

Effect of the Feed Composition

In addition to the azeotropic composition, different feed compositions were also studied. The results of these experiments for four sintered stainless steel plates and in the normal six stages are given in Table 1. A selectivity, S, defined as the ratio of the ratio of the distillate composition of the two components to that for the feed composition, i.e.,

$$S \equiv \frac{x_{1D}/x_{2D}}{x_{1F}/x_{2F}} \tag{8}$$

may be used as a measure of the efficiency of separation in the continuous separation process. The results for steady-state selectivity in distillation with

four porous sintered stainless steel plates and in the normal six stages are shown in Fig. 8. These results show that the selectivity of distillation in both cases was high at a low concentration feed, which is also evident from the VLE diagram for the ethanol–water system (Fig. 4). Comparison between the two cases shows, however, that selectivity in the capillary porous plates, even though smaller in number, was always greater than that in the normal stages. The difference is particularly significant at a feed composition >80 mol% ethanol, when the selectivity in the normal stages has an asymptote of $S \rightarrow 1$ while the selectivity in the porous plates was always >1.

Further, as can be seen from Table 1(a), a distillate with a composition of 90.8 mol% ethanol resulted when the feed composition was 83.5%. This means that separation beyond the normal azeotropic point was achieved even for a feed composition well below the normal azeotropic point. These results show that this process can be used to achieve compositions higher than the azeotropic composition from a low feed composition.

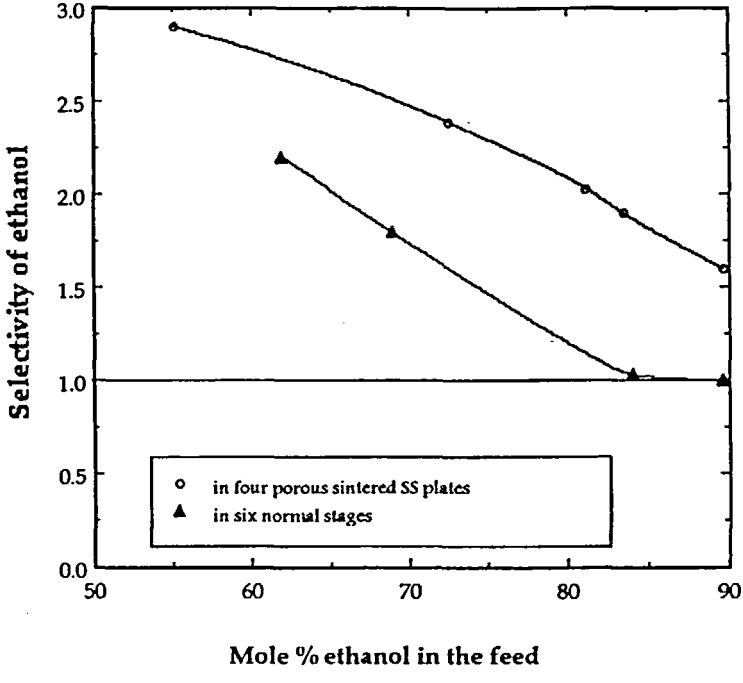

FIG. 8 Selectivity of continuous distillation of ethanol–water system as a function of the feed composition.

Ethanol–Benzene System

The normal VLE (17) and the predicted VLE in porous sintered stainless steel plates of this system, with $\kappa_s = -0.00719$ (16), using the approximate expression, Eq. (6), is shown Fig. 9. As can be seen from this figure, the capillary porous plates is predicted not to eliminate the azeotropic point but to shift it from 40 mol% ethanol to about 35 mol% ethanol. This means that in the case of distillation in porous plates, if the feed composition was <35 mol% ethanol, the composition of ethanol in the distillate would be higher than that in the feed and would reach a maximum value of 35 mol% ethanol. However, if the feed composition was >35 mol% ethanol, then the composition of ethanol in the distillate would be lower than that in the feed and would reach a minimum value of 35 mol% ethanol. Similar conclusions can be reached for the normal stages approaching 40 mol% ethanol.

The experiments for this system were conducted with six porous sintered stainless steel plates and with six normal sieve plates. The results for different feed compositions are shown in Table 2. As can be seen from this table, for

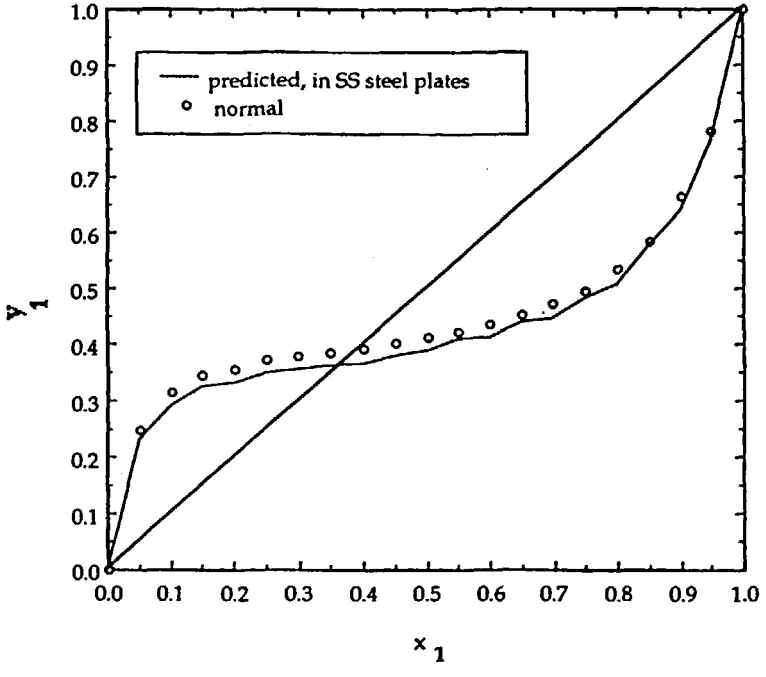

FIG. 9 x_1–y_1 diagram (isothermal) for ethanol–benzene system at 50°C.

TABLE 2
Distillation of Ethanol–Benzene System

Mol% ethanol in the feed	Mol% ethanol in the distillate
a. In Six Porous Sintered S.S. Plates of 13.5 μm Pore Diameter with Distillate Flow Rate of 20 mL/min	
19.6	29.3
29.1	29.1
42.0	30.9
58.0	33.8
72.0	37.1
86.0	42.4
b. In Six Normal Stages with Total Reflux	
33.0	38.1
40.0	40.0
52.2	37.5
73.0	43.5

a given feed composition, the concentration of ethanol in the distillate in the porous plates was always lower than that in the normal stages. This is due to the high polarization of ethanol relative to that of benzene. Thus, the polar intermolecular interactions between the porous plates and ethanol are greater than that with benzene, which thus enhances the relative volatility of benzene with respect to ethanol. However, the experimental results in the porous plates suggested that the azeotropic point was shifted to about 30 mol% ethanol rather than to 35 mol% ethanol as predicted by the approximate expression, Eq. (6). This is not unexpected since this system has a relatively large polarization difference between the mixture components, and for such systems, as discussed previously, Eq. (6) is not accurate.

The selectivity of ethanol with respect to benzene for this system is shown in Fig. 10. It can be seen from this figure that, due to the reason discussed above, the selectivity in the porous plates was always less than that in the normal stages. A selectivity of 1 corresponds to the azeotropic point.

Acetone–Ethanol System

The VLE for the acetone–ethanol system at 32°C under normal and in a porous sintered stainless steel plate of 13.5 μm pore diameter is shown in Fig. 11 (16). As can seen from this figure, although this system can be considered as a polar–polar mixture and significant vapor pressure reduction was found for each of the pure components in the porous plates (16), the effect

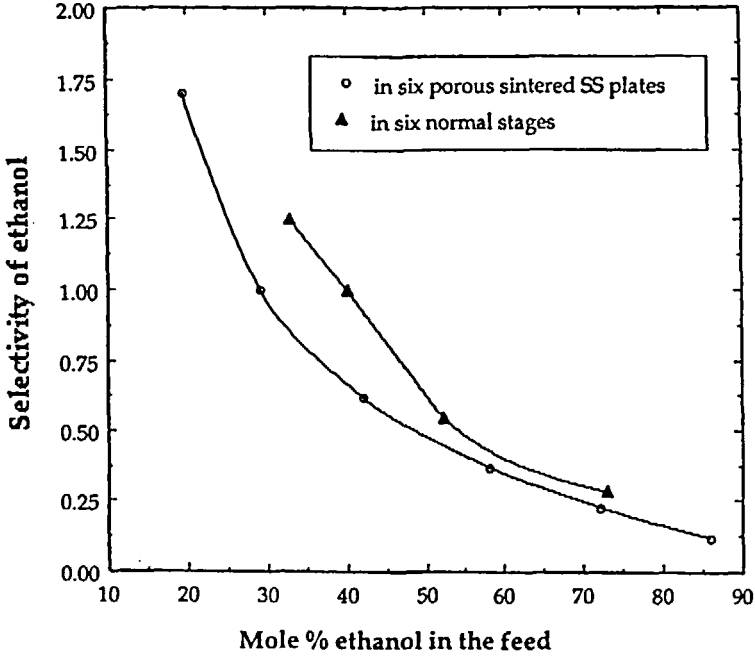

FIG. 10 Selectivity of continuous distillation of ethanol–benzene system as a function of the feed composition.

of the porous plate on the VLE was insignificant, as is evident from Eq. (6). This is due to the fact that the polarizations of both components are similar, which means that the intermolecular interactions between each component and the porous plate will be similar. Thus, the intermolecular interactions among the mixture components are expected to be essentially unchanged from the normal one.

The experimental results of distillation of the acetone–ethanol mixture of different feed composition in six porous sintered stainless steel plates and in six normal stages are shown in Table 3. As is evident from these results, there was no significant difference in the distillate composition in the two cases. This can also be seen in Fig. 12 which shows the change of selectivity with feed composition. As can be seen from this figure, the selectivity of acetone in both cases is similar and greater than 1. These results suggest that for this system, porous sintered stainless steel plates have no particular advantage over the normal stages.

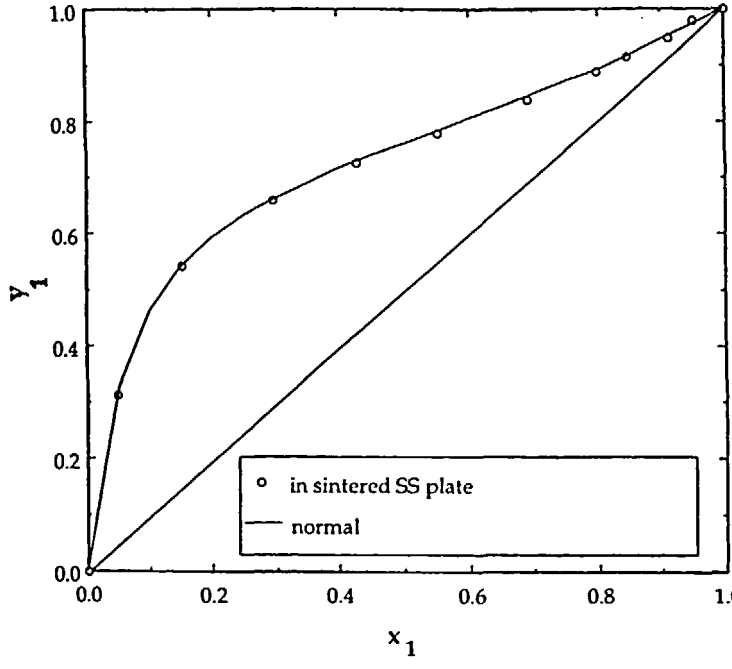

FIG. 11 x_1–y_1 diagram (isothermal) for acetone–ethanol system at 32°C.

TABLE 3
Distillation of Acetone–Ethanol System

Mol% acetone in the feed	Mol% acetone in the distillate
a. In Six Porous Sintered S.S. Plates of 13.5 μm Pore Diameter with Distillate Flow Rate of 20 mL/min	
34.0	67.0
52.0	80.4
62.0	86.6
b. In Six Normal Stages with Total Reflux	
34.5	66.6
57.0	83.9
61.0	86.2

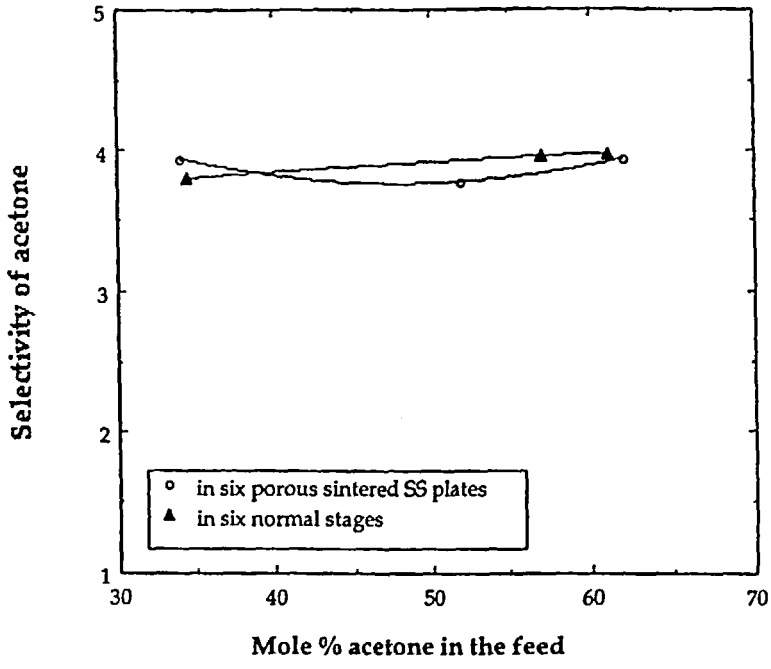

FIG. 12 Selectivity of continuous distillation of acetone–ethanol system as a function of the feed composition.

CONCLUSIONS

The feasibility of using polar capillary porous plates instead of the normal plates in a continuous distillation column to alter the VLE of a given system has been proven for some systems where the azeotropic point was broken and a distillate "beyond" the azeotropic point composition was obtained. However, although the distillate composition of these systems was different from that in normal plates, this does not mean that this process always enhances the vaporization of the more volatile component and increases the separation efficiency. In the case of the ethanol–benzene system, the composition of ethanol in the distillate was less than that obtained with the normal stages. The main factors affecting the efficiency and the applicability of this process are the polarization difference between the mixtures' components as well as the polarization of the liquids and the solid. For liquids of similar polarization, porous plates provide no particular advantage. A larger number of stages than were used in this study should enable further separation.

NOTATION

n	number of components
p	pressure (kPa; mmHg)
p_v	vapor pressure over interface of radius of curvature r and in the presence of external fields (kPa; mmHg)
$p_{v,0}$	vapor pressure over a plane interface and in the absence of external fields (kPa; mmHg)
$\tilde{P}$	molar polarization, Eq. (6) ($m^3 \cdot mol^{-1}$)
r	radius of curvature; pore radius (d)
R	universal gas constant ($N_A k = 8.3143$ $J \cdot mol^{-1} \cdot K^{-1}$)
T	temperature (K)
$\tilde{V}$	molar volume ($\equiv M/\rho$, $m^3 \cdot mol^{-1}$)
x_i	molar fraction of species i in the liquid phase
y_i	molar fraction of species i in the vapor phase

Greek Letters

ϵ_r	relative permittivity, or dielectric constant ($\equiv \epsilon/\epsilon_0$)
σ	surface energy or tension ($mJ \cdot m^{-2}$ or $mN \cdot m^{-1}$)

Subscripts

i	species i
l	liquid phase
0	property in the absence of external fields
s	solid phase
v	vapor phase

Superscripts

r	property with radius of curvature r
~	molar thermodynamic property

Abbreviations

C.I.	cast iron
S.S.	stainless steel
VLE	vapor–liquid equilibrium

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