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On the Possibility of Effective Helium Extraction from Air

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ABSTRACT

The possibility for using air as an alternative source for obtaining He is considered. The process of He–Ne concentrate extraction in a large air separation plant is studied to determine the optimal methods and conditions.

INTRODUCTION

The new industrial branches (nuclear, space, cryogenic, and lighting technologies, some special spheres of metallurgy and semiconductors, etc.) increase the importance of the inert gases, primarily helium. Unfortunately, the reserves of natural gases containing helium are limited, and though the most pessimistic prognoses have not been fulfilled (see, e.g., Ref. 1), their exhaustion has begun. Therefore the need to search for alternative helium sources is pressing.

The extraction of relatively large quantities of helium is possible in large air separation plants (ASP). A gas mixture, consisting mainly of nitrogen but containing from 3 to 8% helium and neon (the He/Ne ratio is approximately 1:3), can be extracted as a waste product from ASP. It is usually vented out, but it is sometimes used for extracting neon and can be used for helium extraction as well (see, e.g., Refs. 2–7).

The extraction coefficient for He and Ne from this concentrate is usually in the range of 0.45 to 0.50 (see, e.g., Refs. 2–6). The low values of the coefficient are due to the fact that the process has been studied insufficiently. To increase it up to 0.9 and more will essentially decrease the working expenses and make this concentrate a promising source for helium extraction.

MAIN LOSSES OF HELIUM AND NEON THROUGH THE EXTRACTION PROCESS

The main losses of the two inert gases in the extraction process are due to their relatively high solubility in liquid nitrogen. This can be illustrated with the help of the Fig. 1 scheme of a lower column and a condenser of an ASP with a reflux condenser joined to them for enrichment of the extracted helium–neon concentrate.

Atmospheric air (L_0 mol/s), cooled down to the condensation temperature and under a pressure of 0.6 MPa (usually), enters the lower column 2 (LC) through pipeline 1. It contains y_0 mole fractions of nitrogen and x_0 mole fractions of helium and neon ($x_0 \approx 2.3 \times 10^{-5}$, $y_0 \approx 0.78$). A liquid (R, mol/s) containing y_R mole fractions of nitrogen ($y_R = 0.60 \pm 0.05$, usually) and not containing helium and neon ($x_R \approx 0$), is led out from the bottom of the LC through pipeline 6. A gaseous nitrogen (L_C, mol/s) leaves from the LC top and enters condenser 3 where it condenses entirely ($L_C \approx L_0$). After that, N mol/s of the condensate go to the upper column (UC) of the ASP (not shown in the scheme) through pipelines 8 and 9. The nitrogen concentration in the condensate is y_N mol/s. As a rule, $y_N > 0.95$ (most often $y_N \geq 0.999$ mole fractions), so one can consider $y_N \approx 1$. The concentration of helium and neon dissolved in the condensate is x_N mole fractions. Its value is of the same order of magnitude as x_0 (see, e.g., Ref. 6). So it is evident that $x_N \ll 1$. The remaining part of the condensate goes back to the top of the LC through pipeline 8. A noncondensed gas mixture (L mol/s), enriched with inert gases, is led out of condenser 3 ($L \ll L_C$). It contains y_L mole fractions of nitrogen and x_L mole fractions of He and Ne. The value of x_L is usually in the 0.03 to 0.05 range and rarely reaches the 0.05 to 0.08 range (see, e.g., Refs. 2–5). This He–Ne concentrate enters reflux condenser 4 (RC) through pipeline 10. The main part of the nitrogen, contained in the concentrate, condenses at 80–83 K in the RC. As a result, a P mol/s enriched He–Ne mixture and a W mol/s condensate are obtained. They are led out through pipelines 13 and 11 respectively. The He–Ne mixture and the condensate contain y_P and y_W mole fractions of nitrogen and x_P and x_W mole fractions of Ne and He, respectively ($x_P = 0.40$–0.75 usually, rarely 0.80–0.90, and $x_W < 0.01$ (see, e.g., Refs. 2–6). The condensate obtained in the RC

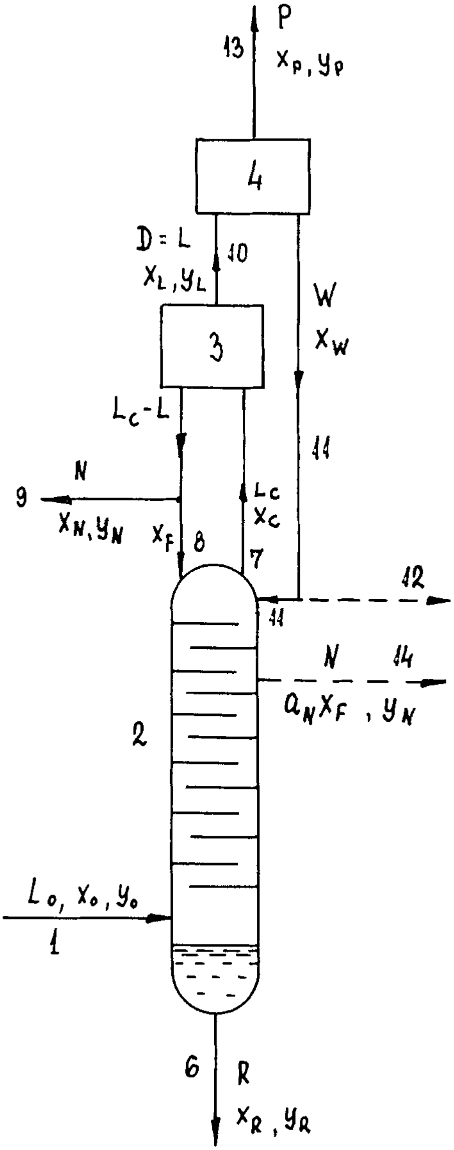

FIG. 1 Principal scheme of the lower column (LC) of ASP with a one-stage condenser and a reflux condenser for enrichment of He–Ne concentrate.

is sent to the UC through pipelines 11 and 12 or to the LC through pipeline 11.

So Nx_N mol/s of Ne and He are lost, carried away by the condensate going to the UC. Wx_W mole fractions are lost as well if the condensate obtained in the RC is sent to the UC.

Therefore, the extraction coefficient (α) for the He–Ne mixture can be defined as

$$\alpha = Px_P/L_0x_0 \tag{1}$$

because only Px_P mol/s are extracted from the entire quantity of He and Ne (L_0x_0 mol/s) entering the LC.

The losses of Ne and He carried away by the condensate from the RC (Wx_W mol/s) can be avoided entirely if the condensate is sent back to the highest plate of the LC. The losses with the condensate sent to the UC (Nx_N mol/s) cannot be avoided but they can be lowered if a sufficiently low value of x_N is ensured by using a suitable organization of the processes in the ASP. The possibilities for such technological decisions are proposed in Refs. 6 and 7 (see also Ref. 5).

The aim of this paper is to obtain analytical dependencies for calculation of the extraction coefficient to ascertain the possibilities of the proposed new methods and to compare them with the above-described conventional scheme. They will allow us to draw conclusions and generalizations for the applicability of all the methods and provide ways for increasing extraction process efficiency.

ANALYTICAL DEPENDENCIES FOR CALCULATION OF THE EXTRACTING COEFFICIENT

As mentioned above, the use of the conventional scheme allows extraction of only 45–50% of the Ne and He. Two new methods for obtaining a He–Ne mixture have been proposed (see Refs. 5 and 6). They are characterized by the following features.

First Method (Fig. 1). Here the reflux liquid nitrogen for the UC comes through pipeline 14 under the III–IV upper plates of the LC and not from the liquid, obtained in condenser 3. In this case, the He and Ne dissolved in the condensate are desorbed almost entirely.

Second Method (Fig. 2). This method uses a two-stage nitrogen condensation in the ASP. Primary condenser 3 (PC) condenses a portion of the gaseous nitrogen entering through pipeline 7. The concentration of He and Ne in the PC is low, and their solubility in the condensate is negligible. Therefore, only the liquid obtained here must be used as a reflux nitrogen for the UC. The condensate obtained in the PC cannot be less than N

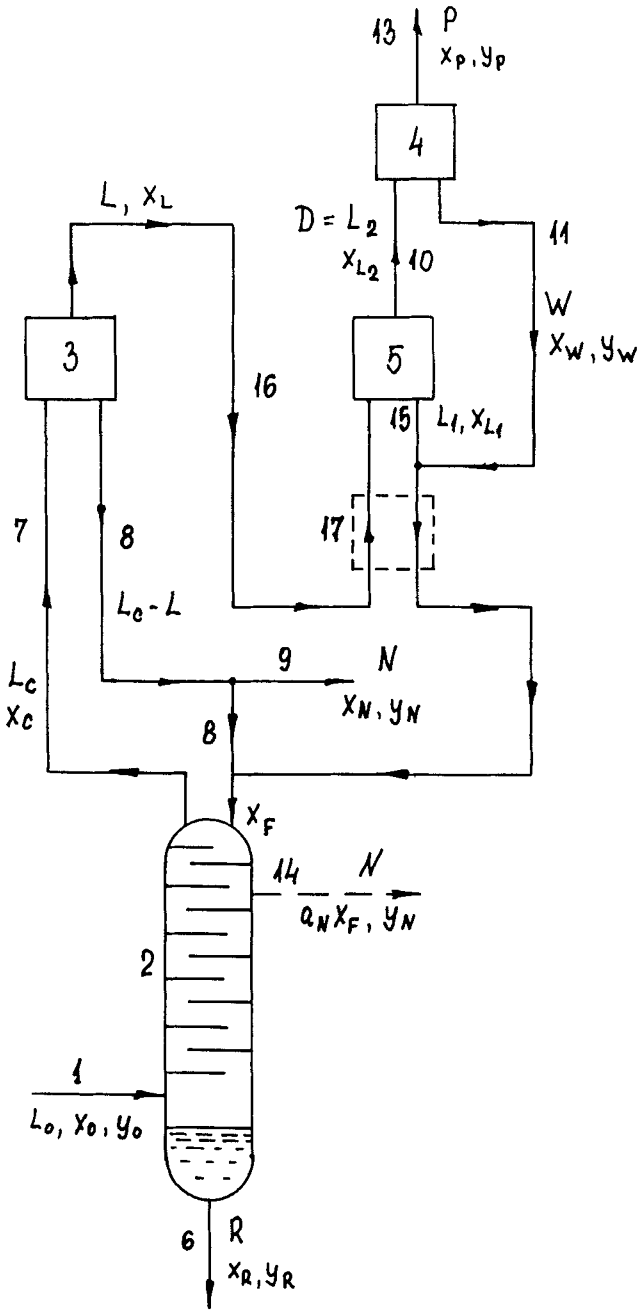

FIG. 2 Principal scheme of the lower column of ASP with two-stage condensers and a reflux condenser for enrichment of He–Ne concentrate.

mol/s. It is led to the UC through pipelines 8 and 9 (see Fig. 2). The noncondensed part of it (L mol/s) enters the secondary condenser 5 (SC) through pipeline 16. An L_1 mol/s condensate and an L_2 mol/s He–Ne concentrate containing x_{L2} mole fractions of He and Ne are obtained here. It is important to know that $L_2 \ll L$ and $L_1 \approx L$. The He–Ne concentrate is sent through pipeline 10 to reflux condenser 4 (RC) for enrichment, whereas the condensate from the RC and the SC goes to the highest plate of the LC for desorption of the dissolved inert gases through pipelines 15 and 11.

One more method for obtaining the He–Ne mixture from air is proposed in Ref. 7 (see Fig. 2). It uses a two-stage condensation of the nitrogen in the ASP, and the reflux liquid nitrogen for the UC is taken under III–IV upper plates of the LC, as in the two methods described above. The essential difference is that a desorption column (see position 17 in Fig. 2) is used. Mass transfer between the gaseous nitrogen going from the PC to the SC and the condensate obtained in the SC is carried out here. The use of a desorption stage allows both the circulation of inert gases and their mean concentration in the condensers to be substantially lowered. This circumstance intensifies the heat and mass transfer in the condensers and lowers the concentrations of He and Ne in the condensate going to the highest plate of the LC and in the condensate under the III–IV upper plates of the LC, respectively. Consequently, the extraction coefficient increases.

We shall now consider the following four schemes for extraction of an He–Ne mixture from air:

Scheme I: Conventional extraction method
Scheme II: First method described in Ref. 6
Scheme III: Second method described in Ref. 6
Scheme IV: The method described in Ref. 7

It is necessary to make a material balance of the LC (position 2 in Figs. 1 and 2) to obtain the analytical dependencies for calculation of the extraction coefficient. As a result, a system of equations valid for all four schemes is obtained:

$$L_0 = N + R + P \tag{2}$$

$$L_0 x_0 = N x_N + R x_R + P x_P \tag{3}$$

$$L_0 y_0 = N y_N + R y_R + P y_P \tag{4}$$

If a D mol/s gas mixture enters the RC (position 3 in Figs. 1 and 2), its mass (material) balance gives another system of equations:

$$D = P + W \tag{5}$$

$$Dx_D = Px_P + Wx_W \tag{6}$$

It is evident from Figs. 1 and 2 that for Schemes I and II, $D = L$, $x_D = x_L$, and for Schemes III and IV, $D = L_2$, $x_D = x_{L2}$, and $y_D = y_{L2}$. Now, from Eqs. (5) and (6) one can easily obtain

$$P = D(x_D - x_W)/(x_P - x_W) \tag{7}$$

$$W = D(x_P - x_D)/(x_P - x_W) \tag{8}$$

As pointed out above, $x_R \approx 0$, $x_N \ll 1$, $x_P \geq 0.40$, $D \ll L_0$ ($L \ll L_0$ or $L_2 \ll L_0$), $y_D > 0.90$ ($y_L > 0.90$ or $y_{L2} > 0.90$), and $y_N \approx 1$. So the simultaneous solution of Eqs. (2), (3), (4), (7), and (8) yields for the extraction coefficient

$$\alpha = Px_0/L_0x_0 = k_0(1 - k_Nx_N/x_0) \tag{9}$$

where

$$k_0 = 1/(1 - k_Nx_N/x_P) \approx 1 \tag{10}$$

$$k_N = \frac{N}{L_0} = \frac{y_0 - y_R}{y_N - y_R} - \frac{D}{L_0}\frac{y_D - y_R}{y_N - y_R}$$

$$\approx (y_0 - y_R)/(y_N - y_R) \tag{11}$$

It is obvious from Eq. (9) that the extraction coefficient α depends on x_N only because x_0 is a constant (He–Ne concentration in air) and the coefficient k_N changes very little (see Eq. 11 and the values of y_0, y_N, and y_R). It is practically constant for every ASP. The value of x_N depends on the extraction scheme and the method of condensation. In parallel-flow condensers the gaseous nitrogen and inert gases move in the same direction as the condensate, and in countercurrent condensers they move in opposite directions. The concentration of inert gases in the gaseous nitrogen is highest at the condenser outlet. This enriched gas mixture is in contact with the entire amount of condensate in parallel-flow condensers and with a small fraction of it in countercurrent condensers. So in parallel-flow condensers, the quantity of dissolved He and Ne is essentially higher.

As both types of condensers are used in practice, we shall consider all four schemes in two versions: with parallel-flow condensers and with countercurrent condensers.

As pointed out above, the value of x_N also depends on the extraction scheme. Employing the notation x_F for the He–Ne concentration in the condensate entering the top of the LC (position 1 in Figs. 1 and 2), we obtain the following.

Scheme I (see Fig. 1). In this case $x_N = x_F$ because the distribution of the condensate obtained in condenser 2 to the LC and UC is carried out after the condensation of all nitrogen.

Scheme II (see Fig. 1). Here the condensate for the UC is let out of the active zone of the LC under the III–IV upper plates, where the essential part of the inert gases is already desorbed. If we accept the notation a_N for the relative quantity of nondesorbed He and Ne, the value of x_N will obviously be $a_N x_F$.

Scheme III (see Fig. 2). In this case $x_N < x_F$ because the reflux nitrogen for the UC is only obtained from the PC where the concentration of inert gases is smaller.

Scheme IV (see Fig. 2). It is not difficult to see that here $x_N = a_N x_F$ and that the value of x_F depends on the condenser type. As we shall see later, when parallel-flow condensation is used, the concentration of inert gases in the condensate from both groups of condensers is the same, whereas if countercurrent condensation is used, the concentration of inert gases differs in the two condensates obtained in the PC and the SC.

Countercurrent Condensation

According to Refs. 5 and 6, the concentration of He and Ne in the condensate for modern longtube condensers is calculated using the formula

$$x_i = x_1 x_2/(x_2 + c) \qquad (12)$$

where $c = 0.00534$.

By using Figs. 1 and 2, one can easily see that $x_1 = x_C$ and $x_2 = x_L$. x_L is an independent variable. It can be fixed through the construction engineering of the new ASP. At the same time, x_C depends on the extracting scheme, x_L, and other factors, and it is necessary to make a material balance of the LC for every scheme to calculate it.

Scheme I (see Fig. 1)

The material balance of the LC leads to the expression

$$L_C x_C = L_0 x_0 + (L_C - L)x_F - N x_N + W x_W \qquad (13)$$

As mentioned above, $L_C \approx L_0$, and for this scheme, $L \ll L_0$ and $x_N = x_F$. Having this in mind and taking into account Eqs. (8) and (11), Eq. (13) can be reduced to

$$x_C = x_0 + (1 - k_N)x_F + \frac{L}{L_C} x_W \frac{x_P - x_L}{x_P - x_W} \tag{14}$$

The following equation is obtained from the material balance of condenser 3:

$$L_C x_C = L x_L + (L_C - L)x_N \tag{15}$$

One can obtain from Eq. (15) that

$$L/L_C = (x_C - x_N)/(x_L - x_N) \approx x_C/x_L \tag{16}$$

because $x_N \ll x_C < x_L$ [the equilibrium concentration of He and Ne in the liquid at this condition is about 2 orders of magnitude lower than their concentration in the vapors (5, 6, 8)].

Having in mind Eq. (1), in this case one can show that

$$\frac{W}{L_C} x_W = \frac{L}{L_C} x_W \frac{x_P - x_L}{x_P - x_W} = \alpha x_0 A \tag{17}$$

where

$$A = x_W(1 - x_L/x_P)/(x_L - x_W) \tag{18}$$

or using the notations accepted in Eqs. (5), (6), (7), and (8):

$$A = x_W(1 - x_D/x_P)/(x_D - x_W) \tag{19}$$

It follows from Eqs. (14) and (17) that

$$x_C = x_0(1 + \alpha A) + (1 - k_N)x_F \tag{20}$$

As shown above, $x_N = x_F$, and it can be seen from Fig. 1 that $x_F = x_i$. So it follows from Eqs. (12) and (20) that for Scheme I,

$$x_N = \frac{x_0 x_L(1 + \alpha A)}{k_N x_L + 1} \tag{21}$$

Scheme II (see Fig. 1)

Using the material balance of the LC, one can show that

$$L_C x_C = L_0 x_0 + (L_C - L)x_F - N x_N + W x_W \tag{22}$$

Taking into account Eqs. (11) and (17), as well as the fact that $L_C \approx L_0$, $L \ll L_C$, and $x_N = a_N x_F$, one can obtain from Eq. (22)

$$x_C = x_0(1 + \alpha A) + (1 - k_N a_N)x_F \tag{23}$$

As shown above, $x_F = x_i$ for this scheme, and then from Eqs. (12) and (23) we have for Scheme II

$$x_N = \frac{a_N x_0 x_L(1 + \alpha A)}{k_N a_N x_L + 1} \tag{24}$$

Scheme III (see Fig. 2)

The material balance of the LC, in this case, leads to the expression

$$L_C x_C = L_0 x_0 + (L_C - N - L)x_N - L_1 x_{L1} + W x_W \tag{25}$$

It can be shown that Eqs. (16), (17), and (19) are valid for this scheme too, but here $x_D = x_{L2}$. According to this, and having in mind that $L_C \approx L_0$, $L_1 \approx L$, and $L_2 \ll L$, Eq. (25) can be written in the form

$$x_C[1 - (x_{L1} + x_N)/x_L] = x_0(1 + \alpha A) + (1 - k_N)x_N \tag{26}$$

It was previously shown that $x_N \ll x_L$. For the same reasons, $x_{L1} \ll x_L$, so one can obtain with sufficient accuracy

$$x_C = x_0(1 + \alpha A) + (1 - k_N)x_N \tag{27}$$

It was evident from Fig. 2 that $x_i = x_N$, and then it is easy to show, using Eqs. (12) and (27), that in this case x_N is calculated from Eq. (21).

Analysis of Eqs. (21) and (24) shows that when $a_N = 1$, Eq. (24) transforms into Eq. (21). So Eq. (24) can be used for Schemes I, II, and III, but for Schemes I and III, $a_N = 1$.

Scheme IV (see Fig. 2)

In this case the next expression is obtained from the material balance of the LC:

$$L_C x_C = L_0 x_0 + (L_C - L)x_N - (L - P)x'_{L1} + N x_N \tag{28}$$

where x'_{L1} is the He–Ne concentration in the condensate leaving desorption column 17.

As pointed out above, $x_N = a_N x_F$ and Henry's law is valid, so

$$x'_{L1} = k x_L \tag{29}$$

There are now no difficulties in showing that

$$(L_C - P)x_F = (L_C - L)x_N + (L - P)x'_{L1} \tag{30}$$

Taking into account that $P \ll L_C$ and $P \ll L$ and using Eqs. (16) and (29), Eq. (30) can be transformed into

$$x_F = x_N + x_C(k - x_N/x_L) \tag{31}$$

Keeping in mind the above, Eq. (28) can be reduced to

$$x_C[1 - (1 - k_N a_N)(k - x_N/x_L)] = x_0 + (1 - k_N a_N)x_N \qquad (32)$$

It is already known that $x_N \ll x_L < 1$ and $k \ll 1$ (see Refs. 5, 6, and 8). So it is evident that $(k - x_N/x_L) \ll 1$, and one can accept that

$$x_C = x_0 + (1 - k_N a_N)x_N \qquad (33)$$

Because $x_N = x_i$, one can obtain from Eqs. (12) and (33), after elementary transformation,

$$x_N = x_0 x_L/(k_N a_N x_L + 1) \qquad (34)$$

A formula for the extraction coefficient α can now be obtained. With this objective, x_N in Eq. (9) has to be substituted for from Eqs. (24) and (34) while taking into account Eq. (10). So for the case of countercurrent condensation, one obtains:

a) For Schemes I, II, and III:

$$\alpha = c/(k_L a_N x_L + c) \qquad (35)$$

where

$$k_L = k_N(1 + A) = k_N(1 - x_W/x_P)/(1 - x_W/x_D)$$

$$\approx k_N/(1 - x_W/x_D) \qquad (36)$$

b) For Scheme IV:

$$\alpha = c/(k_N a_N x_L + c) \qquad (37)$$

Parallel-Flow Condensation

The condensate in parallel-flow condensers is in contact with the gas mixture that is most enriched in He and Ne. This circumstance leads to dissolution of larger quantities of the inert gases. As a result, their circulation in the system increases and the mean temperature difference in the ASP condensers is lowered by 0.2–0.4 K (see, e.g., Ref. 5).

As mentioned above, the concentrations of inert gases in the ASP are small and Henry's law is valid. So

$$x_N = kx_L \qquad (38)$$

Taking into account Eqs. (9), (10), and (38), one obtains

$$\alpha = 1 - k_N a_N k x_L/x_0 \qquad (39)$$

To calculate α using Eq. (39), one has to know the value of the coefficient k. There are no data for He–Ne mixtures, so the coefficient $k_{\text{Ne–He}}$

will have to be calculated by using well-known data for He and Ne. It is known from Ref. 8 (see also Refs. 5 and 6) that at 0.6 MPa,

$$k_{\mathrm{Ne}} = 1/7.97T^{0.45} \tag{40}$$

$$k_{\mathrm{He}} = T^{3.9}/1.88 \times 10^{10} \tag{41}$$

where T is the condensation temperature in the ASP. Usually $T \approx 96$–97 K and then

$$k_{\mathrm{Ne}} \approx 0.016 \tag{42}$$

$$k_{\mathrm{He}} \approx 0.003 \tag{43}$$

It is not difficult to show that

$$\begin{aligned}\alpha_{\mathrm{Ne-He}} &= \frac{L_0 x_0^{\mathrm{Ne}}}{L_0 x_0}\alpha_{\mathrm{Ne}} + \frac{L_0 x_0^{\mathrm{He}}}{L_0 x_0}\alpha_{\mathrm{He}} \\ &= \frac{x_0^{\mathrm{Ne}}}{x_0}\alpha_{\mathrm{Ne}} + \frac{x_0^{\mathrm{He}}}{x_0}\alpha_{\mathrm{He}} \end{aligned} \tag{44}$$

where

$$x_0 = x_0^{\mathrm{Ne}} + x_0^{\mathrm{He}} \tag{45}$$

It follows from Eqs. (39), (44), and (45) that

$$\alpha_{\mathrm{Ne-He}} = 1 - (k_{\mathrm{Ne}} x_{\mathrm{L}}^{\mathrm{Ne}} + k_{\mathrm{He}} x_{\mathrm{L}}^{\mathrm{He}}) k_{\mathrm{N}} a_{\mathrm{N}} / x_0 \tag{46}$$

The Ne/He ratio in air is about 78:22. It changes through nitrogen condensation to (70–75):(30–25) for the He–Ne mixture obtained (see, e.g., Refs. 3–5) because the solubilities of the two gases are different. Therefore, to a first approximation, the mean ratio is approximately 75:25 and

$$x_{\mathrm{L}}^{\mathrm{Ne}} \approx 0.75 x_{\mathrm{L}} \tag{47}$$

$$x_{\mathrm{L}}^{\mathrm{He}} \approx 0.25 x_{\mathrm{L}} \tag{48}$$

Taking into account Eq. (39), one obtains for the coefficient $k_{\mathrm{Ne-He}}$ from Eqs. (46), (47), and (48) the expression

$$k_{\mathrm{Ne-He}} \approx 0.75 k_{\mathrm{Ne}} + 0.25 k_{\mathrm{He}} \tag{49}$$

If one substitutes the values of k_{Ne} and k_{He} from Eqs. (42) and (43) into Eq. (49), the result will be

$$k_{\mathrm{Ne-He}} \approx 0.013 \tag{50}$$

RESULTS AND DISCUSSION

The analytical dependencies of $\alpha(x_L)$ obtained above are plotted in Fig. 3. The symbols on the separate curves correspond to the number of the discussed extraction scheme. The letter symbols show the type of condensation in ASP. The symbol "c" means countercurrent condensation and the symbol "p" means parallel-flow condensation. So "1c" means Scheme I with countercurrent condensers, "2p" means Scheme II with parallel-flow condensers, etc.

Through the calculations, it is found that:

$x_0 = 2.3 \times 10^{-5}$ $x_P = 0.50$ $x_W = 0.003$ $x_D = 0.04$
$y_0 = 0.78$ $y_P = 0.50$ $y_N = 1.0$ $y_R = 0.60$

$k = 0.013$

It was also found that for Schemes II and IV, $a_N = 0.05$ (degree of desorption, 95%) and for Schemes I and III, $a_N = 1$ (no desorption).

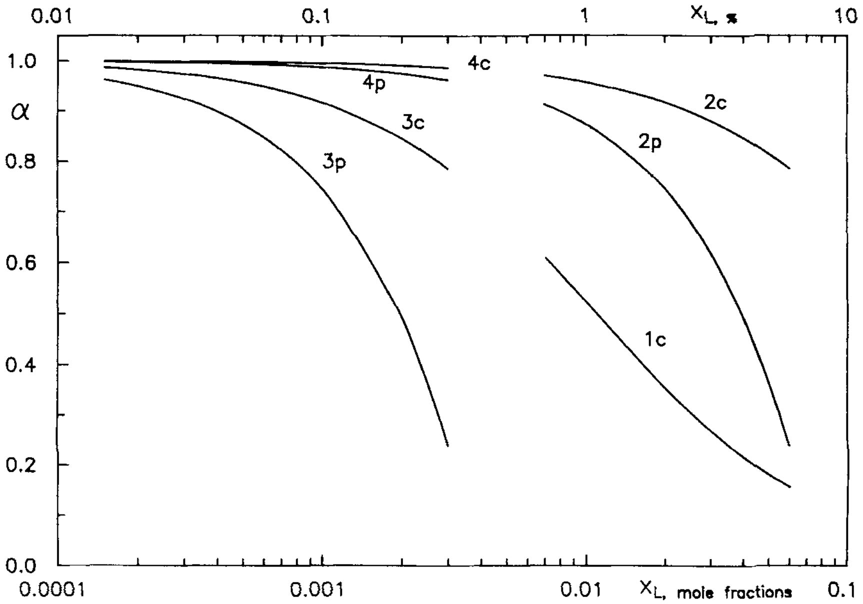

FIG. 3 Calculated dependencies $\alpha(x_L)$ for the four schemes discussed for extraction with parallel-flow and countercurrent condensers in ASP.

By looking at the dependencies of $\alpha(x_L)$ plotted in Fig. 3, one can see there is no curve marked "1p." This is because α calculated from Eq. (39) for Scheme I with parallel-flow condensers is <0, which means that it is impossible to extract He–Ne mixture efficiently by using this scheme.

Analysis of the results obtained makes it possible to draw the following conclusions:

1. The conventional method for extracting He–Ne concentrate (Scheme I) is not efficient. The extraction coefficient is low (see Refs. 2–5).
2. The application of Scheme II can give satisfactory results, but if the condensers are of the parallel-flow type, the degree of desorption must be more than 99% ($a_N < 0.01$). One can easily show this by using Eq. (39).
3. The method of condensation in the RC and the He–Ne concentration in the condensate (x_W) is of negligible importance to the value of α if the condensate obtained in the RC goes back to the LC. One can see this from Eqs. (35), (36), and (39). This means that α depends only on the value of x_L.
4. The highest degree of separation occurs in methods which use a two-stage condensation in the ASP (Schemes III and IV). When parallel-flow condensation is used, their efficiency can be increased a little by using multistage condensation (3 or 4 steps are sufficient). In this case, the condensate for the UC must be obtained from the first 2 or 3 condensation steps. Because the vapors are only in contact with the condensate obtained in the corresponding step, the quantity of dissolved inert gases will be less.
5. The use of multistage parallel-flow condensation is also recommended for Scheme II because the smaller quantities of He and Ne in the liquid lead to smaller concentrations of them in the condensate going to the UC ($a_N x_N$ is smaller), and therefore α increases.

CONCLUSIONS

The results obtained in this paper are not of high accuracy, in particular for Schemes I and II, because of the imperfect theoretical model. Nevertheless, they give a sufficiently accurate estimation of the different methods and of the way of organizing the process in ASP to ensure maximum extraction of inert gases. We believe the above conclusions are correct and we hope they will be useful.

SYMBOLS

α	extraction coefficient
$\alpha_{\mathrm{He-Ne}}$	extraction coefficient for He–Ne mixture
A	coefficient used in this paper (see Eqs. 18 and 19)
a_{N}	relative quantity of nondesorbed gases in the condensate
c	= 0.00534, experimental constant (see Refs. 5 and 6)
D	gas mixture flow entering the reflux condenser (mol/s)
k	Henry's law coefficient
$k_{\mathrm{He-Ne}}$, k_{Ne}, k_{He}	Henry coefficients for He–Ne mixture, Ne, and He, respectively
k_0, k_{N}, k_{L}	coefficients used in this paper (see Eqs. 10, 11, and 36)
L_0	atmospheric air entering the lower column (LC) of an air separation plant (ASP) for rectification (mol/s)
L	noncondensed gas mixture flow leaving the ASP condensers or the primary condensers of the ASP when two-stage condensation is used (mol/s)
L_1	condensate obtained in the secondary condenser (SC) of an ASP when two-stage condensation is used (mol/s)
L_2	noncondensed gas mixture from the secondary ASP condensers (mol/s)
L_{C}	gaseous nitrogen flow going out from the top of the LC of an ASP to the condensers (mol/s)
N	reflux liquid nitrogen for the UC (mol/s)
P	enriched He–Ne mixture obtained from the ASR (mol/s)
R	liquid obtained in the lower column (LC) of an ASP (mol/s)
W	condensate obtained in the reflux condenser (RC) (mol/s)
x_0, y_0	mole fractions of inert gases and nitrogen, respectively, in air entering the LC
x_0^{Ne}, x_0^{He}	mole fractions of Ne and He, respectively, in air entering the LC

x_C	mole fraction of Ne and He in the nitrogen leaving from the top of the LC to the ASP condensers
x_D	mole fraction of inert gases in the gas mixture entering the RC
x_L, y_L	mole fractions of inert gases and nitrogen, respectively, correspondingly in the noncondensed gas mixture leaving the ASP condensers or the primary condensers of an ASP when two-stage condensation is used
x_L^{Ne}, x_L^{He}	mole fractions of Ne and He, respectively, in the noncondensed gas mixture leaving the ASP condensers or the primary condensers of an ASP when two-stage condensation is used
x_W, y_W	mole fractions of inert gases and nitrogen, respectively, correspondingly in the condensate obtaining in the RC
x_P, y_P	mole fractions of inert gases and nitrogen, respectively, correspondingly in the enriched He–Ne mixture obtained from the He–Ne concentrate in the RC
x_{L1}	mole fraction of inert gases in the condensate obtaining in the secondary condensers (SC)
x'_{L1}	mole fraction of inert gases in the condensate leaving desorption column 17 (Fig. 2)
x_{L2}	mole fraction of inert gases in the noncondensed gas mixture leaving the SC
x_N, y_N	mole fractions of inert gases and nitrogen, respectively, in the reflux liquid nitrogen for the UC
x_R, y_R	mole fractions of inert gases and nitrogen, respectively, at the bottom of the LC
x_F	mole fraction of inert gases in the reflux liquid nitrogen entering the top of the LC
x_i	mole fraction of inert gases in the condensate obtained in the countercurrent condenser
x_1, x_2	mole fractions of inert gases in the vapor at the inlet (x_1) and outlet (x_2) of the countercurrent condenser

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