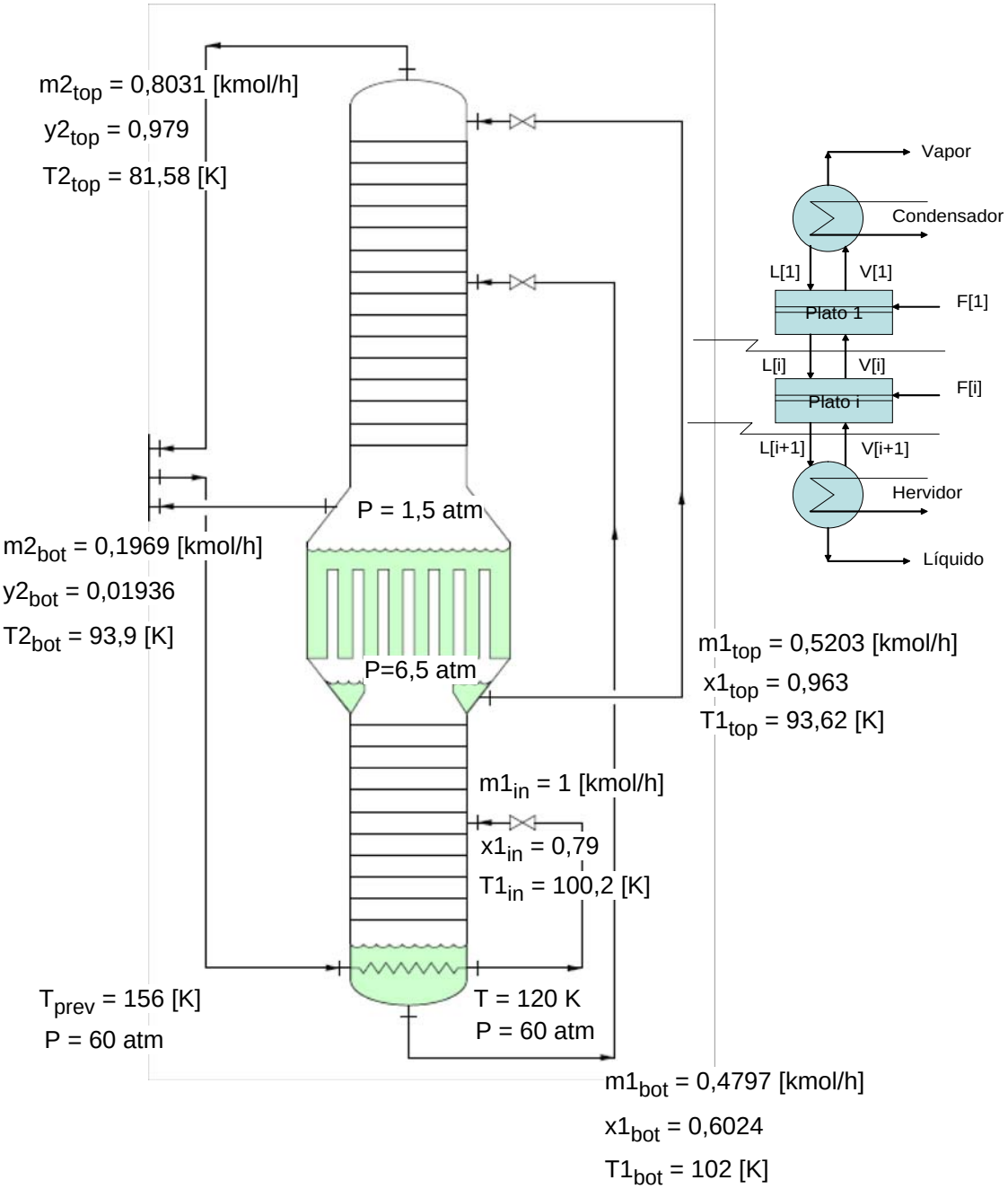


Destilación del aire por doble columna. Copyright 2008 J.I. Zubizarreta.
Determinar la cantidad de aire líquido enriquecido (40 % molar de O2) que se obtiene cada kmol/h de aire de alimentación por cola de la columna inferior a 6,5 ata en una planta de doble columna a 6,5 y 1,5 ata, sabiendo que el aire comprimido (21% molar O2) antes de la válvula de expansión está a 60 ata y 120 K.
Calcular la relación de reflujo de la columna superior, que trabaja a presión de 1,5 ata, y la cantidad de oxígeno que sale de ella con una riqueza del 98% molar de O2.
A partir de los datos de equilibrio, dibujar los diagramas y-x a 1,5 y 6,5 ata y representar sobre ellos las dos rectas de operación y determinar, aplicando el método de McCabe-Thiele, el número de etapas teóricas de las dos columnas de fraccionamiento.
Calcular la temperatura que debe tener el aire de alimentación a la columna de alta presión,antes de pasar por el hervidor de fondo.
Estimar aproximadamente la carga térmica del condensador-hervidor de la doble columna, referida a 1 kmol/h de alimentación.

$x1_{in}$ = 0,79

$m1_{in}$ = 1 [kmol/h]

$$h1_{in} = x1_{in} \cdot \mathbf{h}\left[\text{'Nitrogen'}; T = 120; P = 60\ [atm] \cdot \left|1{,}01325 \cdot \frac{bar}{atm}\right|\right] + \left[1 - x1_{in}\right] \cdot \mathbf{h}\left[\text{'Oxygen'}; T = 120; P = 60\ [atm] \cdot \left|1{,}01325 \cdot \frac{bar}{atm}\right|\right]$$

$$h1_{in} = V_{in} \cdot \left[y \cdot \mathbf{h}\left(\text{'Nitrogen'}; T = T1_{in}; x = 1\right) + \left(1 - y\right) \cdot \mathbf{h}\left(\text{'Oxygen'}; T = T1_{in}; x = 1\right)\right] + \left[1 - V_{in}\right] \cdot \left[x \cdot \mathbf{h}\left(\text{'Nitrogen'}; T = T1_{in}; x = 0\right) + \left(1 - x\right) \cdot \mathbf{h}\left(\text{'Oxygen'}; T = T1_{in}; x = 0\right)\right]$$

$$x1_{in} = V_{in} \cdot y + \left[1 - V_{in}\right] \cdot x$$

$$x = \mathbf{Interpolate}\left[\text{'Equilibrio P = 6,5 atm'}; \text{'T'}; \text{'x'}; \text{'T'} = T1_{in}\right]$$

$$y = \mathbf{Interpolate}\left[\text{'Equilibrio P = 6,5 atm'}; \text{'T'}; \text{'y'}; \text{'T'} = T1_{in}\right]$$

$$m1_{in} \cdot h1_{in} + Q1hervidor = m1_{in} \cdot \left[x1_{in} \cdot \mathbf{h}\left(\text{'Nitrogen'}; T = T_{prev}; P = 60\ [atm] \cdot \left|1{,}01325 \cdot \frac{bar}{atm}\right|\right) + \left(1 - x1_{in}\right) \cdot \mathbf{h}\left(\text{'Oxygen'}; T = T_{prev}; P = 60\ [atm] \cdot \left|1{,}01325 \cdot \frac{bar}{atm}\right|\right)\right]$$

$$V1_1 = L1_1 + m1_{top}$$

$$V1_1 \cdot y1_1 - L1_1 \cdot x1_1 - m1_{top} \cdot x1_{top} = 0$$

$$h1_{top} = x1_{top} \cdot \mathbf{h}\left[\text{'Nitrogen'}; T = T1_{top}; x = 0\right] + \left[1 - x1_{top}\right] \cdot \mathbf{h}\left[\text{'Oxygen'}; T = T1_{top}; x = 0\right]$$

$$hL1_1 = x1_1 \cdot \mathbf{h}\left[\text{'Nitrogen'}; T = T1_{top}; x = 0\right] + \left[1 - x1_1\right] \cdot \mathbf{h}\left[\text{'Oxygen'}; T = T1_{top}; x = 0\right]$$

$$V1_1 \cdot hV1_1 - L1_1 \cdot hL1_1 - m1_{top} \cdot h1_{top} + Q1condensador = 0$$

$$x1_{top} = x1_1$$

$$x1_1 = \mathbf{Interpolate}\left[\text{'Equilibrio P = 6,5 atm'}; \text{'T'}; \text{'x'}; \text{'T'} = T1_{top}\right]$$

$$n1 = 7$$

$$F1_1 = 0$$

$$F1_2 = 0$$

$$F1_3 = 0$$

$$F1_4 = 0$$

$$F1_5 = 1$$

$$F1_6 = 0$$

$$F1_i = 0 \quad \text{for } i = 7 \text{ to } n1$$

$$L1_i - V1_i - L1_{i+1} + V1_{i+1} + F1_i \cdot m1_{in} = 0 \quad \text{for } i = 1 \text{ to } n1$$

$$L1_i \cdot x1_i - V1_i \cdot y1_i - L1_{i+1} \cdot x1_{i+1} + V1_{i+1} \cdot y1_{i+1} + F1_i \cdot m1_{in} \cdot x1_{in} = 0 \quad \text{for } i = 1 \text{ to } n1$$

$$L1_i \cdot hL1_i - V1_i \cdot hV1_i - L1_{i+1} \cdot hL1_{i+1} + V1_{i+1} \cdot hV1_{i+1} + F1_i \cdot m1_{in} \cdot h1_{in} = 0 \quad \text{for } i = 1 \text{ to } n1$$

$$y1_i = \mathbf{Interpolate}\left[\text{'Equilibrio P = 6,5 atm'}; \text{'T'}; \text{'y'}; \text{'T'} = TP1_i\right] \quad \text{for } i = 1 \text{ to } n1$$

$$x1_{i+1} = \mathbf{Interpolate}\left[\text{'Equilibrio P = 6,5 atm'}; \text{'T'}; \text{'x'}; \text{'T'} = TP1_i\right] \quad \text{for } i = 1 \text{ to } n1$$

$$hV1_i = y1_i \cdot \mathbf{h}\left[\text{'Nitrogen'}; T = TP1_i; x = 1\right] + \left[1 - y1_i\right] \cdot \mathbf{h}\left[\text{'Oxygen'}; T = TP1_i; x = 1\right] \quad \text{for } i = 1 \text{ to } n1$$

$hL1_{i+1} = x1_{i+1} \cdot \mathbf{h}[\text{'Nitrogen'}; T = TP1_i; x = 0] + [1 - x1_{i+1}] \cdot \mathbf{h}[\text{'Oxygen'}; T = TP1_i; x = 0]$ for $i = 1$ to $n1$

$-V1_8 + L1_8 - m1_{bot} = 0$

$-V1_8 \cdot y1_8 + L1_8 \cdot x1_8 - m1_{bot} \cdot x1_{bot} = 0$

$-V1_8 \cdot hV1_8 + L1_8 \cdot hL1_8 - m1_{bot} \cdot h1_{bot} + Q1hervidor = 0$

$y1_8 = \mathbf{Interpolate}[\text{'Equilibrio P = 6,5 atm'}; \text{'T'}; \text{'y'}; \text{'T'} = T1_{bot}]$

$x1_{bot} = \mathbf{Interpolate}[\text{'Equilibrio P = 6,5 atm'}; \text{'T'}; \text{'x'}; \text{'T'} = T1_{bot}]$

$T1_{bot} = 102$ *Se fija la temperatura de fondo*

$TP1_8 = T1_{bot}$

$hV1_8 = y1_8 \cdot \mathbf{h}[\text{'Nitrogen'}; T = T1_{bot}; x = 1] + [1 - y1_8] \cdot \mathbf{h}[\text{'Oxygen'}; T = T1_{bot}; x = 1]$

$h1_{bot} = x1_{bot} \cdot \mathbf{h}[\text{'Nitrogen'}; T = T1_{bot}; x = 0] + [1 - x1_{bot}] \cdot \mathbf{h}[\text{'Oxygen'}; T = T1_{bot}; x = 0]$

$V2_1 = L2_1 + m2_{top}$

$V2_1 \cdot y2_1 - L2_1 \cdot x2_1 - m2_{top} \cdot y2_{top} = 0$

$h2_{top} = y2_{top} \cdot \mathbf{h}[\text{'Nitrogen'}; T = T2_{top}; x = 1] + [1 - y2_{top}] \cdot \mathbf{h}[\text{'Oxygen'}; T = T2_{top}; x = 1]$

$hL2_1 = x2_1 \cdot \mathbf{h}[\text{'Nitrogen'}; T = T2_{top}; x = 0] + [1 - x2_1] \cdot \mathbf{h}[\text{'Oxygen'}; T = T2_{top}; x = 0]$

$V2_1 \cdot hV2_1 - L2_1 \cdot hL2_1 - m2_{top} \cdot h2_{top} = 0$ *Sin condensador*

$y2_{top} = \mathbf{Interpolate}[\text{'Equilibrio P = 1,5 atm'}; \text{'T'}; \text{'y'}; \text{'T'} = T2_{top}]$

$x2_1 = \mathbf{Interpolate}[\text{'Equilibrio P = 1,5 atm'}; \text{'T'}; \text{'x'}; \text{'T'} = T2_{top}]$

$n2 = 10$

$F2_1 = 1$

$F2_2 = 0$

$F2_3 = 0$

$F2_i = 0$ for $i = 4$ to $n2$

$G2_i = 0$ for $i = 1$ to $n2-7$

$G2_4 = 0$

$G2_5 = 1$

$G2_6 = 0$

$G2_7 = 0$

$G2_8 = 0$

$G2_9 = 0$

$G2_{10} = 0$

$L2_i - V2_i - L2_{i+1} + V2_{i+1} + F2_i \cdot m1_{top} + G2_i \cdot m1_{bot} = 0$ for $i = 1$ to $n2$

$L2_i \cdot x2_i - V2_i \cdot y2_i - L2_{i+1} \cdot x2_{i+1} + V2_{i+1} \cdot y2_{i+1} + F2_i \cdot m1_{top} \cdot x1_{top} + G2_i \cdot m1_{bot} \cdot x1_{bot} = 0$
for $i = 1$ to $n2$

$L2_i \cdot hL2_i - V2_i \cdot hV2_i - L2_{i+1} \cdot hL2_{i+1} + V2_{i+1} \cdot hV2_{i+1} + F2_i \cdot m1_{top} \cdot h1_{top} + G2_i \cdot m1_{bot} \cdot h1_{bot} = 0$
for $i = 1$ to $n2$

$y2_i$ = **Interpolate** ['Equilibrio P = 1,5 atm'; 'T'; 'y'; 'T' = $TP2_i$] for $i = 1$ to $n2$

$x2_{i+1}$ = **Interpolate** ['Equilibrio P = 1,5 atm'; 'T'; 'x'; 'T' = $TP2_i$] for $i = 1$ to $n2$

$hV2_i = y2_i \cdot$ **h** ['Nitrogen' ; T = $TP2_i$; x = 1] + [1 − $y2_i$] · **h** ['Oxygen' ; T = $TP2_i$; x = 1] for $i = 1$ to $n2$

$hL2_{i+1} = x2_{i+1} \cdot$ **h** ['Nitrogen' ; T = $TP2_i$; x = 0] + [1 − $x2_{i+1}$] · **h** ['Oxygen' ; T = $TP2_i$; x = 0] for $i = 1$ to $n2$

$-V2_{11} + L2_{11} - m2_{bot} = 0$

$-V2_{11} \cdot y2_{11} + L2_{11} \cdot x2_{11} - m2_{bot} \cdot y2_{bot} = 0$

$-V2_{11} \cdot hV2_{11} + L2_{11} \cdot hL2_{11} - m2_{bot} \cdot h2_{bot} + Q2hervidor = 0$

$y2_{11}$ = **Interpolate** ['Equilibrio P = 1,5 atm'; 'T'; 'y'; 'T' = $T2_{bot}$]

$y2_{bot} = y2_{11}$

$T2_{bot} = 93,9$ *Se fija la temperatura de fondo*

$TP2_{11} = T2_{bot}$

$hV2_{11} = y2_{11} \cdot$ **h** ['Nitrogen' ; T = $T2_{bot}$; x = 1] + [1 − $y2_{11}$] · **h** ['Oxygen' ; T = $T2_{bot}$; x = 1]

$h2_{bot} = y2_{bot} \cdot$ **h** ['Nitrogen' ; T = $T2_{bot}$; x = 1] + [1 − $y2_{bot}$] · **h** ['Oxygen' ; T = $T2_{bot}$; x = 1]

Q1condensador = − Q2hervidor

SOLUTION

Unit Settings: [kJ]/[K]/[bar]/[kmol]/[degrees]

$h1_{bot}$ = -11266 [kJ/kmol]	$h1_{in}$ = -9774 [kJ/kmol]
$h1_{top}$ = -11184 [kJ/kmol]	$h2_{bot}$ = -6050 [kJ/kmol]
$h2_{top}$ = -6432 [kJ/kmol]	$m1_{bot}$ = 0,4797 [kmol/h]
$m1_{in}$ = 1 [kmol/h]	$m1_{top}$ = 0,5203 [kmol/h]
$m2_{bot}$ = 0,1969 [kmol/h]	$m2_{top}$ = 0,8031 [kmol/h]
n1 = 7	n2 = 10
Q1condensador = -4867 [kJ/h]	Q1hervidor = 3417 [kJ/h]
Q2hervidor = 4867 [kJ/h]	$T1_{bot}$ = 102 [K]
$T1_{in}$ = 100,2 [K]	$T1_{top}$ = 93,62 [K]
$T2_{bot}$ = 93,9 [K]	$T2_{top}$ = 81,58 [K]
T_{prev} = 156 [K]	V_{in} = 0,2718
x = 0,757	$x1_{bot}$ = 0,6024
$x1_{in}$ = 0,79	$x1_{top}$ = 0,963
y = 0,8796	$y2_{bot}$ = 0,01936
$y2_{top}$ = 0,979	

No unit problems were detected.

Arrays Table

	$F1_i$	$L1_i$ [kmol/h]	$TP1_i$ [K]	$V1_i$ [kmol/h]	$hL1_i$ [kJ/kmol]	$hV1_i$ [kJ/kmol]	$x1_i$	$y1_i$	$F2_i$	$G2_i$
1	0	0,4584	98,54	0,9787	-11184	-6211	0,963	0,963	1	0
2	0	0,4795	98,98	0,9998	-10948	-6203	0,9188	0,9418	0	0
3	0	0,4733	99,4	0,9936	-10994	-6196	0,8748	0,921	0	0
4	0	0,4676	99,79	0,9879	-11037	-6188	0,8336	0,9017	0	0
5	1	0,4628	100,1	0,983	-11074	-6182	0,797	0,8848	0	1
6	0	1,189	100,3	0,7092	-11106	-6179	0,7659	0,8766	0	0
7	0	1,184	100,7	0,7043	-11121	-6169	0,7512	0,8525	0	0
8		1,17	102	0,6908	-11162	-6143	0,7096	0,7841	0	0
9									0	0
10									0	0
11										

Arrays Table

	$L2_i$ [kmol/h]	$TP2_i$ [K]	$V2_i$ [kmol/h]	$hL2_i$ [kJ/kmol]	$hV2_i$ [kJ/kmol]	$x2_i$	$y2_i$
1	1,751E-15	81,58	0,8031	-11950	-6432	0,9327	0,979
2	0,4469	81,96	0,7298	-11950	-6423	0,9327	0,962
3	0,4403	82,61	0,7231	-12008	-6408	0,8821	0,9315
4	0,4301	83,59	0,7129	-12102	-6385	0,7988	0,8819
5	0,4171	84,82	0,6999	-12230	-6354	0,6822	0,814
6	0,7962	86,2	0,5992	-12365	-6318	0,553	0,7283
7	0,7746	88,44	0,5777	-12486	-6255	0,4277	0,5669
8	0,7511	90,88	0,5542	-12621	-6174	0,2649	0,3521
9	0,7361	92,62	0,5392	-12703	-6107	0,13	0,1704
10	0,7299	93,51	0,533	-12730	-6068	0,0537	0,06639
11	0,7278	93,9	0,5308	-12737	-6050	0,01936	0,01936

Lookup Table: Equilibrio P = 1,5 atm

	T [K]	x	y
Row 1	94,06	0	0
Row 2	93,36	0,025	0,08464
Row 3	92,71	0,05	0,1599
Row 4	92,1	0,075	0,2272
Row 5	91,52	0,1	0,2875
Row 6	90,98	0,125	0,3419
Row 7	90,47	0,15	0,3911
Row 8	89,98	0,175	0,4357
Row 9	89,53	0,2	0,4764
Row 10	89,09	0,225	0,5137
Row 11	88,67	0,25	0,5479
Row 12	88,28	0,275	0,5793
Row 13	87,9	0,3	0,6084
Row 14	87,54	0,325	0,6354
Row 15	87,19	0,35	0,6605
Row 16	86,86	0,375	0,6839
Row 17	86,54	0,4	0,7057
Row 18	86,24	0,425	0,7262
Row 19	85,94	0,45	0,7455
Row 20	85,65	0,475	0,7636
Row 21	85,38	0,5	0,7807

Lookup Table: Equilibrio P = 1,5 atm

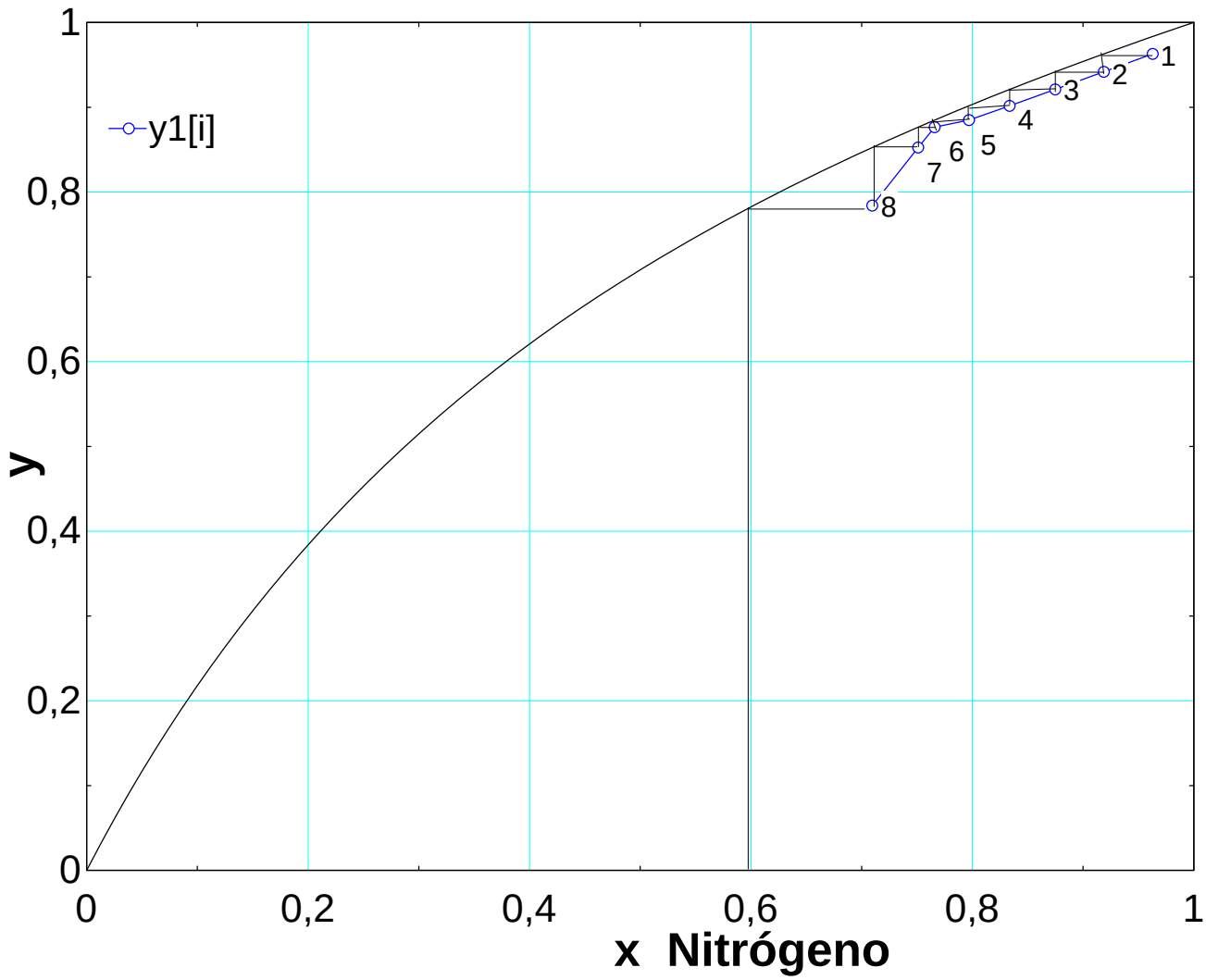
	T [K]	x	y
Row 22	85,11	0,525	0,7969
Row 23	84,85	0,55	0,8122
Row 24	84,6	0,575	0,8268
Row 25	84,35	0,6	0,8406
Row 26	84,11	0,625	0,8539
Row 27	83,88	0,65	0,8665
Row 28	83,65	0,675	0,8785
Row 29	83,43	0,7	0,8901
Row 30	83,22	0,725	0,9012
Row 31	83,01	0,75	0,9118
Row 32	82,8	0,775	0,9221
Row 33	82,6	0,8	0,9319
Row 34	82,4	0,825	0,9415
Row 35	82,2	0,85	0,9506
Row 36	82,01	0,875	0,9595
Row 37	81,83	0,9	0,9681
Row 38	81,64	0,925	0,9765
Row 39	81,46	0,95	0,9845
Row 40	81,28	0,975	0,9924
Row 41	81,1	1	1

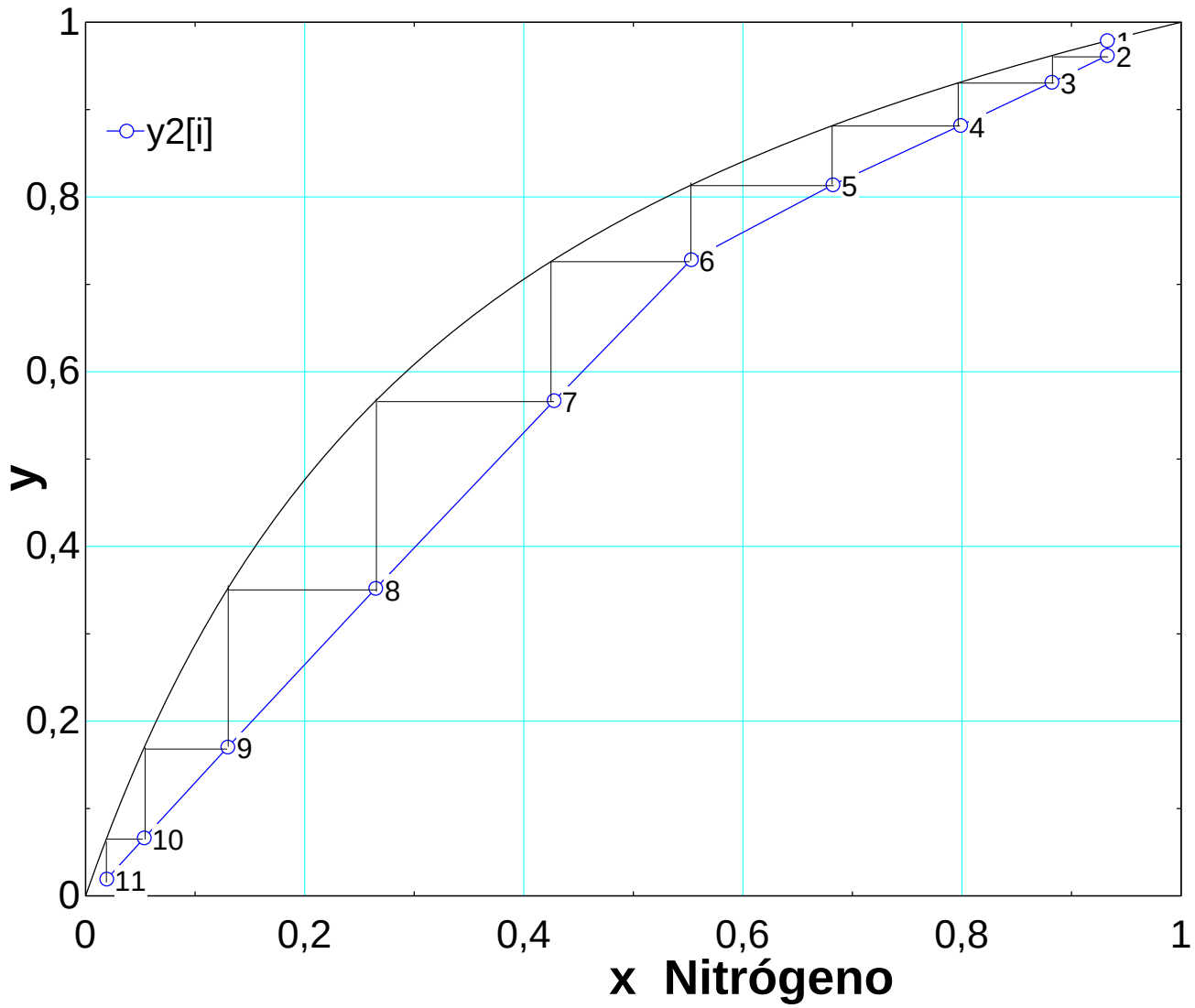
Lookup Table: Equilibrio P = 6,5 atm

	T [K]	x	y
Row 1	112,7	0	0
Row 2	112,1	0,025	0,06039
Row 3	111,4	0,05	0,1166
Row 4	110,8	0,075	0,1689
Row 5	110,3	0,1	0,2177
Row 6	109,7	0,125	0,2634
Row 7	109,2	0,15	0,3061
Row 8	108,6	0,175	0,3463
Row 9	108,2	0,2	0,384
Row 10	107,7	0,225	0,4196
Row 11	107,2	0,25	0,4531
Row 12	106,8	0,275	0,4848
Row 13	106,3	0,3	0,5148
Row 14	105,9	0,325	0,5433
Row 15	105,5	0,35	0,5703
Row 16	105,1	0,375	0,596
Row 17	104,7	0,4	0,6205
Row 18	104,4	0,425	0,6439
Row 19	104	0,45	0,6663
Row 20	103,7	0,475	0,6877
Row 21	103,3	0,5	0,7082
Row 22	103	0,525	0,7278
Row 23	102,7	0,55	0,7468
Row 24	102,3	0,575	0,7649
Row 25	102	0,6	0,7825
Row 26	101,7	0,625	0,7994
Row 27	101,4	0,65	0,8157
Row 28	101,1	0,675	0,8315
Row 29	100,8	0,7	0,8468

Lookup Table: Equilibrio P = 6,5 atm

	T [K]	x	y
Row 30	100,6	0,725	0,8616
Row 31	100,3	0,75	0,8759
Row 32	100	0,775	0,8898
Row 33	99,75	0,8	0,9034
Row 34	99,49	0,825	0,9165
Row 35	99,23	0,85	0,9294
Row 36	98,98	0,875	0,9418
Row 37	98,73	0,9	0,954
Row 38	98,48	0,925	0,9659
Row 39	98,23	0,95	0,9775
Row 40	97,99	0,975	0,9889
Row 41	97,75	1	1




y2[i]
1
2
3
4
5
6
7
8
9
10
11
y
x Nitrógeno
0
0,2
0,4
0,6
0,8
1