

Electronic Supplementary Material

1. Original experimental data

The original experimental data are shown in **Tables S1–S5**. The cumulative total gas production in the table is calculated based on the pressure difference within the sampling interval. Moreover, the cumulative recovery factor calculation in the original manuscript is also based on the differential pressure and gas molar concentration within the sampling interval.

Table S1 Experimental data of pure CO₂ gas injection displacement experiment

Time/min	CO ₂ molar concentration/%	CH ₄ molar concentration/%	Cumulative total gas production/kPa	Cumulative total gas production/mol
0	0.000	100.000	0.000	0.000
25	0.000	100.000	25.906	0.011
50	0.000	100.000	58.113	0.028
75	0.000	100.000	82.619	0.035
100	0.000	100.000	100.823	0.044
125	0.945	99.055	115.667	0.049
150	4.882	95.118	131.861	0.055
175	12.441	87.559	144.655	0.060
200	22.677	77.323	160.954	0.067
225	34.803	65.197	175.989	0.074
250	44.567	55.433	196.198	0.083
275	54.646	45.354	216.267	0.089
300	62.205	37.795	242.202	0.099
325	69.291	30.709	260.442	0.107
350	74.488	25.512	290.630	0.119
375	79.370	20.630	321.176	0.133
400	82.835	17.165	357.886	0.148
425	85.827	14.173	402.348	0.166
450	88.347	11.654	438.395	0.185
475	90.236	9.764	502.931	0.203
500	91.654	8.346	561.656	0.225
525	93.228	6.772	613.350	0.247
550	94.803	5.197	667.239	0.282
575	95.591	4.409	746.643	0.299
600	95.906	4.094	815.051	0.325
625	96.378	3.622	844.279	0.346
650	96.850	3.150	855.126	0.346
675	97.008	2.992	878.523	0.346
700	97.323	2.677	904.682	0.359

Table S2 Experimental data of pure N₂ gas injection displacement experiment

Time/min	CO ₂ molar concentration/%	CH ₄ molar concentration/%	Cumulative total gas production/kPa	Cumulative total gas production/mol
0	0.000	100.000	0.000	0.000
25	0.000	100.000	31.507	0.013
50	0.000	100.000	65.815	0.027
75	1.575	98.425	93.558	0.039
100	3.307	96.693	111.661	0.046
125	6.772	93.228	125.930	0.052
150	11.181	88.819	138.543	0.057
175	16.850	83.150	152.858	0.063

200	23.780	76.221	164.799	0.068
225	32.284	67.717	178.241	0.073
250	40.158	59.843	191.110	0.079
275	48.347	51.654	206.021	0.085
300	55.748	44.252	221.843	0.091
325	62.677	37.323	236.851	0.098
350	69.449	30.551	255.185	0.105
375	75.118	24.882	274.882	0.113
400	79.528	20.472	302.242	0.124
425	83.465	16.535	327.649	0.135
450	86.772	13.228	354.115	0.146
475	88.976	11.024	379.519	0.156
500	91.024	8.976	418.520	0.172
525	92.913	7.087	467.919	0.193
550	94.488	5.512	493.324	0.203
575	95.591	4.409	556.845	0.229
600	96.220	3.780	630.935	0.260
625	97.165	2.835	705.022	0.290
650	97.480	2.520	788.379	0.325
675	97.795	2.205	915.392	0.377
700	97.794	2.206	957.286	0.394

Table S3 Experimental data of CO₂/N₂ (8/2) mixture gas injection displacement experiment

Time/min	CO ₂ molar concentration/%	N ₂ molar concentration/%	CH ₄ molar concentration/%	Cumulative	Cumulative total
				total gas production/kPa	gas production/mol
0	0.000	0.000	100.000	0.000	0.000
25	0.000	0.000	100.000	22.668	0.010
50	0.000	0.000	100.000	48.461	0.020
75	0.000	1.920	98.080	71.571	0.030
100	0.000	3.527	96.473	89.403	0.038
125	0.000	7.714	92.286	106.352	0.045
150	7.124	12.367	80.509	123.844	0.052
175	14.325	15.427	70.248	140.556	0.059
200	25.640	18.861	55.499	161.703	0.067
225	36.915	19.559	43.526	183.291	0.076
250	48.068	20.608	31.324	215.780	0.088
275	55.096	20.661	24.243	251.318	0.102
300	62.529	21.170	16.301	304.171	0.125
325	66.667	20.386	12.947	370.729	0.154
350	71.396	20.041	8.563	462.203	0.196
375	73.554	19.835	6.611	604.361	0.243
400	76.196	19.754	4.050	797.857	0.323
425	77.135	19.559	3.306	963.946	0.406
450	76.485	19.640	3.875	1125.836	0.463
475	77.411	19.284	3.305	1292.087	0.520
500	77.562	19.355	3.083	1444.866	0.598
525	77.961	19.284	2.755	1615.900	0.648
550	78.303	19.238	2.459	1775.848	0.746
575	78.512	19.284	2.204	1989.629	0.808
600	78.365	19.462	2.173	2134.626	0.887
625	78.512	19.284	2.204	2206.723	0.903
650	78.315	19.514	2.171	2243.966	0.942
675	78.512	19.284	2.204	2315.498	0.942
700	78.431	19.398	2.171	2353.314	0.958

Table S4 Experimental data of CO₂/N₂ (5/5) mixture gas injection displacement experiment

Time/min	CO ₂ molar concentration/%	N ₂ molar concentration/%	CH ₄ molar concentration/%	Cumulative total gas production/kPa	Cumulative total gas production/mol
0	0.000	0.000	100.000	0.000	0.000
25	0.000	0.000	100.000	17.984	0.007
50	0.000	0.000	100.000	37.529	0.015
75	0.000	2.915	97.085	55.867	0.023
100	0.000	5.045	94.955	70.462	0.029
125	0.000	11.365	88.635	87.410	0.036
150	0.000	16.317	83.683	102.962	0.042
175	0.219	24.779	75.002	121.894	0.050
200	0.692	32.522	66.786	143.044	0.059
225	1.786	41.161	57.053	173.604	0.071
250	3.637	48.662	47.701	203.595	0.084
275	9.052	55.745	35.204	239.141	0.098
300	14.865	58.395	26.740	291.993	0.120
325	20.808	58.384	20.808	358.538	0.148
350	27.656	58.752	13.593	468.247	0.193
375	32.047	57.841	10.113	586.785	0.242
400	37.321	55.828	6.852	780.235	0.321
425	39.659	55.398	4.944	993.612	0.409
450	42.767	53.841	3.392	1175.651	0.484
475	43.816	53.647	2.538	1365.469	0.562
500	45.402	52.322	2.276	1543.683	0.636
525	45.901	52.758	1.341	1771.330	0.730
550	47.098	51.587	1.316	1962.953	0.808
575	46.467	52.532	1.001	2212.242	0.911
600	48.481	50.225	1.293	2393.071	0.986
625	48.861	50.118	1.021	2500.688	1.030
650	49.553	49.335	1.112	2573.881	1.060
675	49.738	49.230	1.033	2681.414	1.104
700	49.682	49.228	1.089	2718.645	1.120

Table S5 Experimental data of CO₂/N₂ (2/8) mixture gas injection displacement experiment

Time/min	CO ₂ molar concentration/%	N ₂ molar concentration/%	CH ₄ molar concentration/%	Cumulative total gas production/kPa	Cumulative total gas production/mol
0	0.000	0.000	100.000	0.000	0.000
25	0.000	0.000	100.000	14.080	0.006
50	0.000	0.000	100.000	29.722	0.012
75	0.000	1.232	98.768	44.874	0.018
100	0.000	3.065	96.935	58.660	0.024
125	0.000	8.416	91.584	72.226	0.030
150	0.000	13.548	86.452	88.747	0.037
175	0.000	22.277	77.723	106.568	0.044

200	0.968	30.645	68.387	124.906	0.051
225	2.227	41.584	56.189	148.283	0.061
250	3.065	51.774	45.161	178.285	0.073
275	5.941	59.901	34.158	220.264	0.091
300	8.871	68.548	22.581	268.327	0.111
325	10.264	73.762	15.973	340.915	0.140
350	12.355	80.484	7.161	441.507	0.182
375	15.637	81.436	2.928	571.855	0.236
400	16.453	83.065	0.483	784.583	0.323
425	18.126	81.457	0.417	1021.568	0.421
450	18.364	80.807	0.830	1203.613	0.496
475	19.321	79.455	1.224	1417.047	0.584
500	19.526	78.871	1.603	1671.174	0.688
525	19.328	78.218	2.454	1870.548	0.770
550	20.436	77.742	1.822	2093.986	0.862
575	20.536	77.228	2.236	2343.204	0.965
600	20.337	77.258	2.405	2559.962	1.054
625	20.315	76.980	2.705	2773.839	1.142
650	20.142	77.097	2.761	2918.957	1.202
675	21.012	76.733	2.255	3097.327	1.276
700	20.954	76.936	2.111	3206.482	1.321

2. Solution of breakthrough time of gas injection displacement experiment

Taking pure CO₂ or N₂ gas injection displacement experiment as an example for analysis and the experimental data as shown in [Table S1](#). It can be seen from [Table S1](#) that the CO₂ molar concentration is 0 within 100 min, and is no longer 0 from 125 min. The breakthrough time of CO₂ should be between 100 and 125 min. Therefore, the experimental data from 125 min to 150 min are selected as the input values of linear extrapolation, and the following linear extrapolation equation is obtained. According to the linear extrapolation equation, the breakthrough time of CO₂ can be solved as follows:

$$M_{(\text{CO}_2)} = 0.1575t - 18.74 \Rightarrow 0 = 0.1575t_b - 18.74 \Rightarrow t_b \approx 118. \quad (\text{B1})$$

Based on the same method, the breakthrough time of N₂ can be calculated as follows:

$$M_{(\text{N}_2)} = 0.0693t - 3.4646 \Rightarrow 0 = 0.0693t_b - 3.4646 \Rightarrow t_b \approx 49. \quad (\text{B2})$$

The method for solving the breakthrough time of the mixed gases injection displacement experiment is the same, and will not be repeated here.