POLITECNICO MILANO 1863

United Nations Educational, Scientific and Cultural Organization

UNESCO Chair in Energy for Sustainable Development

POLITECNICO DI MILANO

Lo stato eterogeneo

Corso di Fisica Tecnica
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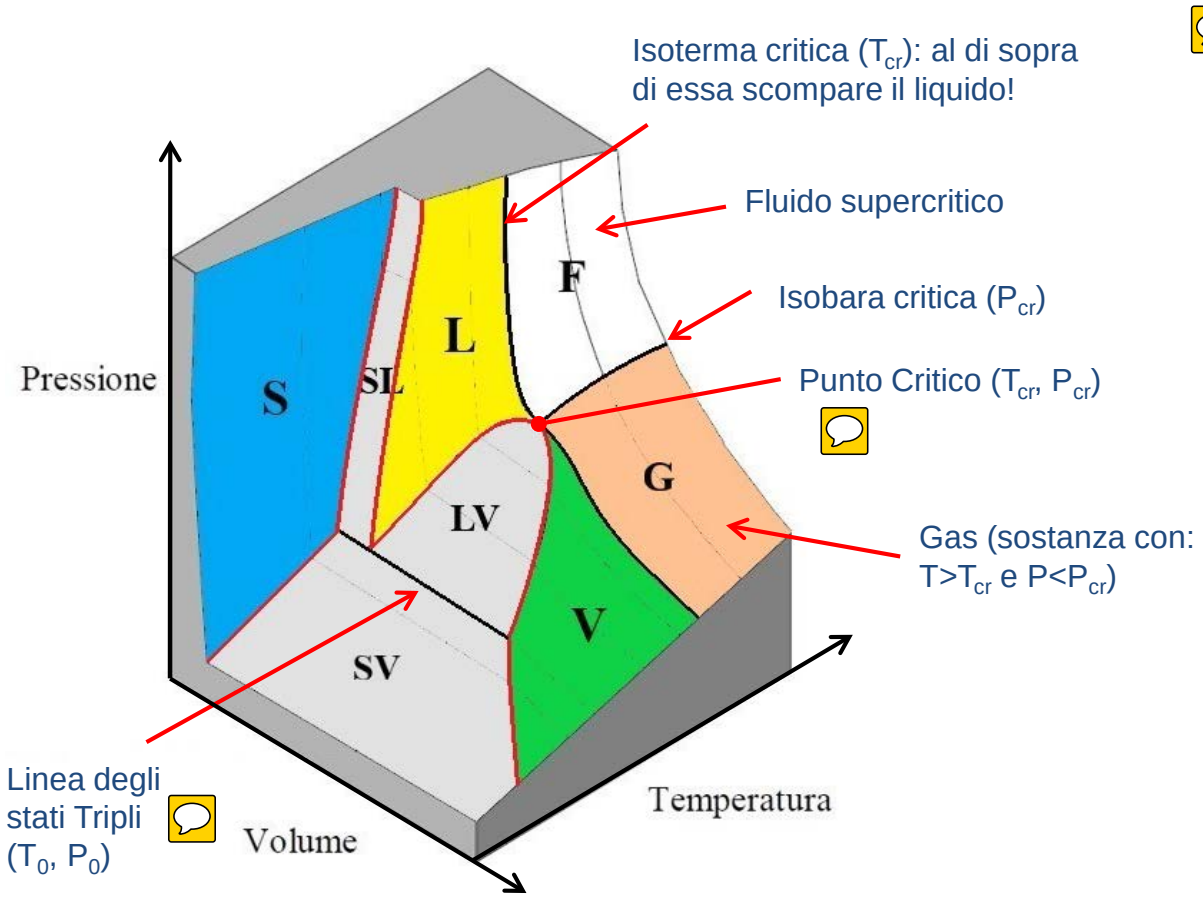
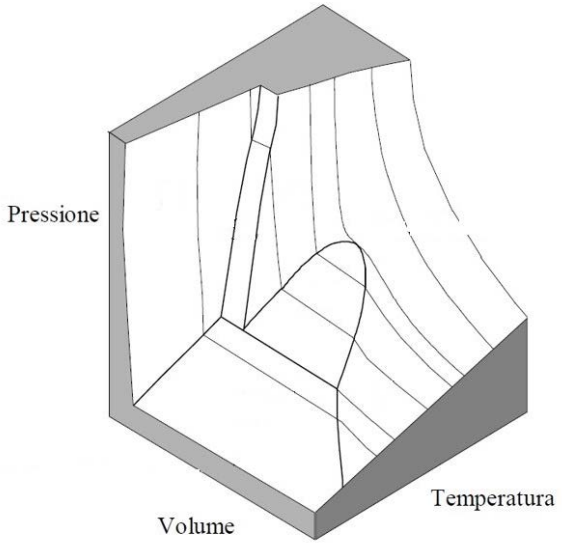
Lo stato eterogeneo

Diagramma di stato P-v-T

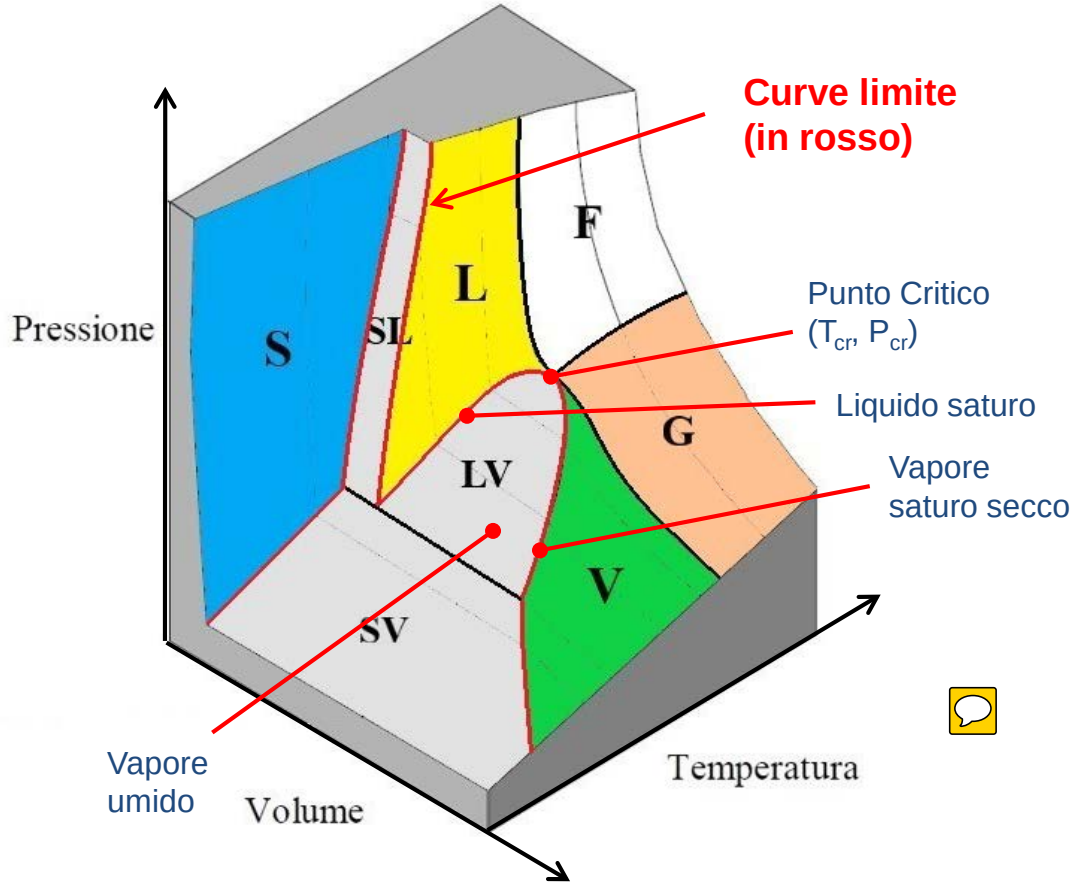
Per un **sistema semplice monocomponente** all'equilibrio: il **diagramma di stato** rappresenta la **superficie di stato** (in bianco) in uno spazio tridimensionale di coordinate P-v-T, luogo dei possibili stati del sistema. La superficie di stato dipende varia da fluido a fluido.





Lo stato eterogeneo

Diagramma di stato P-v-T



Definizioni:

- Solido (S);
- Liquido sottoraffreddato (L);
- Liquido saturo (sulla curva limite inferiore, tra L e LV);
- Vapore umido (miscela liquido vapore, LV);
- Vapore saturo secco (sulla curva limite superiore, tra LV e V);
- Vapore surriscaldato (V);
- Temperatura di saturazione: fissata una P, è la T alla quale:
  - Il liquido inizia a evaporare;
  - Il vapore inizia a condensare;

Lo stato eterogeneo

Diagramma di stato P-v-T: rappresentazione nel piano P-T

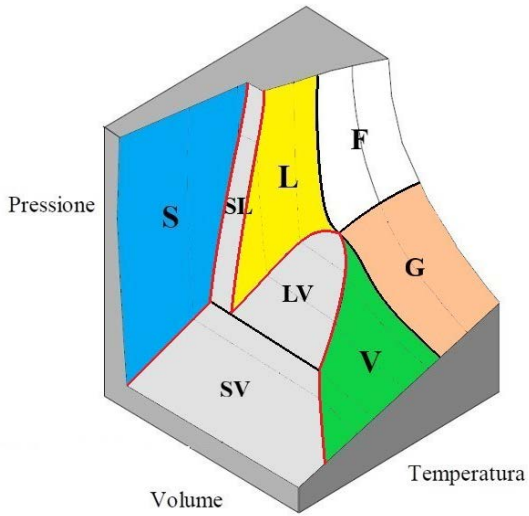
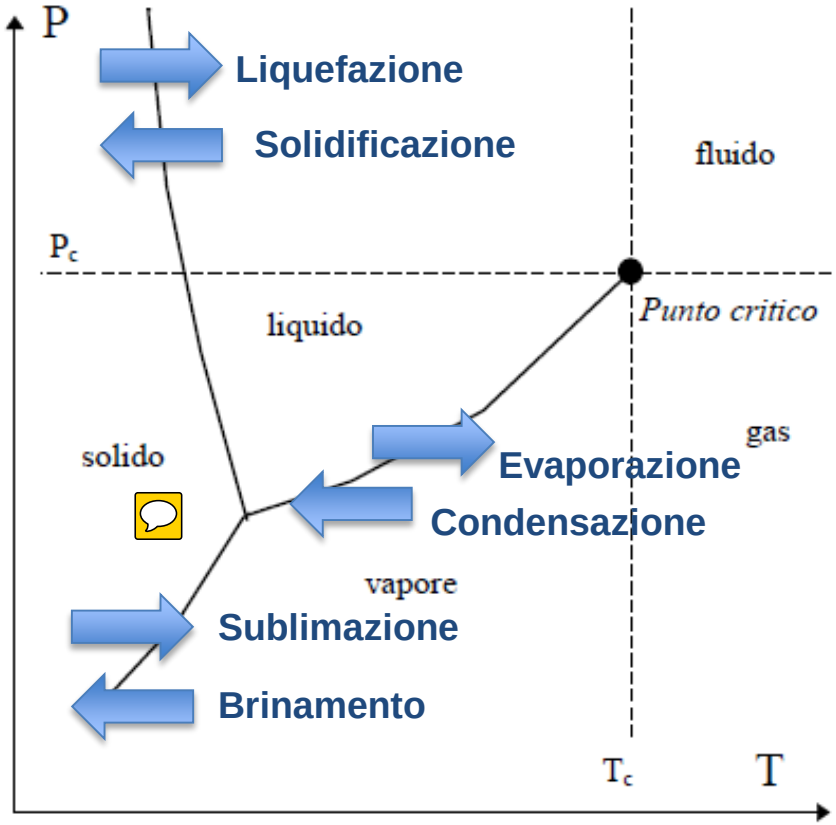


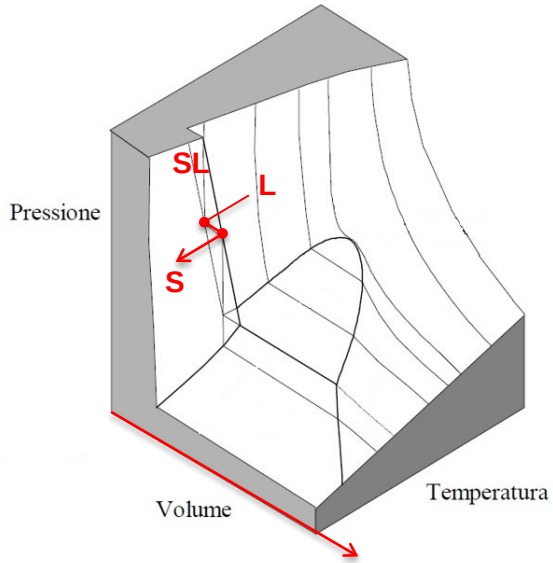
Diagramma P-T

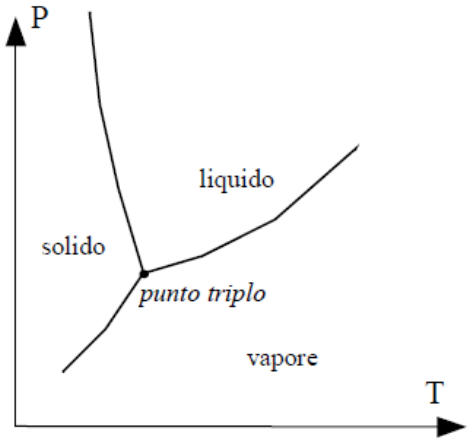
Trasformazioni:



Lo stato eterogeneo

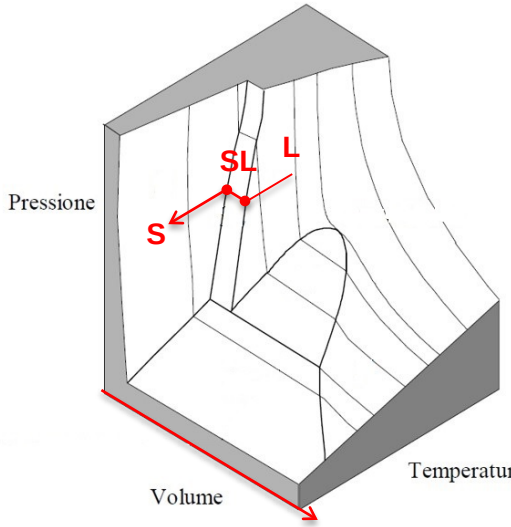
Diagramma di stato P-v-T: rappresentazione nel piano P-T

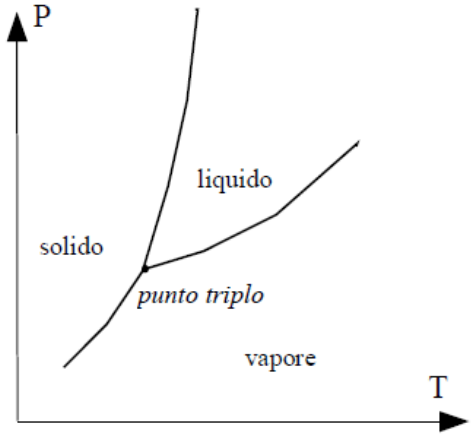




Sostanze che solidificando a P costante **aumentano** il proprio volume

(es. H2O)





Sostanze che solidificando a P costante **diminuiscono** il proprio volume

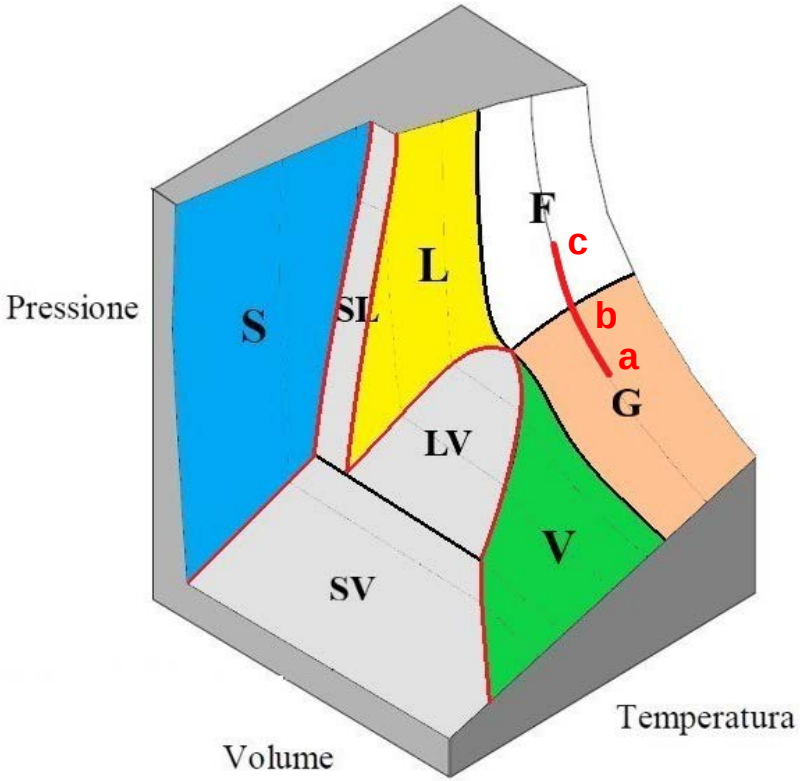
(es. CO2)

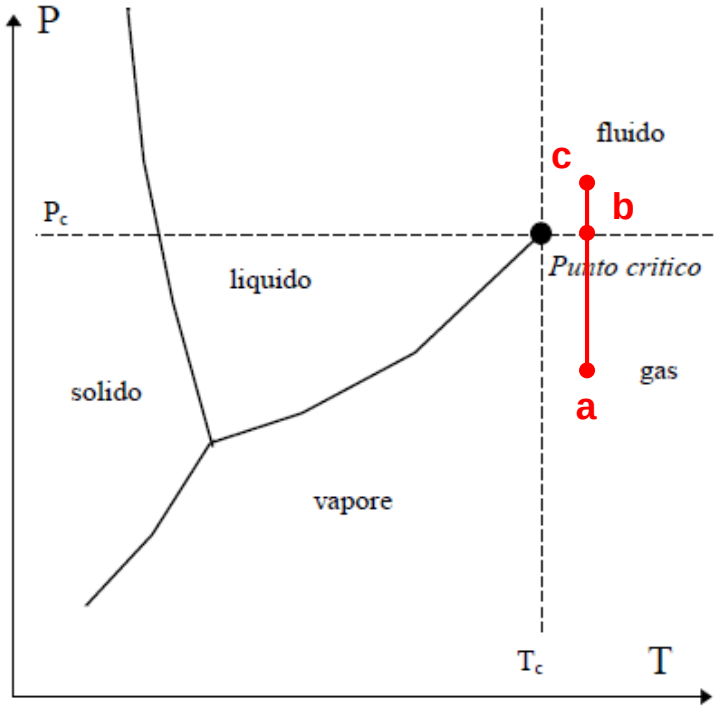
Lo stato eterogeneo

Diagramma di stato P-v-T: rappresentazione nel piano P-T

Definizione di GAS:

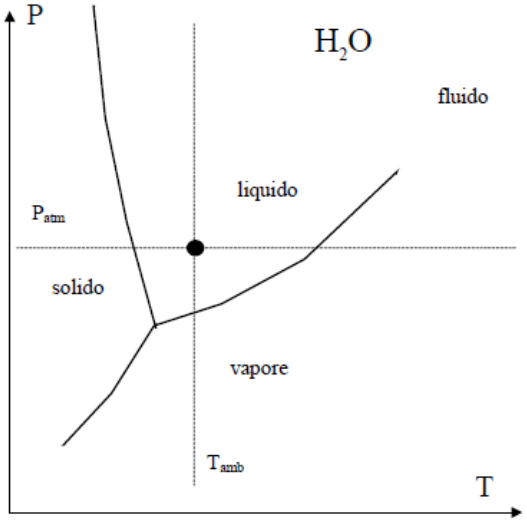
fluido a $P<P_{cr}$ e $T>T_{cr}$, che non può essere liquefatto attraverso una trasformazione di compressione isoterma.

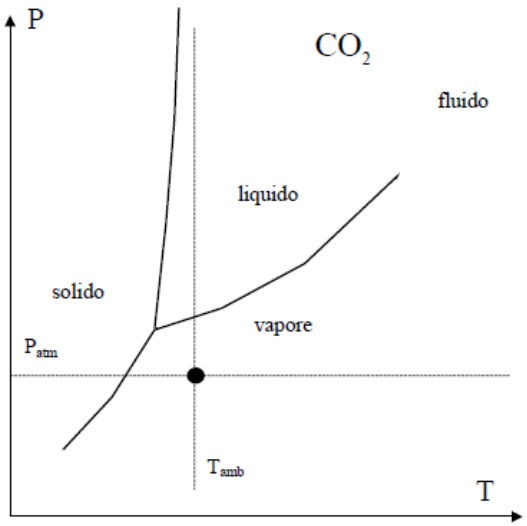


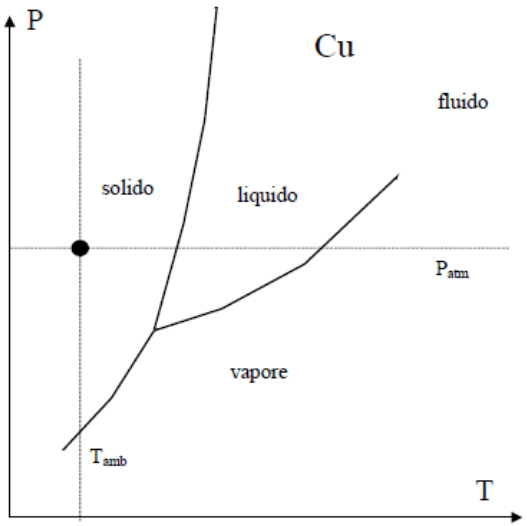


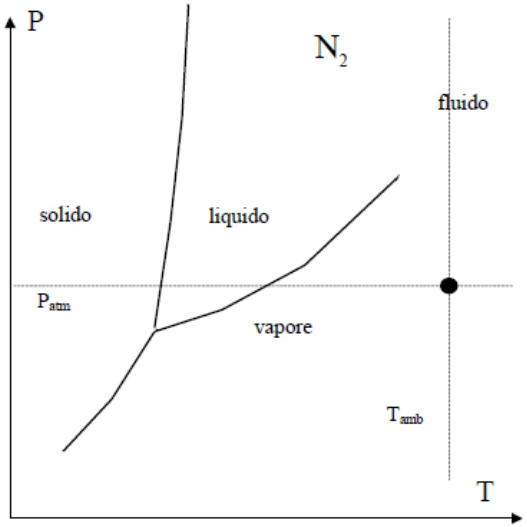
Lo stato eterogeneo

Diagramma di stato P-v-T: rappresentazione nel piano P-T









Stato di alcune sostanze a condizioni ambiente:

P_{amb} = 101325 Pa

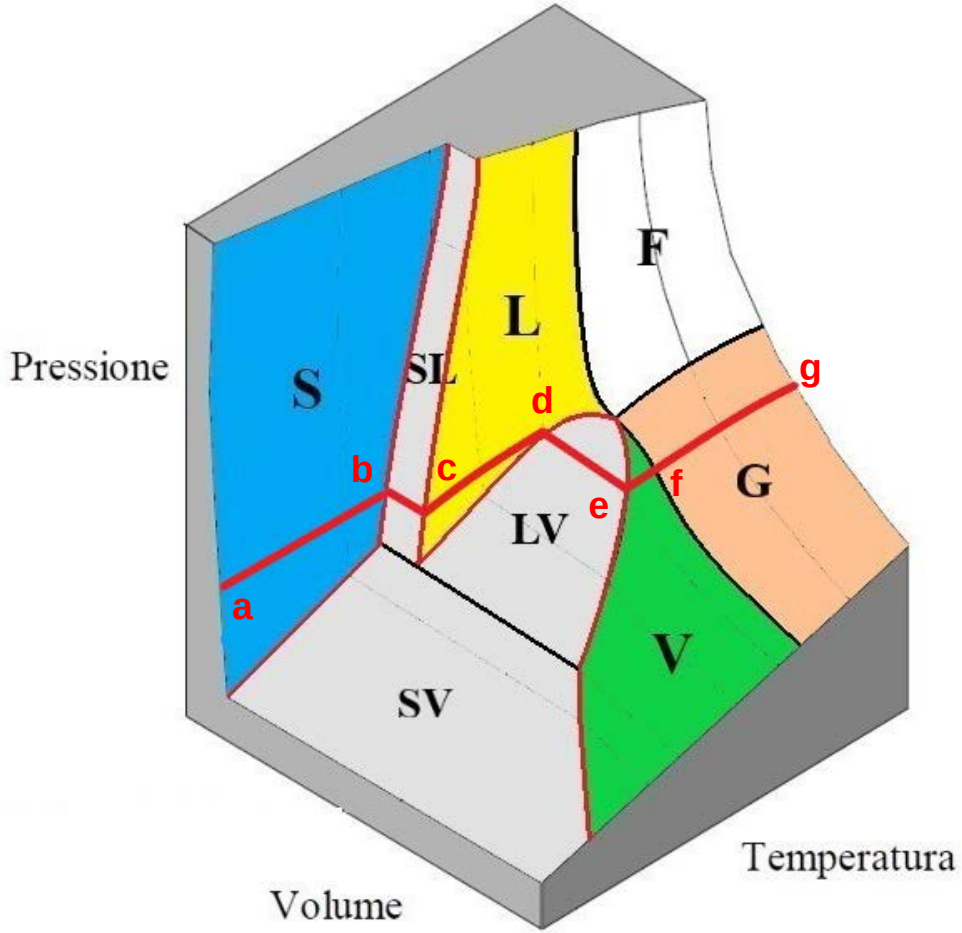
T_{amb} = 20 ° C (293.15 K)

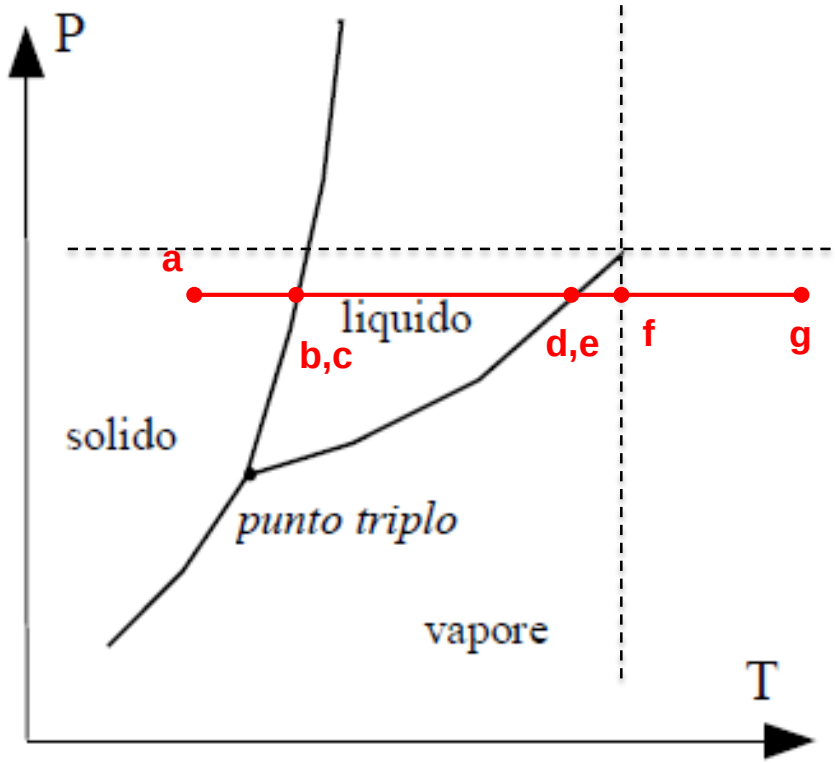
I fluidi che a condizioni ambiente sono in fase gas sono detti «incondensabili»

Lo stato eterogeneo

Diagramma di stato P-v-T: rappresentazione nel piano P-T

Trasformazione **ISOBARA:** fornisco (o sottraggo) calore al sistema a pressione costante

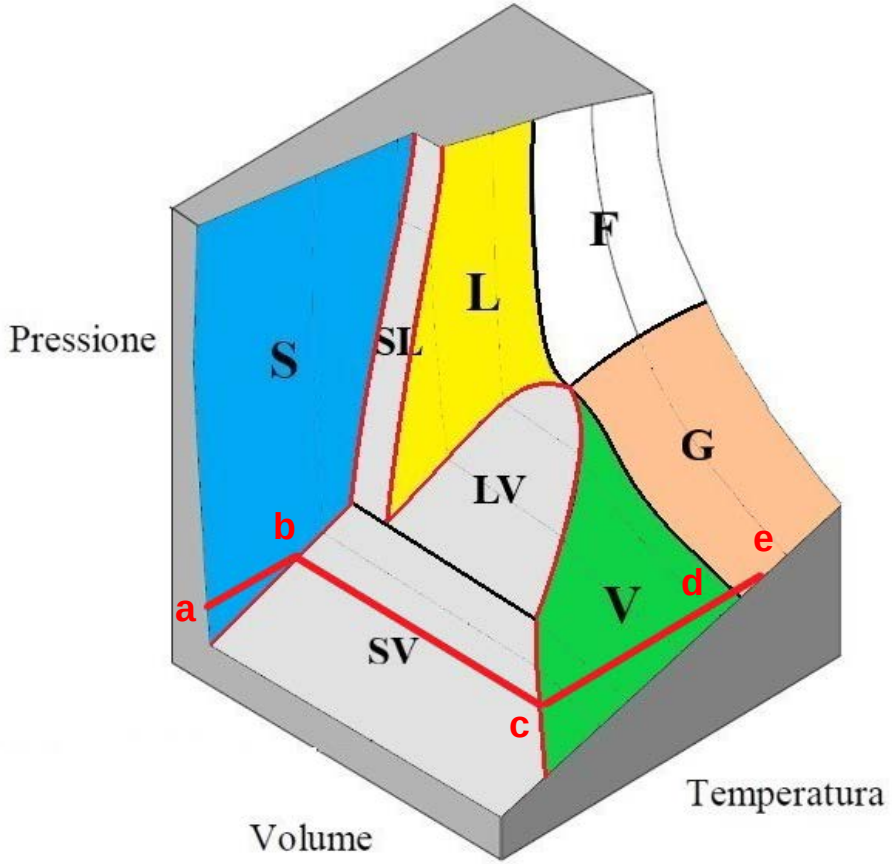


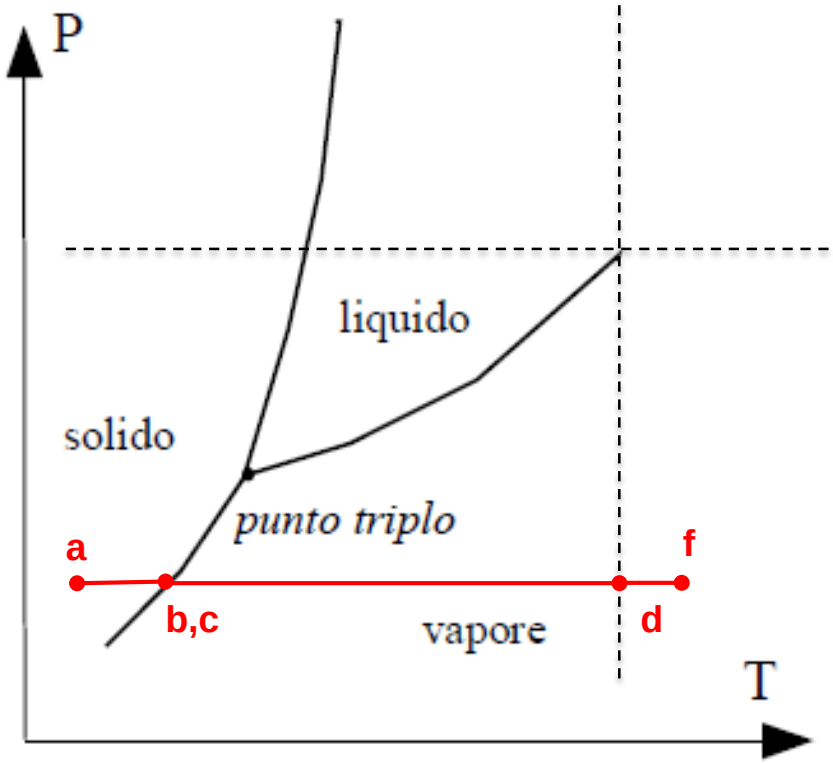


Lo stato eterogeneo

Diagramma di stato P-v-T: rappresentazione nel piano P-T

Trasformazione **ISOBARA:** fornisco (o sottraggo) calore al sistema a pressione costante

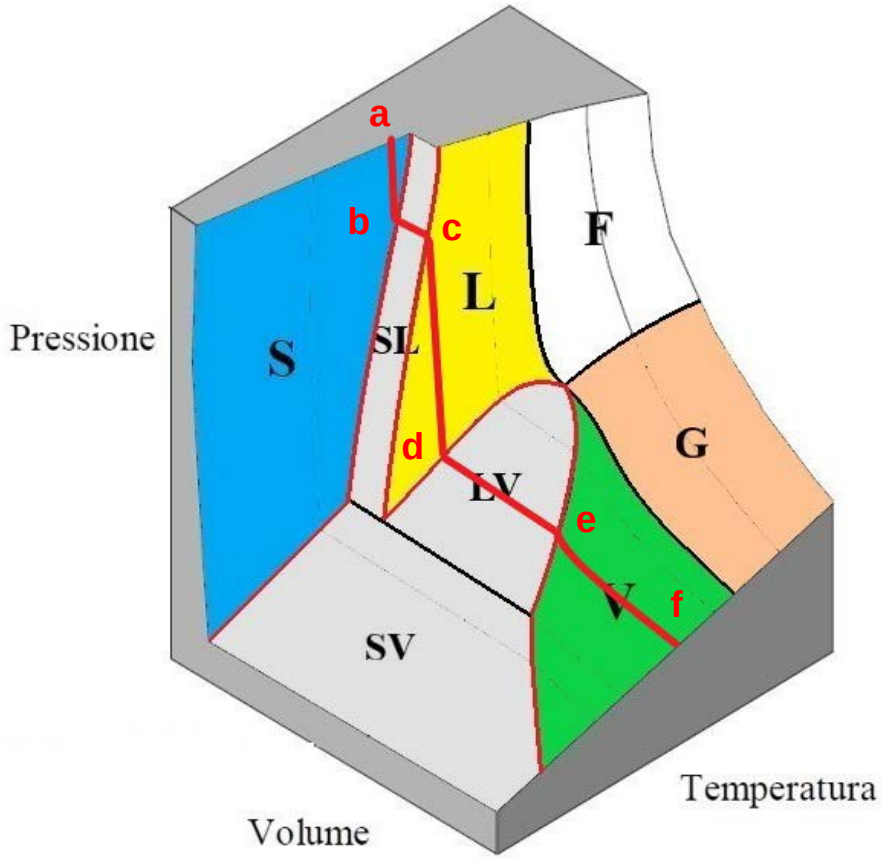


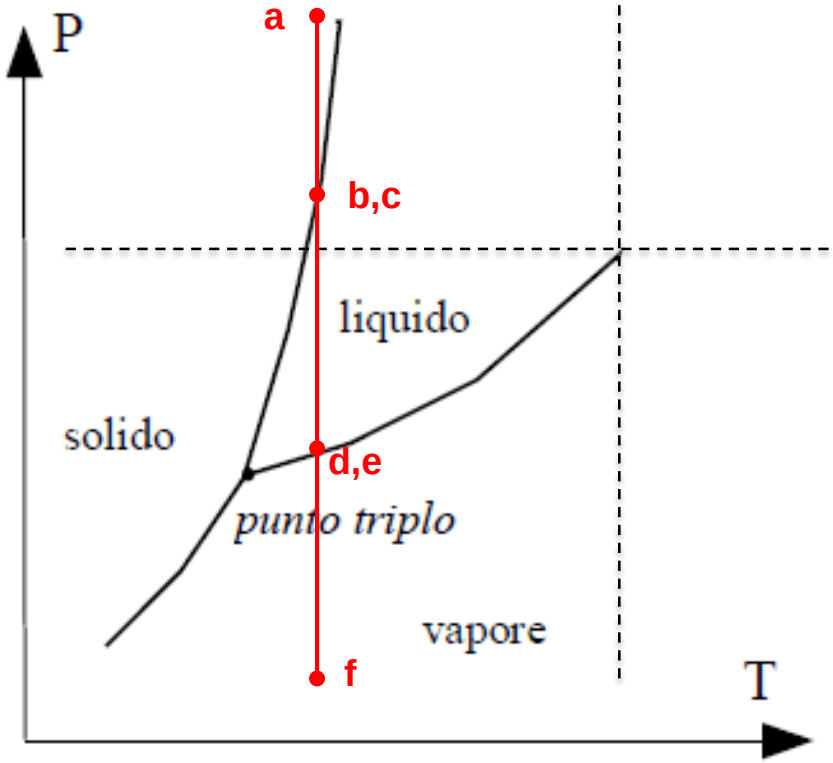


Lo stato eterogeneo

Diagramma di stato P-v-T: rappresentazione nel piano P-T

Trasformazione **ISOTERMA:** espando (o comprimo) il sistema fornendo/estraendo calore per mantenere costante la temperatura





Lo stato eterogeneo

Diagramma di stato P-v-T: rappresentazione su piani T-v, P-v, T-s, P-h, h-s

Trasformazione **ISOBARA:** fornisco (o sottraggo) calore al sistema a pressione costante

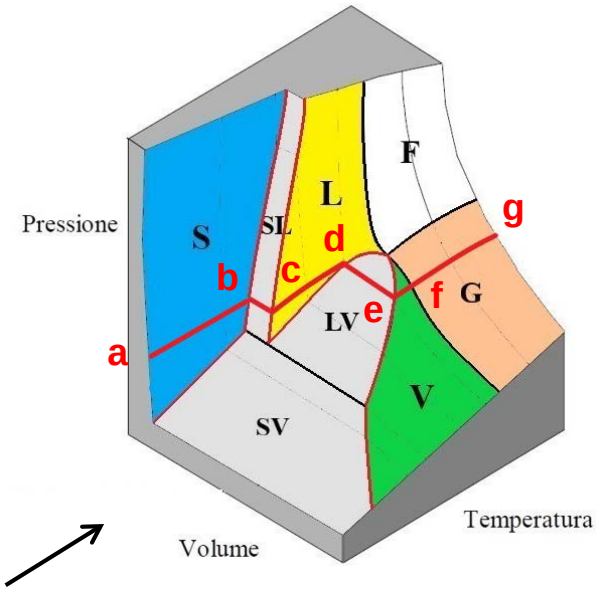
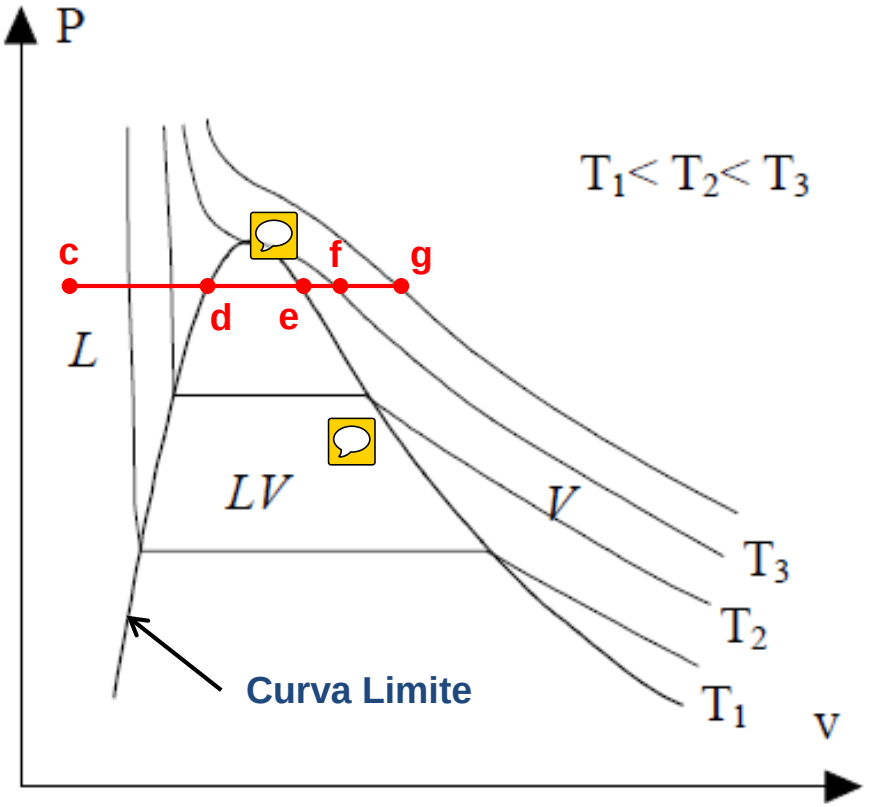


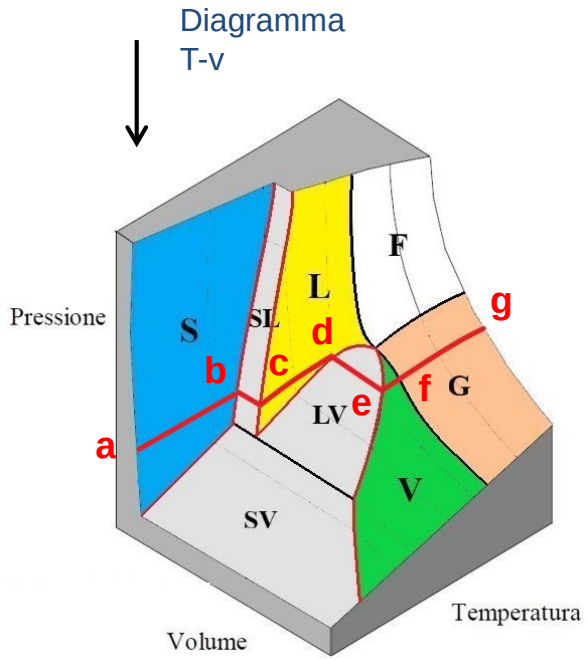
Diagramma P-v



Lo stato eterogeneo

Diagramma di stato P-v-T: rappresentazione su piani T-v, P-v, T-s, P-h, h-s

Trasformazione **ISOBARA:** fornisco (o sottraggo) calore al sistema a pressione costante



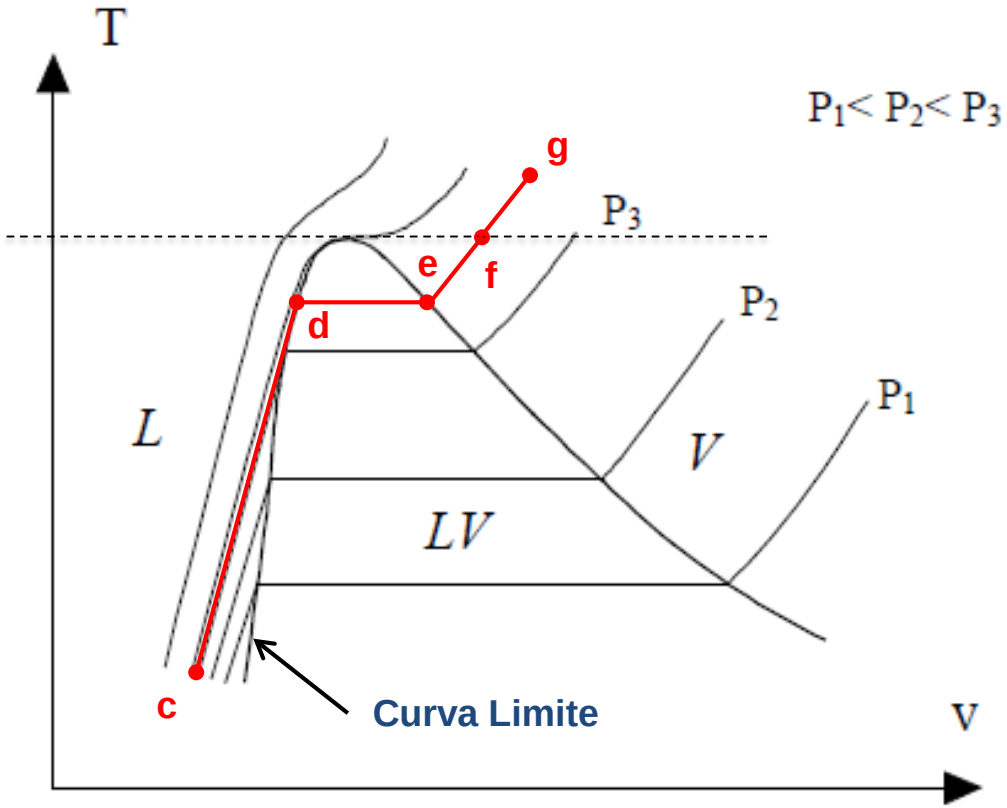


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Diagramma di stato P-v-T: rappresentazione su piani T-v, P-v, T-s, P-h, h-s

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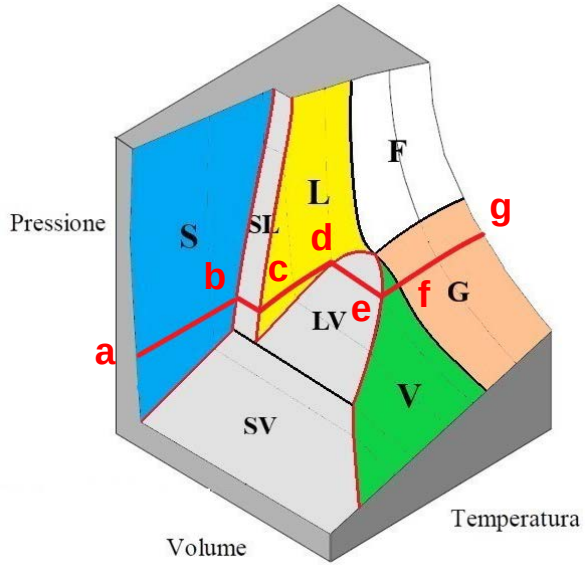

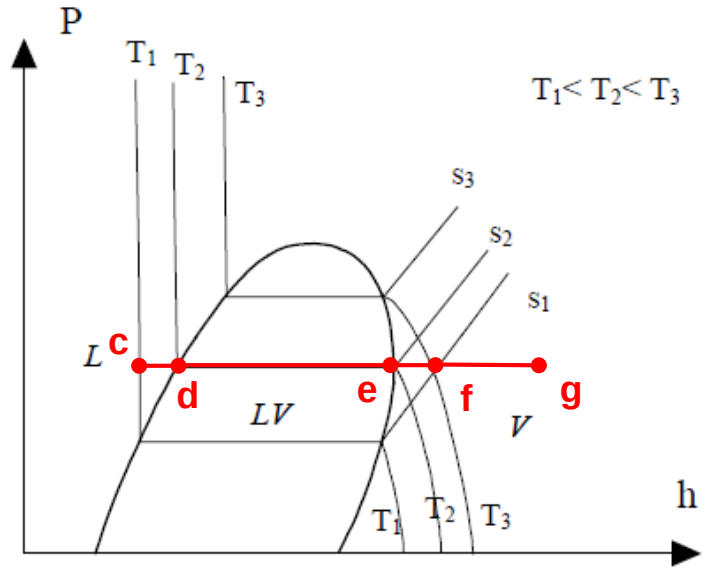

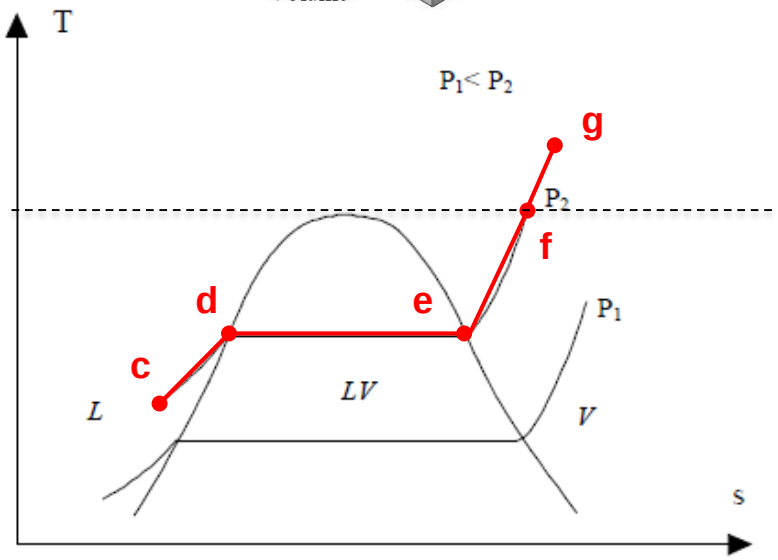

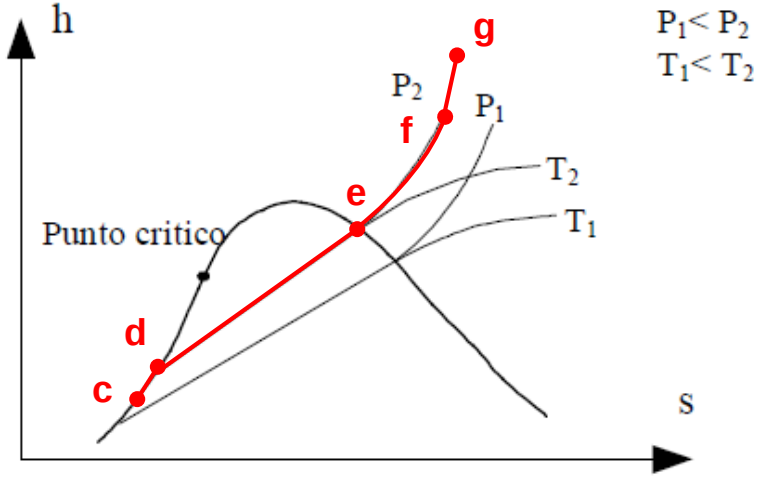

Lo stato eterogeneo

Utilizzo delle tabelle

Tabelle di saturazione (in pressione)

Tabelle di saturazione dell'acqua

Tratto da VDI Atlas/ed. Verein Deutscher Ingenieure. - Düsseldorf: VDI-Verl., 1993

		liquido saturo		vapore saturo	liquido saturo		vapore saturo	liquido saturo		vapore saturo
P (bar)	T (°C)	v_L (m^3/kg)	v_v-v_L (m^3/kg)	v_v (m^3/kg)	h_L (kJ/kg)	h_v–h_L (kJ/kg)	h_v (kJ/kg)	s_L (kJ/kgK)	s_v–s_L (kJ/kgK)	s_v (kJ/kgK)
0.00611	0.01	0.0010002	206.1619	206.1629	0.0	2501.6	2501.6	0.0000	9.1575	9.1575
0.01	6.98	0.0010001	129.2097	129.2107	29.3	2485.0	2514.4	0.1060	8.8706	8.9767
0.02	17.51	0.0010012	67.0106	67.0116	73.5	2460.2	2533.6	0.2606	8.4640	8.7246
0.03	24.10	0.0010027	45.6690	45.6700	101.0	2444.6	2545.6	0.3543	8.2242	8.5785
0.04	28.98	0.0010040	34.8023	34.8033	121.4	2433.1	2554.5	0.4225	8.0530	8.4755
0.05	32.90	0.0010052	28.1935	28.1945	137.8	2423.8	2561.6	0.4763	7.9197	8.3960
0.06	36.18	0.0010064	23.7396	23.7406	151.5	2416.0	2567.5	0.5209	7.8103	8.3312
0.07	39.03	0.0010074	20.5294	20.5304	163.4	2409.2	2572.6	0.5591	7.7176	8.2767
0.08	41.54	0.0010084	18.1028	18.1038	173.9	2403.2	2577.1	0.5926	7.6370	8.2295
0.09	43.79	0.0010094	16.2024	16.2034	183.3	2397.9	2581.1	0.6224	7.5657	8.1881
0.10	45.83	0.0010102	14.6727	14.6737	191.8	2392.9	2584.8	0.6493	7.5018	8.1511
0.15	54.00	0.0010140	10.0211	10.0221	226.0	2373.2	2599.2	0.7549	7.2544	8.0093
0.20	60.09	0.0010172	7.6482	7.6492	251.5	2358.4	2609.9	0.8321	7.0773	7.9094
0.25	64.99	0.0010199	6.2030	6.2040	272.0	2346.4	2618.3	0.8933	6.9390	7.8323
0.30	69.13	0.0010223	5.2280	5.2290	289.3	2336.1	2625.4	0.9441	6.8254	7.7695
0.35	72.71	0.0010245	4.5245	4.5255	304.3	2327.2	2631.5	0.9878	6.7288	7.7166
0.40	75.89	0.0010265	3.9922	3.9932	317.7	2319.2	2636.9	1.0261	6.6448	7.6709
0.45	78.74	0.0010284	3.5751	3.5761	329.6	2312.0	2641.7	1.0603	6.5703	7.6306
0.50	81.35	0.0010301	3.2391	3.2401	340.6	2305.4	2646.0	1.0912	6.5035	7.5947
0.60	85.95	0.0010333	2.7307	2.7317	359.9	2293.6	2653.6	1.1455	6.3872	7.5327
0.70	89.96	0.0010361	2.3637	2.3647	376.8	2283.3	2660.1	1.1921	6.2883	7.4804
0.80	93.51	0.0010387	2.0859	2.0869	391.7	2274.0	2665.8	1.2330	6.2022	7.4352
0.90	96.71	0.0010412	1.8681	1.8691	405.2	2265.6	2670.9	1.2696	6.1258	7.3954
1.00	99.63	0.0010434	1.6927	1.6937	417.5	2257.9	2675.4	1.3027	6.0571	7.3598
1.01325	100.00	0.0010437	1.6720	1.6730	419.1	2256.9	2676.0	1.3069	6.0485	7.3554
1.20	104.81	0.0010476	1.4271	1.4281	439.4	2244.1	2683.4	1.3609	5.9375	7.2984
1.40	109.32	0.0010513	1.2352	1.2363	458.4	2231.9	2690.3	1.4109	5.8356	7.2465
1.60	113.32	0.0010547	1.0900	1.0911	475.4	2220.9	2696.2	1.4550	5.7467	7.2017
1.80	116.93	0.0010579	0.97612	0.9772	490.7	2210.8	2701.5	1.4944	5.6677	7.1622
2.00	120.23	0.0010608	0.88434	0.8854	504.7	2201.6	2706.3	1.5301	5.5967	7.1268
2.50	127.43	0.0010676	0.71733	0.7184	535.4	2181.0	2716.4	1.6072	5.4448	7.0520
3.00	133.54	0.0010735	0.60446	0.6055	561.4	2163.2	2724.7	1.6717	5.3192	6.9909

Lo stato eterogeneo

Utilizzo delle tabelle

Tabelle di saturazione (in temperatura)

Tabelle di saturazione dell'acqua

Tratto da VDI Atlas/ed. Verein Deutscher Ingenieure. - Düsseldorf: VDI-Verl., 1993

		liquido saturo		vapore saturo	liquido saturo		vapore saturo	liquido saturo		vapore saturo
T (°C)	P (bar)	v_L (m^3/kg)	v_V-v_L (m^3/kg)	v_V (m^3/kg)	h_L (kJ/kg)	h_V–h_L (kJ/kg)	h_V (kJ/kg)	s_L (kJ/kgK)	s_V–s_L (kJ/kgK)	s_V (kJ/kgK)
0.01	0.006112	0.001000	206.162	206.163	0.0	2501.6	2501.6	0.0000	9.1575	9.1575
2	0.007055	0.001000	179.922	179.923	8.4	2496.8	2505.2	0.0306	9.0741	9.1047
4	0.008129	0.001000	157.271	157.272	16.8	2492.1	2508.9	0.0611	8.9915	9.0526
6	0.009345	0.001000	137.779	137.78	25.2	2487.4	2512.6	0.0913	8.9102	9.0015
8	0.01072	0.001000	120.965	120.966	33.6	2482.6	2516.2	0.1213	8.8300	8.9513
10	0.01227	0.001000	106.429	106.43	42.0	2477.9	2519.9	0.1510	8.7510	8.9020
15	0.017139	0.001001	77.977	77.978	62.9	2466.1	2529.1	0.2243	8.5582	8.7826
20	0.023366	0.001002	57.837	57.838	83.9	2454.3	2538.2	0.2963	8.3721	8.6684
25	0.03166	0.001003	43.401	43.402	104.8	2442.5	2547.3	0.3670	8.1922	8.5592
30	0.042415	0.001004	32.928	32.929	125.7	2430.7	2556.4	0.4365	8.0181	8.4546
35	0.056216	0.001006	25.244	25.245	146.6	2418.8	2565.4	0.5049	7.8495	8.3543
40	0.07375	0.001008	19.545	19.546	167.5	2406.9	2574.4	0.5721	7.6861	8.2583
45	0.09582	0.001010	15.275	15.276	188.4	2394.9	2583.3	0.6383	7.5277	8.1661
50	0.12335	0.001012	12.045	12.046	209.3	2382.9	2592.2	0.7035	7.3741	8.0776
55	0.15741	0.001015	9.5779	9.5789	230.2	2370.8	2601.0	0.7677	7.2248	7.9925
60	0.1992	0.001017	7.6775	7.6785	251.1	2358.6	2609.7	0.8310	7.0798	7.9108
65	0.25009	0.001020	6.2013	6.2023	272.0	2346.3	2618.4	0.8933	6.9388	7.8321
70	0.31162	0.001023	5.0453	5.0463	293.0	2334.0	2626.9	0.9548	6.8017	7.7565
75	0.38549	0.001026	4.1331	4.1341	313.9	2321.5	2635.4	1.0154	6.6681	7.6835
80	0.4736	0.001029	3.4081	3.4091	334.9	2308.8	2643.8	1.0753	6.5380	7.6133
85	0.57803	0.001033	2.8278	2.8288	355.9	2296.1	2652.0	1.1343	6.4111	7.5454
90	0.70109	0.001036	2.3603	2.3613	376.9	2283.2	2660.1	1.1925	6.2873	7.4798
95	0.84526	0.001040	1.9812	1.9822	398.0	2270.2	2668.1	1.2501	6.1665	7.4166
100	1.01325	0.001044	1.672	1.673	419.1	2256.9	2676.0	1.3069	6.0485	7.3554
105	1.208	0.001048	1.4183	1.4193	440.2	2243.6	2683.7	1.3630	5.9331	7.2962
110	1.4327	0.001052	1.2089	1.2099	461.3	2230.0	2691.3	1.4185	5.8203	7.2388
115	1.6906	0.001056	1.0353	1.0363	482.5	2216.2	2698.7	1.4733	5.7099	7.1832
120	1.9854	0.001061	0.89046	0.89152	503.7	2202.2	2706.0	1.5276	5.6017	7.1293
125	2.321	0.001065	0.76917	0.77023	525.0	2188.0	2713.0	1.5813	5.4957	7.0769
130	2.7013	0.001070	0.66707	0.66814	546.3	2173.6	2719.9	1.6344	5.3917	7.0261

Lo stato eterogeneo

Utilizzo delle tabelle

Tabelle del vapore surriscaldato

Tabelle vapore surriscaldato dell'acqua

Tratto da VDI Atlas/ed. Verein Deutscher Ingenieure. - Düsseldorf: VDI-Verl., 1993

P (bar)			Temperatura											
Ts (°C)			50	100	150	200	250	300	350	400	500	600	700	800
	v	m3/kg	74.524	86.08	97.628	109.171	120.711	132.251	143.79	155.329	178.405	201.482	224.558	247.634
0.02	h	kJ/kg	2594.4	2688.5	2783.7	2880	2977.7	3076.8	3177.7	3279.7	3489.2	3705.6	3928.8	4158.7
17.5	s	kJ/kgK	8.9226	9.1934	9.4327	9.6479	9.8441	10.0251	10.1934	10.3512	10.6413	10.9044	11.1464	11.3712
	v	m3/kg	37.24	43.027	48.806	54.58	60.351	66.122	71.892	77.662	89.201	100.74	112.278	123.816
0.04	h	kJ/kg	2593.9	2688.3	2783.5	2879.9	2977.6	3076.8	3177.4	3279.7	3489.2	3705.6	3928.8	4158.7
29	s	kJ/kgK	8.6016	8.873	9.1125	9.3279	9.5241	9.7051	9.8735	10.0313	10.3214	10.5845	10.8265	11.0513
	v	m3/kg	24.812	28.676	32.532	37.383	40.232	44.079	47.927	51.773	59.467	67.159	74.852	82.544
0.06	h	kJ/kg	2593.5	2688	2783.4	2879.8	2977.6	3076.7	3177.4	3279.6	3489.2	3705.6	3928.8	4158.7
36.2	s	kJ/kgK	8.4135	8.6854	8.9251	9.1406	9.3369	9.5179	9.6863	9.8441	10.1342	10.3973	10.6394	10.8642
	v	m3/kg	18.598	21.501	24.395	27.284	30.172	33.058	35.944	38.829	44.599	50.369	56.138	61.908
0.08	h	kJ/kg	2593.1	2687.8	2783.2	2879.7	2977.5	3076.7	3177.3	3279.6	3489.1	3705.5	3928.8	4158.7
41.5	s	kJ/kgK	8.2797	8.5521	8.7921	9.0077	9.2041	9.3851	9.5535	9.7113	10.0014	10.2646	10.5066	10.7314
	v	m3/kg	14.869	17.195	19.512	21.825	24.136	26.445	28.754	31.062	35.679	40.295	44.91	49.526
0.1	h	kJ/kg	2592.7	2687.5	2783.1	2879.6	2977.4	3076.6	3177.3	3279.6	3489.1	3705.5	3928.8	4158.7
45.8	s	kJ/kgK	8.1757	8.4486	8.6888	8.9045	9.101	9.282	9.4504	9.6083	9.8984	10.1616	10.4036	10.6284
	v	m3/kg		3.4181	3.8893	4.356	4.8205	5.2839	5.7467	6.2091	7.1335	8.0574	8.981	9.9044
0.5	h	kJ/kg		2682.6	2780.1	2877.7	2976.1	3075.7	3176.6	3279	3488.7	3705.2	3928.6	4158.5
81.3	s	kJ/kgK		7.6953	7.9406	8.1587	8.3564	8.538	8.7068	8.8649	9.1552	9.4185	9.6606	9.8855
	v	m3/kg		1.6955	1.9363	2.1723	2.4061	2.6387	2.8708	3.1025	3.5653	4.0277	4.4898	4.9517
1	h	kJ/kg		2676.2	2776.1	2875.4	2974.5	3074.5	3175.6	3278.2	3488.1	3704.8	3928.2	4158.3
99.6	s	kJ/kgK		7.3618	7.6137	7.8349	8.0342	8.2166	8.3858	8.5442	8.8348	9.0982	9.3405	9.5654
	v	m3/kg			0.95954	1.0804	1.1989	1.3162	1.4328	1.5492	1.7812	2.0129	2.2442	2.4754
2	h	kJ/kg			2768.5	2870.5	2971.2	3072.1	3173.8	3276.7	3487	3704	3927.6	4157.8
120.2	s	kJ/kgK			7.2794	7.5072	7.7096	7.8937	8.0638	8.2226	8.5139	8.7776	9.0201	9.2452
	v	m3/kg			0.63374	0.71635	0.79644	0.87529	0.95352	1.0314	1.1865	1.3412	1.4957	1.6499
3	h	kJ/kg			2760.4	2865.5	2967.9	3069.7	3171.9	3275.2	3486	3703.2	3927	4157.3
133.5	s	kJ/kgK			7.0771	7.3119	7.5176	7.7034	7.8744	8.0338	8.3257	8.5898	8.8325	9.0577
	v	m3/kg			0.47066	0.53426	0.59519	0.65485	0.71385	0.7725	0.88919	1.0054	1.1214	1.2372
4	h	kJ/kg			2752	2860.4	2964.5	3067.2	3170	3273.6	3484.9	3702.3	3926.4	4156.9
143.6	s	kJ/kgK			6.9285	7.1708	7.38	7.5675	7.7395	7.8994	8.1919	8.4563	8.6992	8.9246
	v	m3/kg				0.42496	0.47443	0.52258	0.57005	0.61716	0.71078	0.80395	0.89685	0.98956
5	h	kJ/kg				2855.1	2961.1	3064.8	3168.1	3272.1	3483.8	3701.5	3925.8	4156.4
151.8	s	kJ/kgK				7.0592	7.2721	7.4614	7.6343	7.7948	8.0879	8.3626	8.5957	8.8213