

Dispensa del corso di “SISTEMI ENERGETICI”

Argomento: Sistemi Energetici (parte 1)

Prof. Pier Ruggero Spina
Dipartimento di Ingegneria



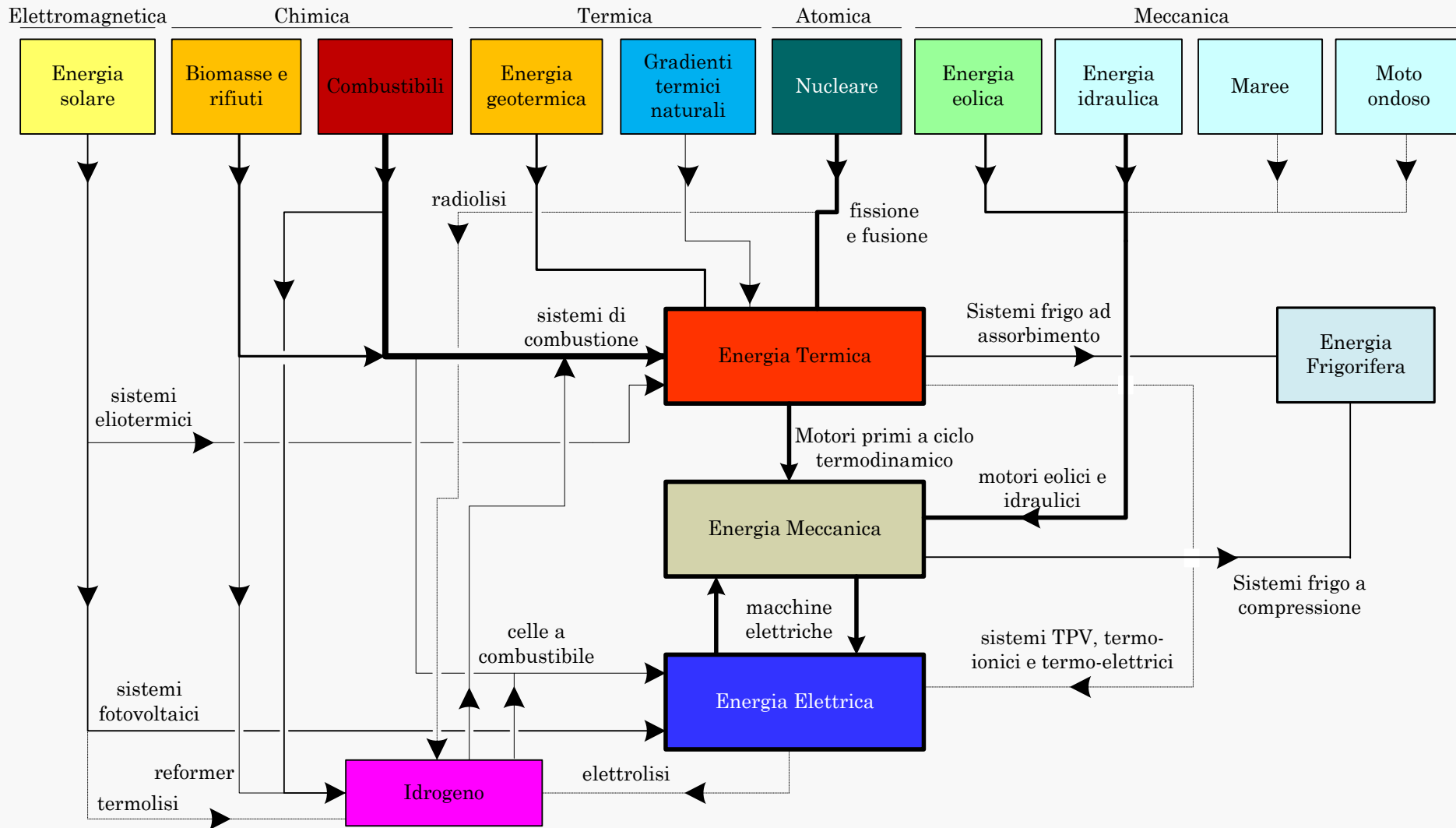
università di ferrara
DA SEICENTO ANNI GUARDIAMO AVANTI.

Sommario

- Forme di energia e loro conversione
- Introduzione: diagrammi termodinamici e ciclo di Carnot
- Sistemi energetici a vapore
- Turbogas
- Impianti a ciclo combinato gas/vapore
- Motori alternativi a combustione interna
- Sistemi energetici cogenerativi



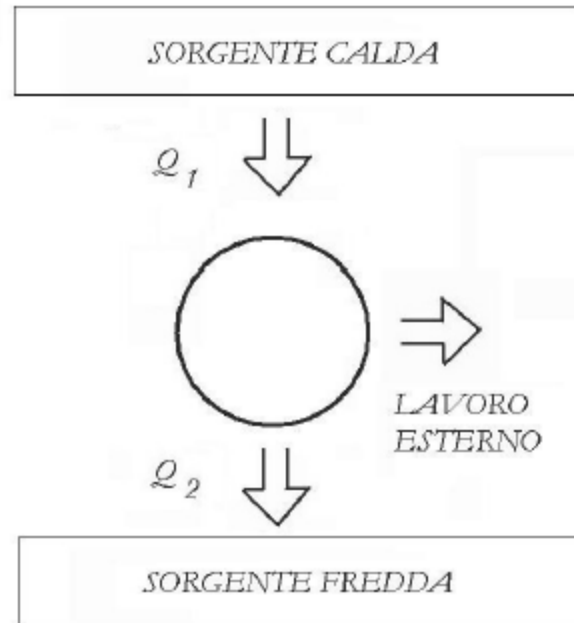
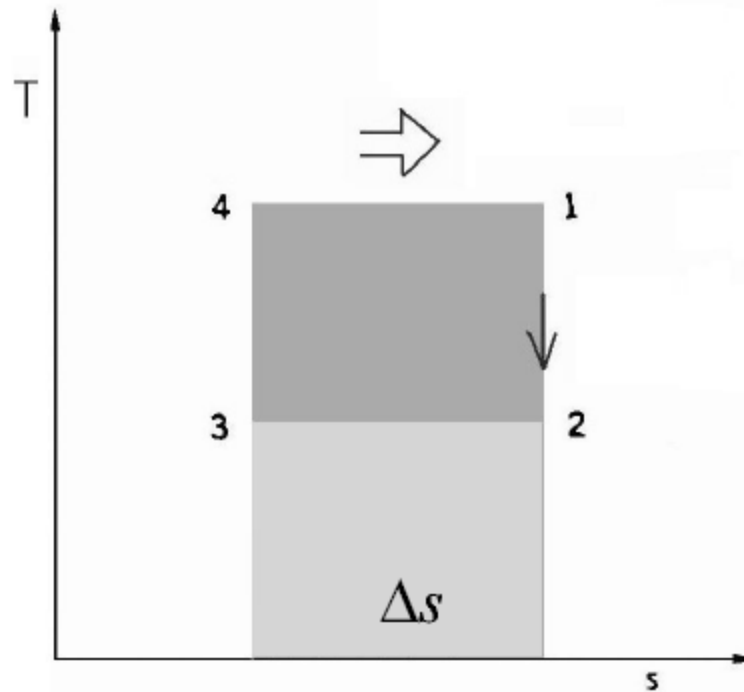
Forme di energia e loro conversione



Introduzione



Ciclo di Carnot (motore)



$$\eta_{\text{carnot}} = \frac{L}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2 \Delta s}{T_1 \Delta s} = 1 - \frac{T_2}{T_1}$$

Ciclo di Carnot diretto (*motore*)



Diagramma termodinamico $\{T,s\}$ del vapore d'acqua

Diagramma entropico:

temperatura T - °C

entropia s - kJ/(kg K)

Punto critico (H₂O):

temperatura: $T_{\text{crit.}}$ 374 °C

pressione: $p_{\text{crit.}}$ 22.1 MPa

volume massico:

$v_{\text{crit.}}$ 0.0032 m³/kg

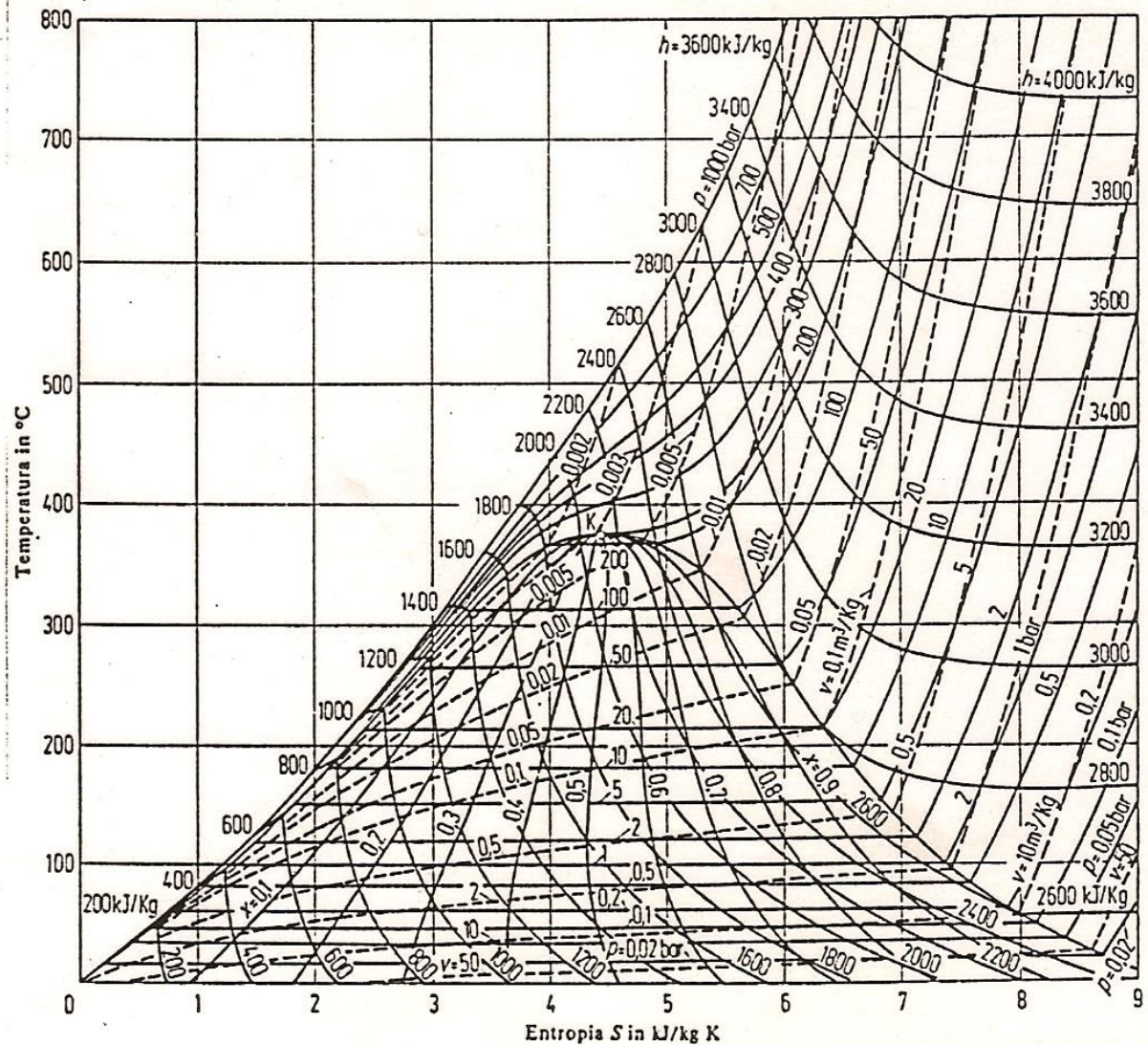
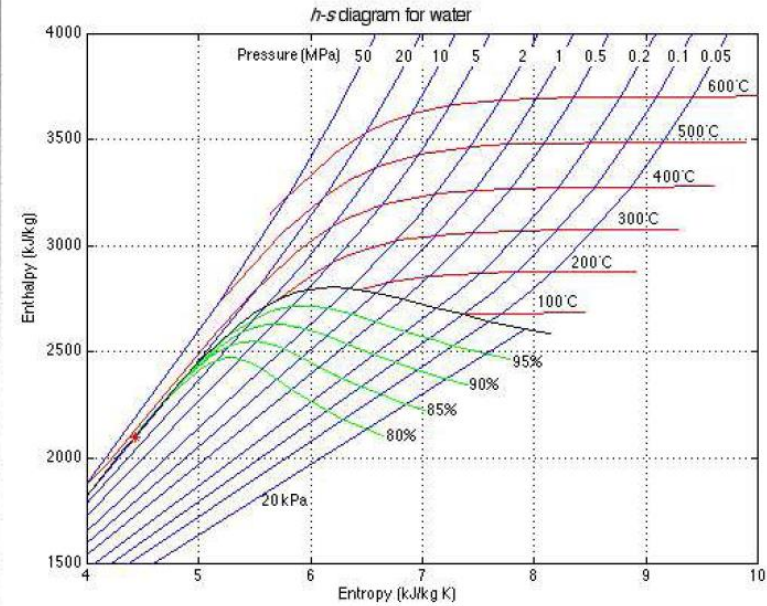
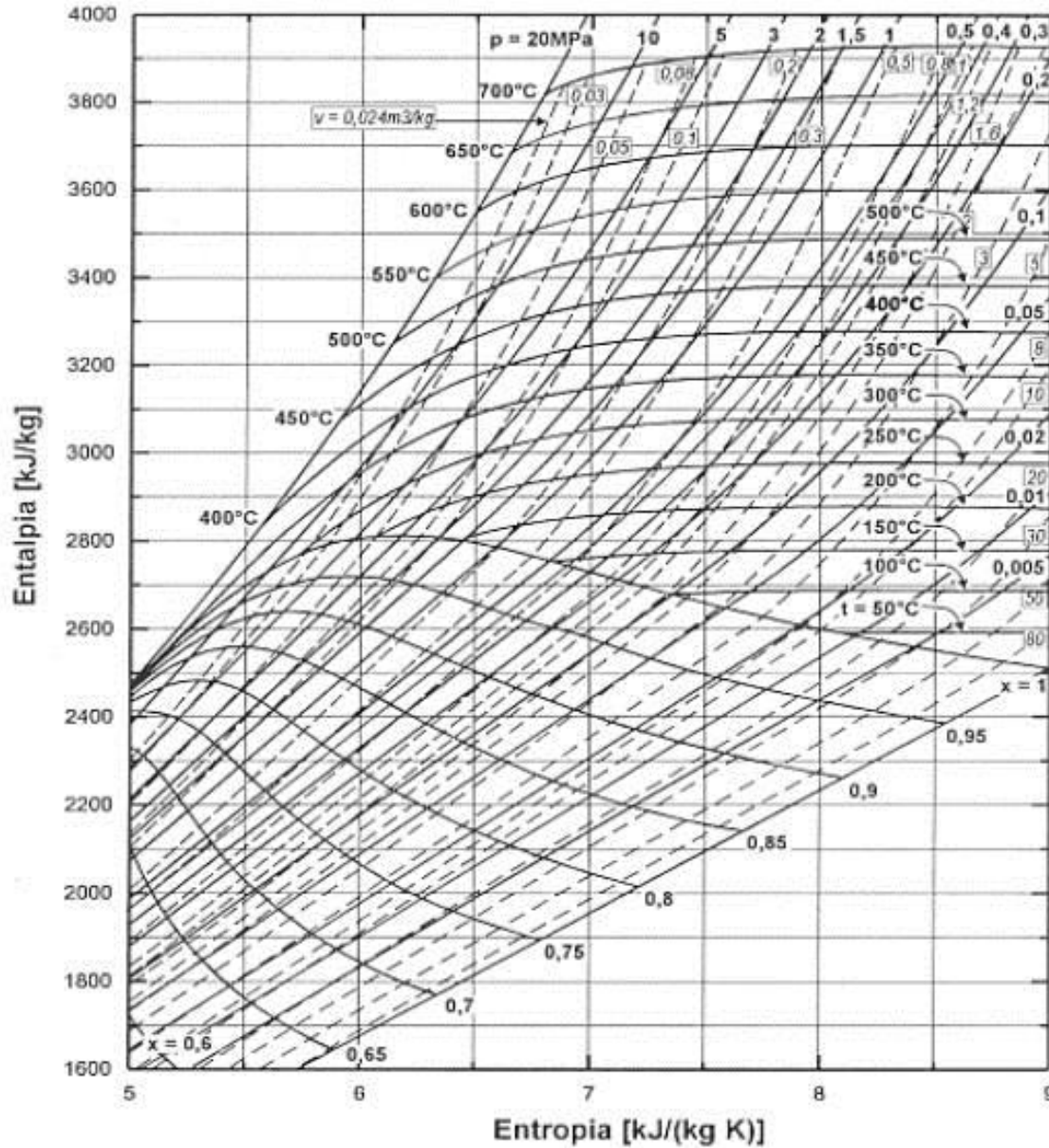


Diagramma T, s per il vapore d'acqua (Editori Springer e R. Oldenbourg)



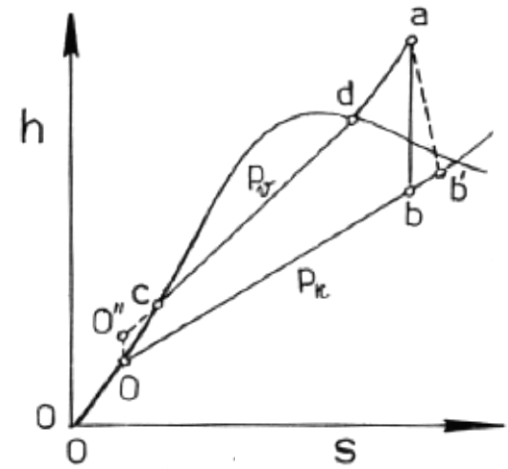
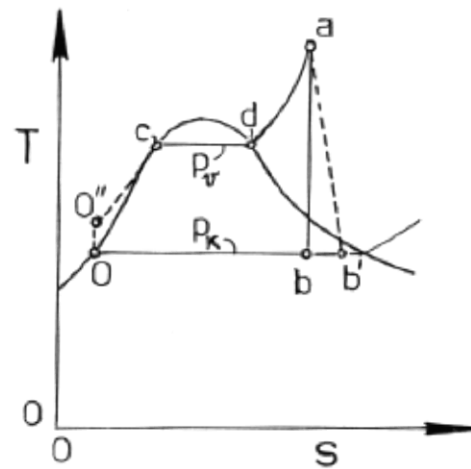
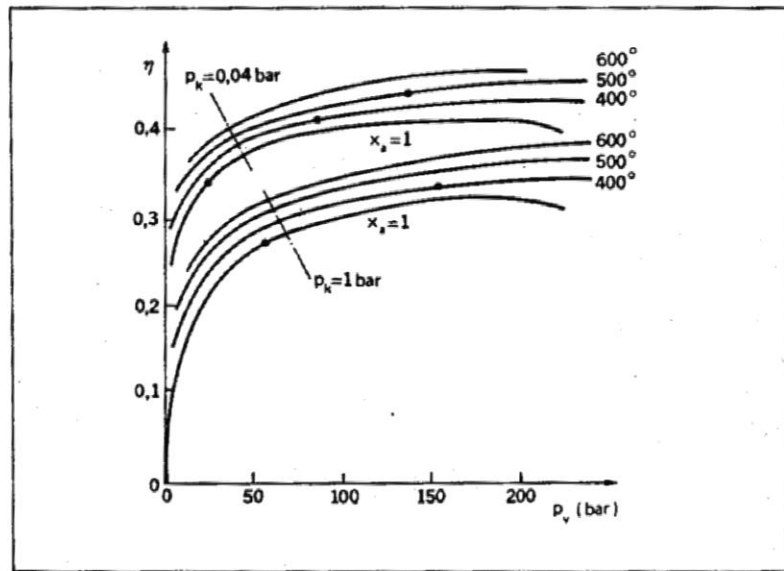
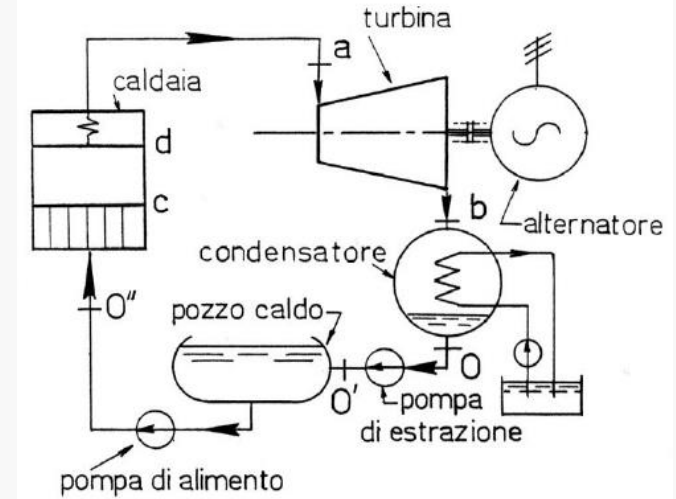
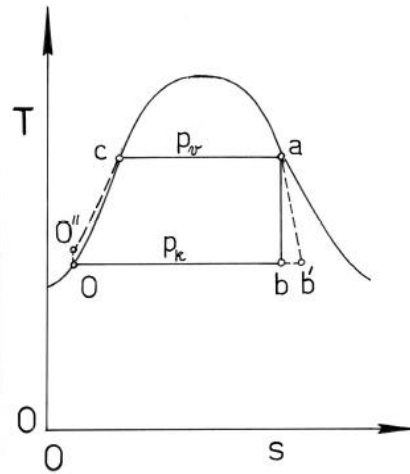
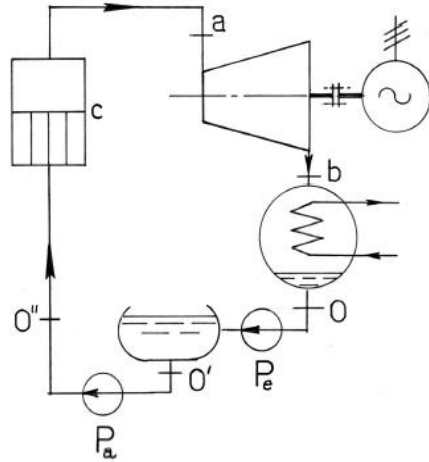
Diagramma termodinamico {h,s} del vapore d'acqua



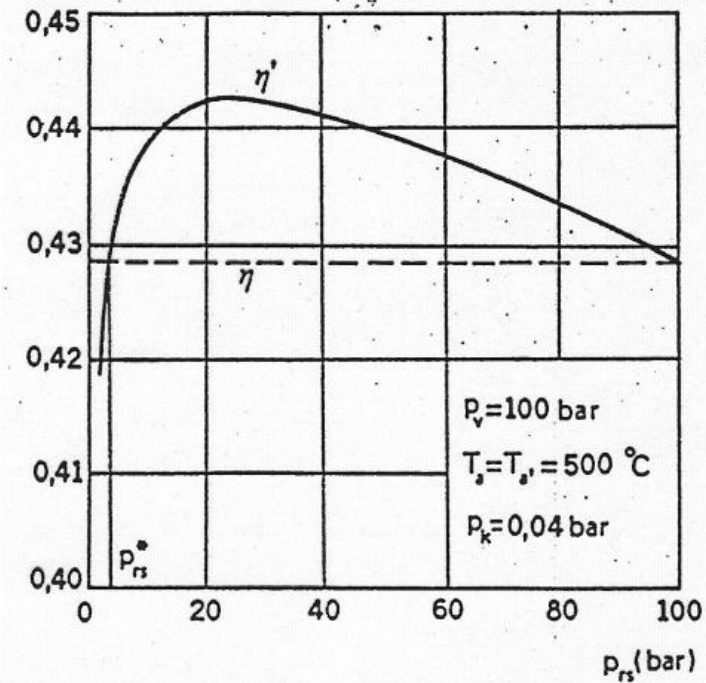
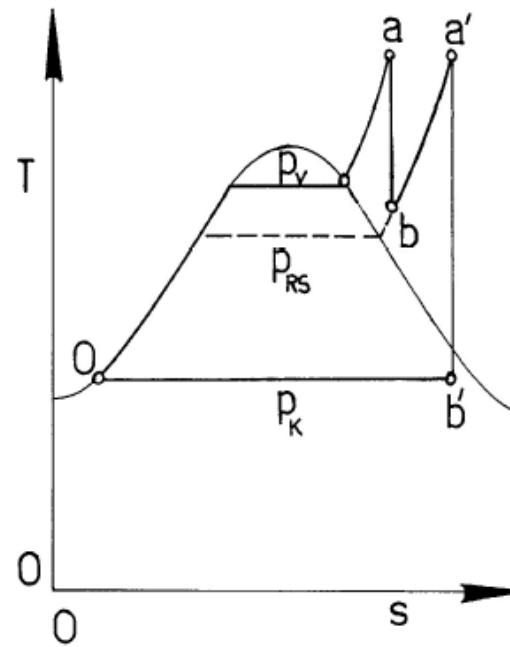
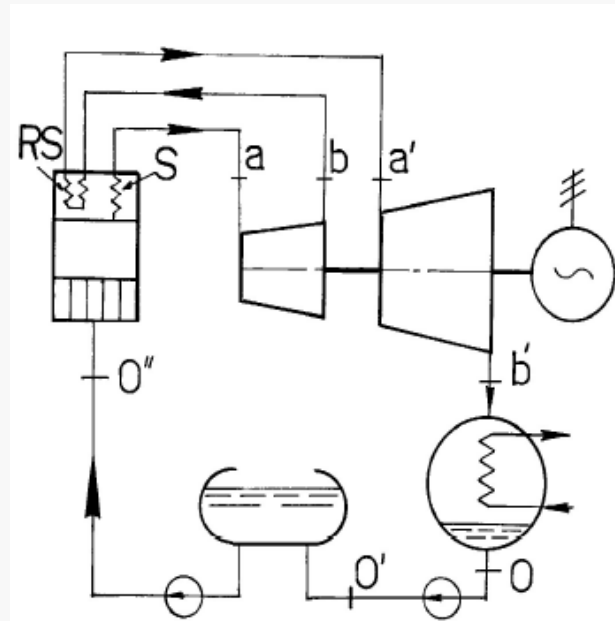
Sistemi energetici a vapore d'acqua



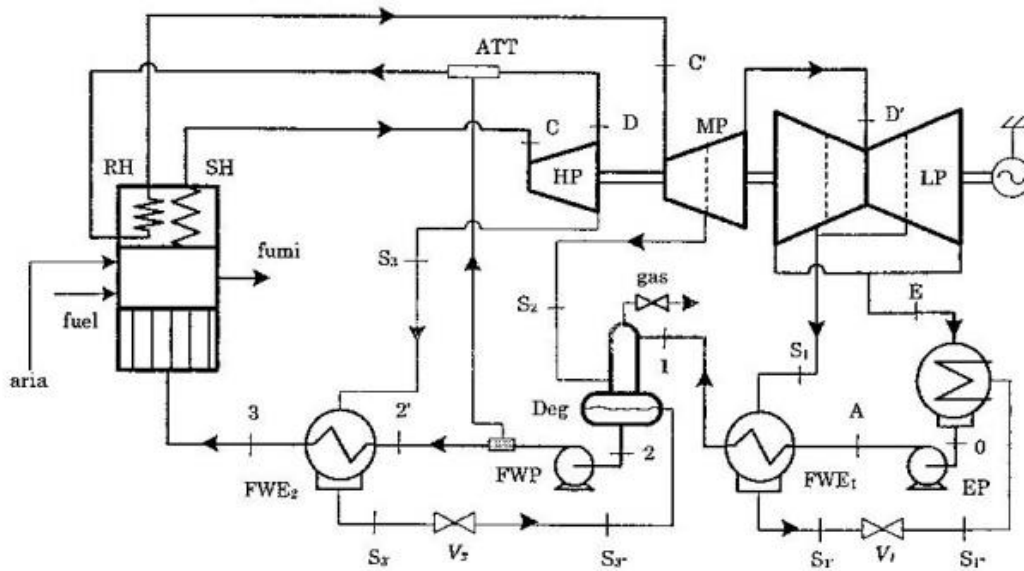
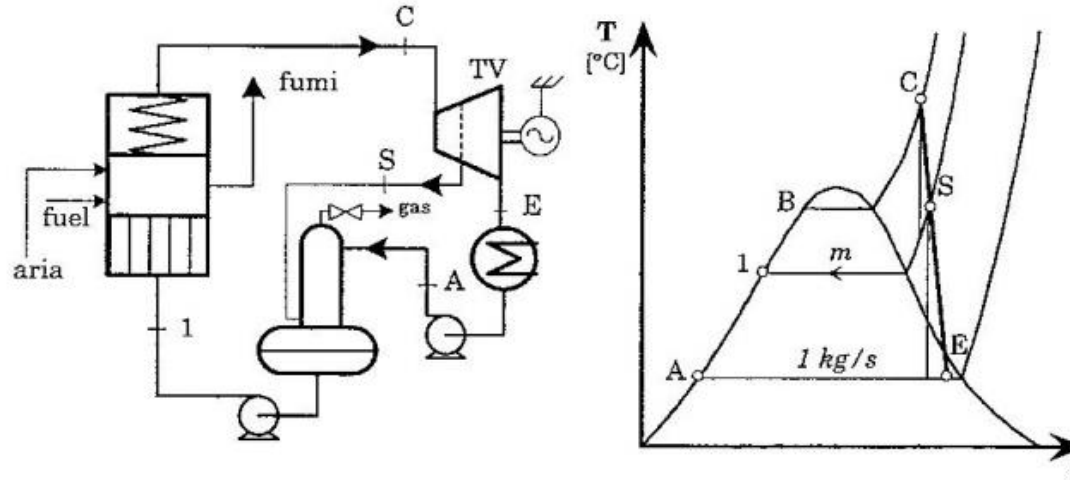
Schema di cicli a vapore



Schema di cicli a vapore



Ciclo a vapore con spillamenti



Evoluzione degli impianti a vapore

- Subcritici: p_v 167 bar, T_s 540 °C
- Supercritici: p_v 250 bar, T_s 540 °C
- Ultrasupercritici: p_v 300 bar, T_s 620 °C
- Tendenza: p_v 350 bar, T_s 700 °C

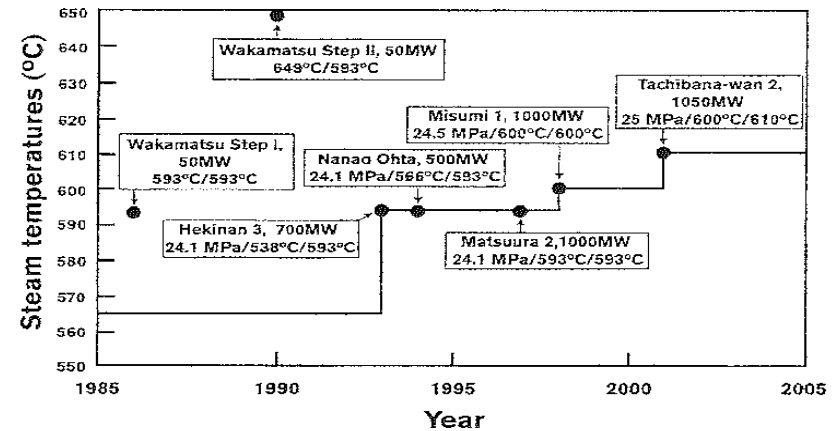
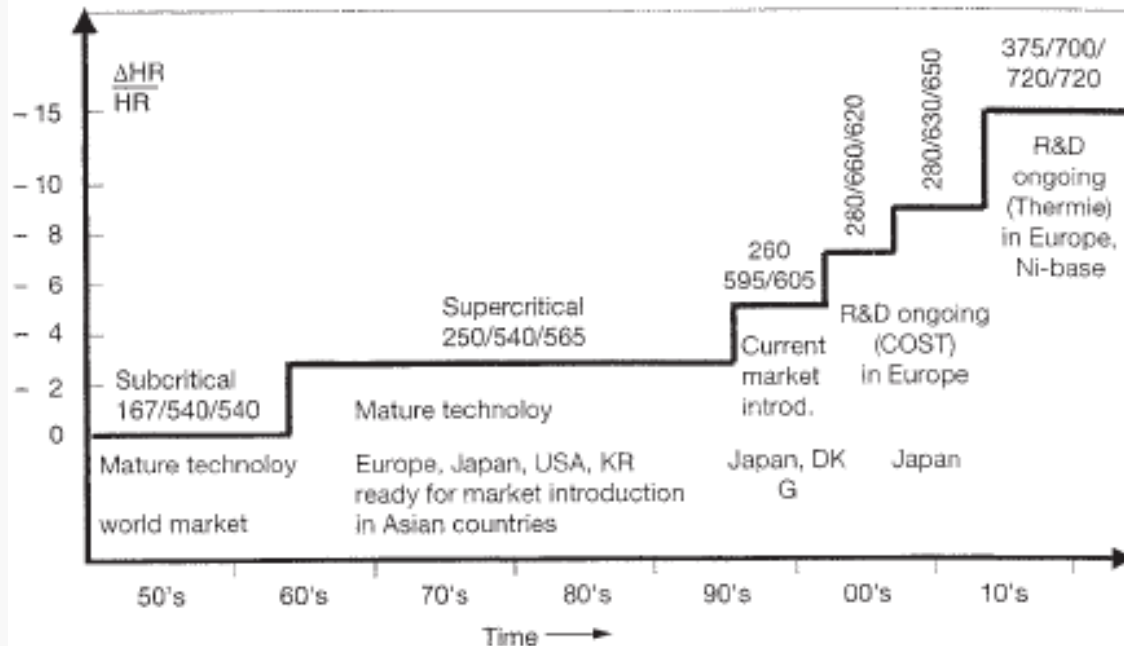
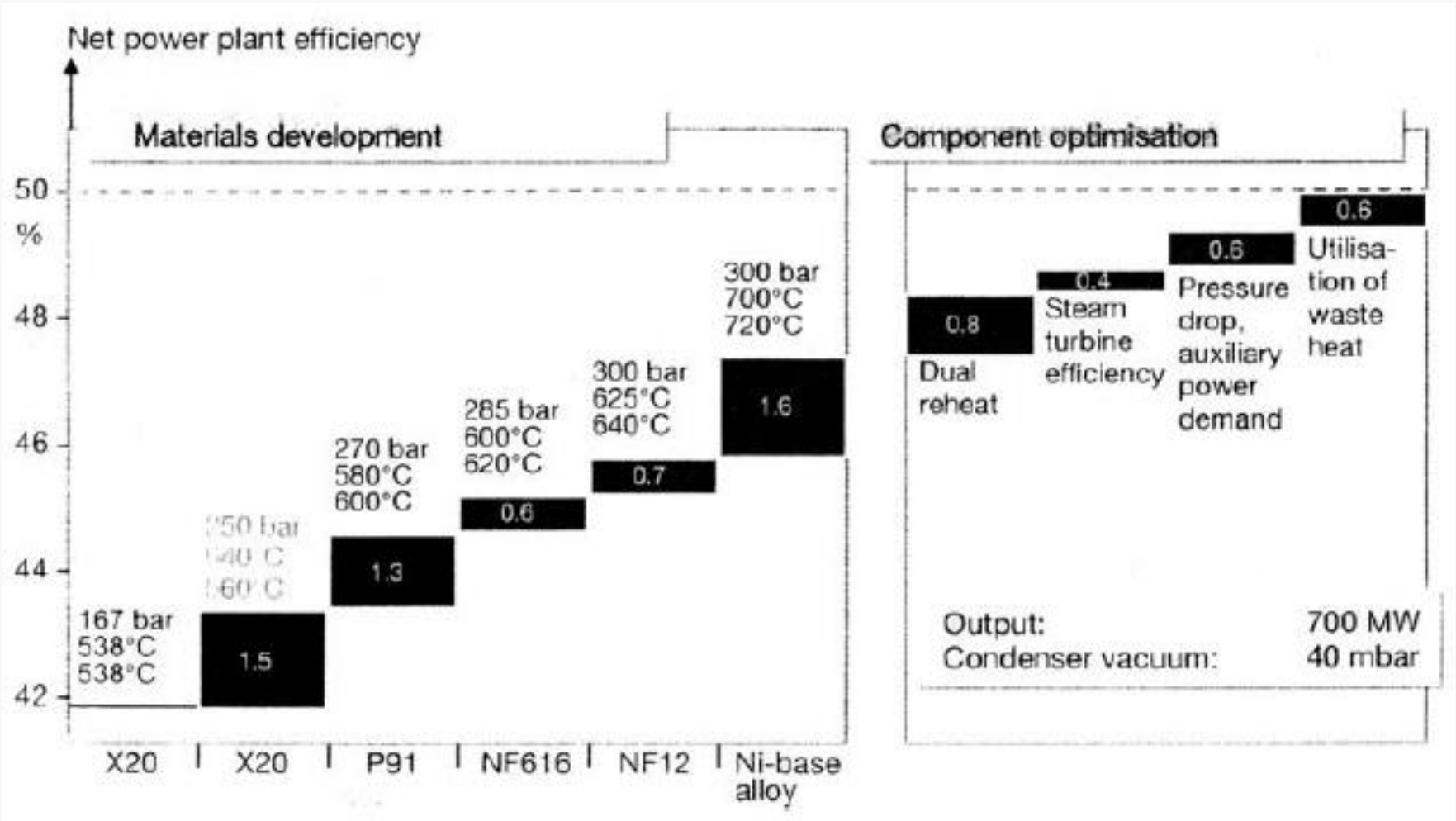


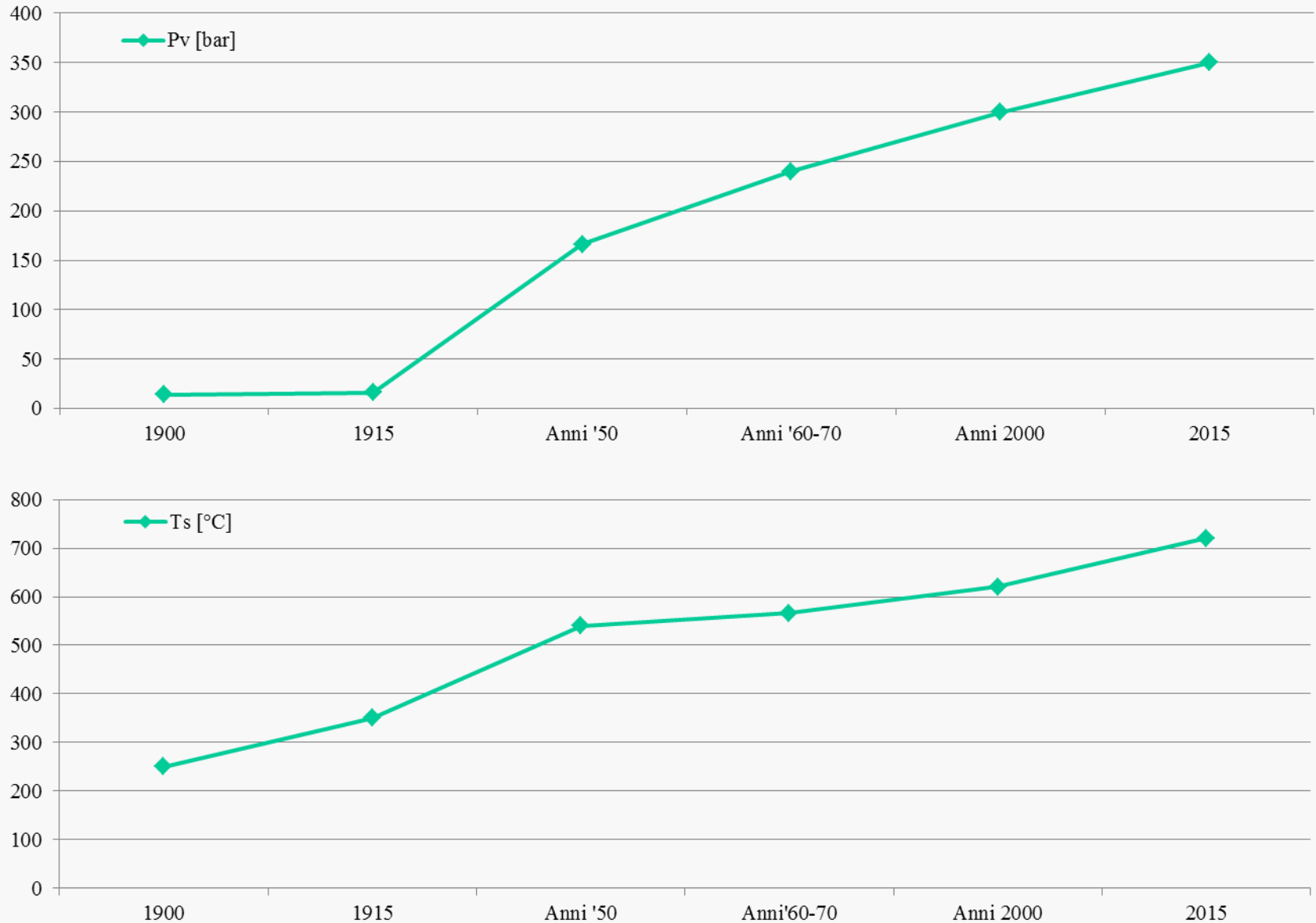
Figure 2-13. Evolution of steam conditions for MHI steam turbines.
Source: By courtesy of Mitsubishi Heavy Industries



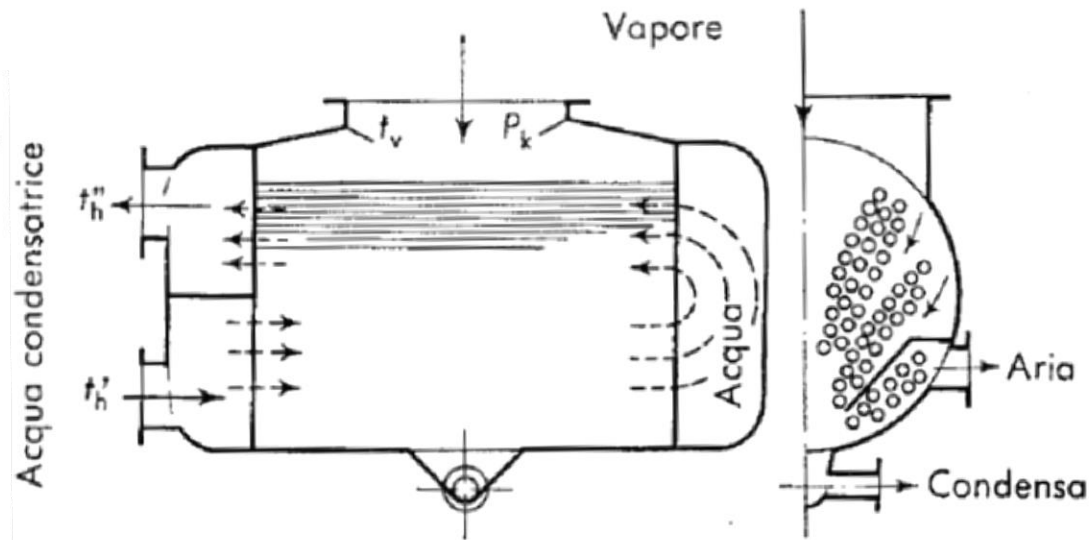
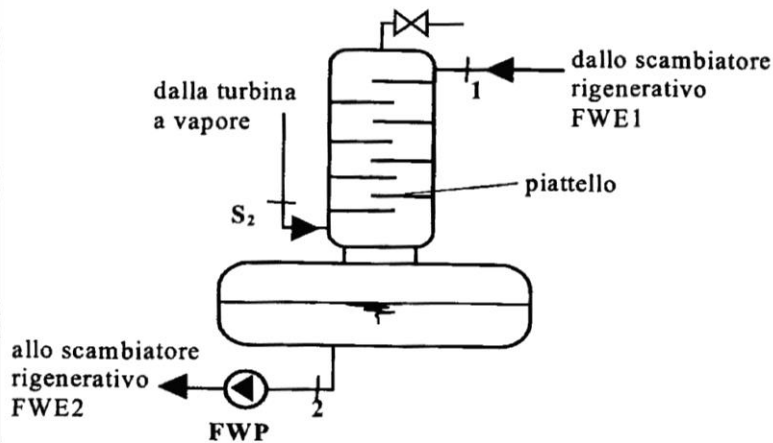
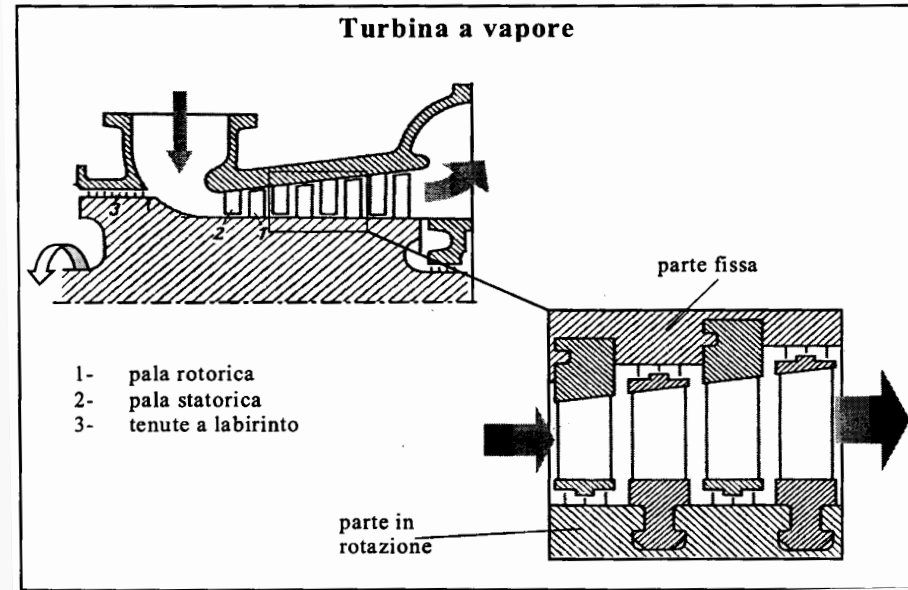
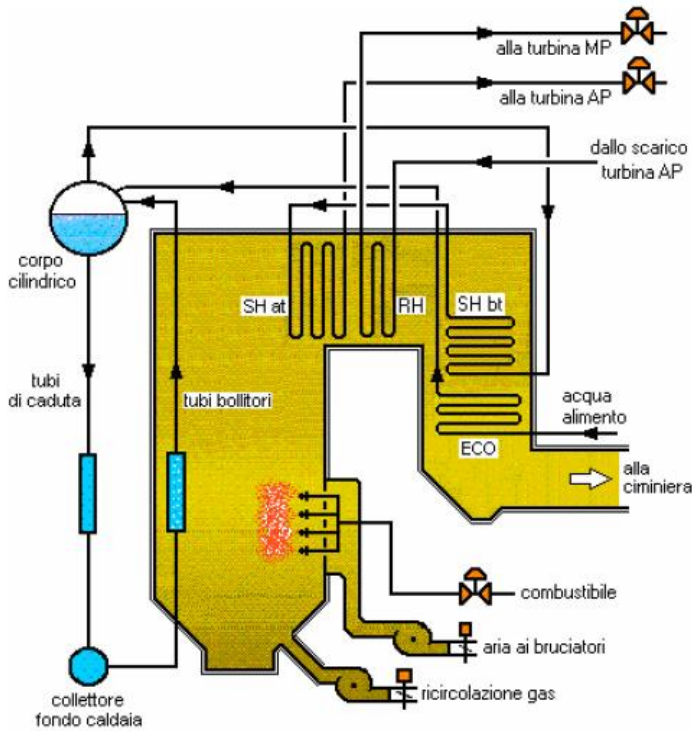
Evoluzione degli impianti a vapore



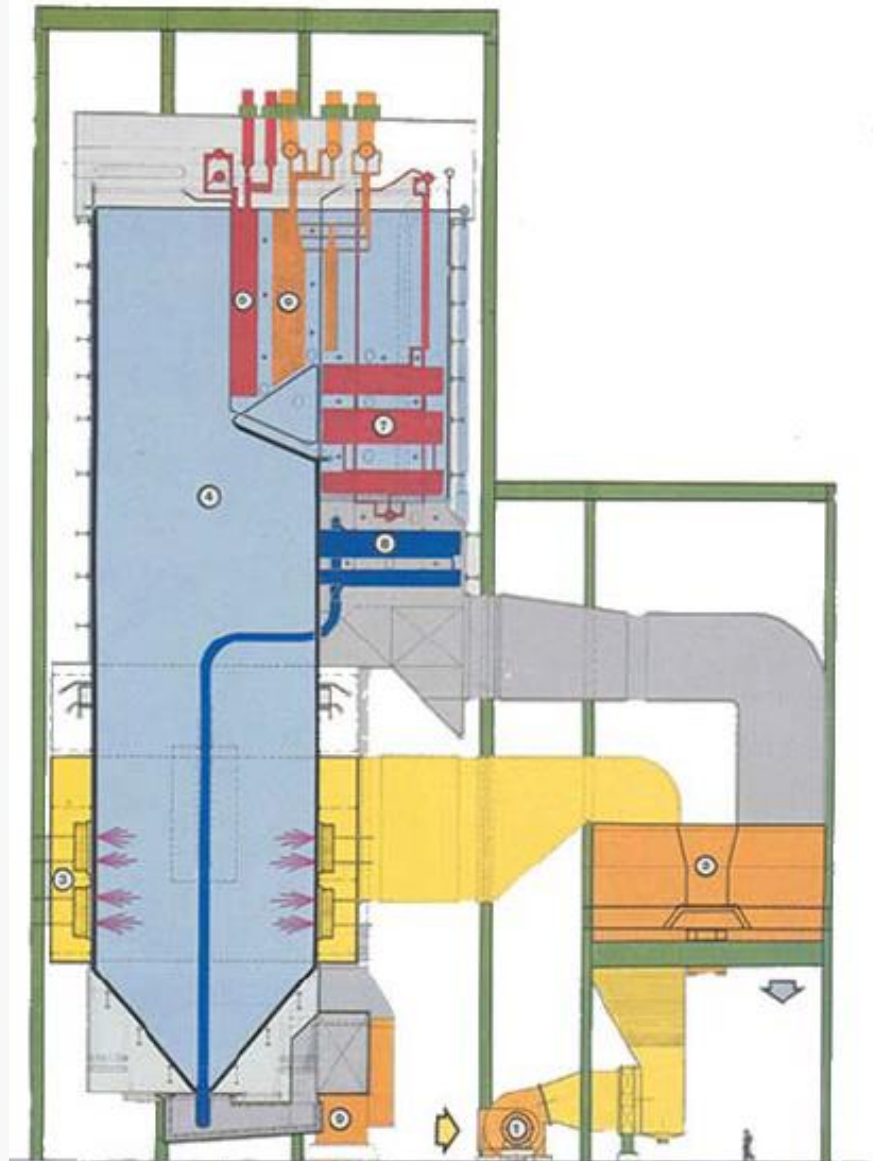
Evoluzione degli impianti a vapore



Componenti degli impianti a vapore



Componenti degli impianti a vapore

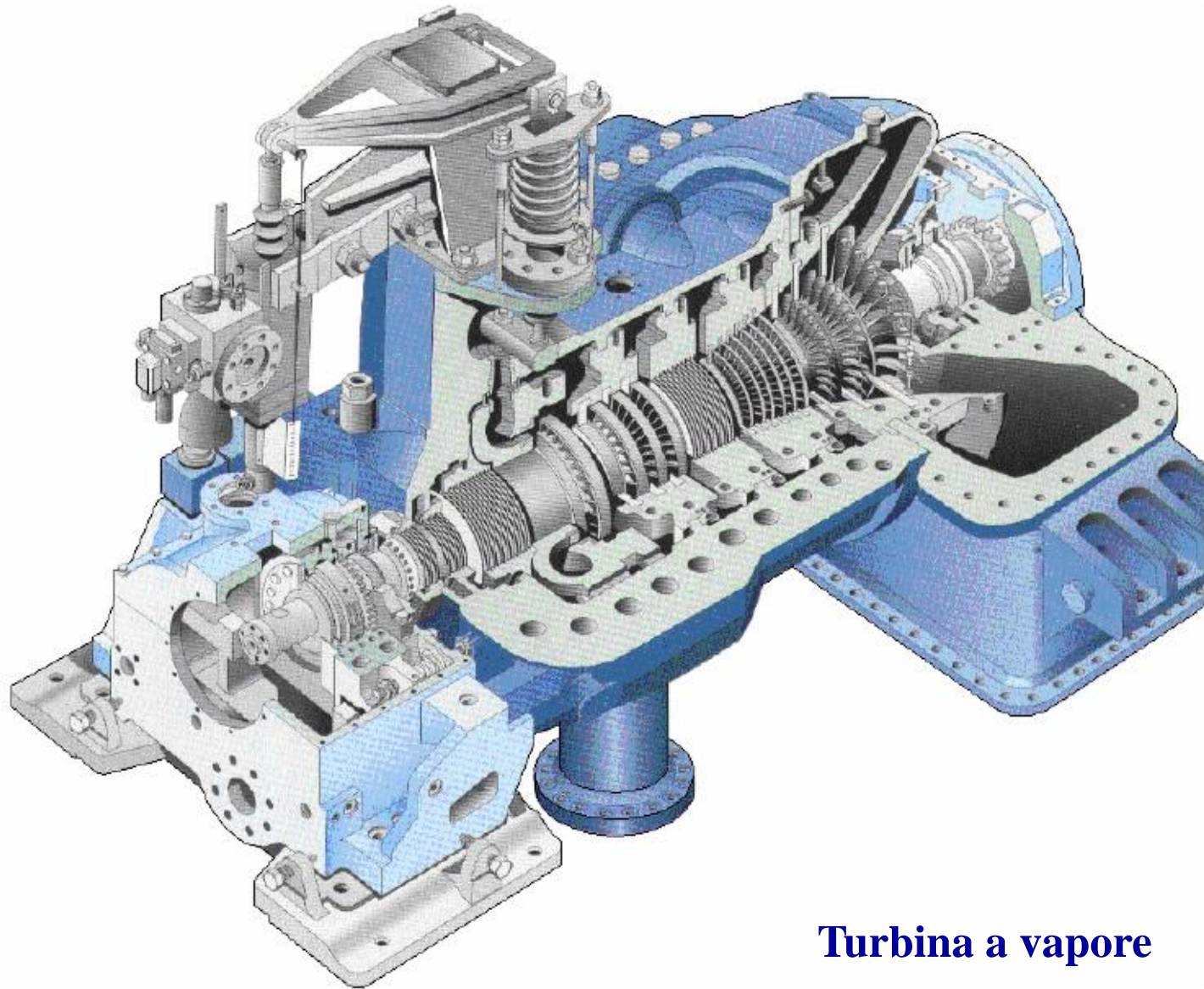


1. F. D. Fans
2. Regenerative Air heater
3. Burners
4. Furnace
5. Secondary Super-heater
6. Reheater
7. Primary Super-heater
8. Economiser
9. G.R. Fan

Caldaia a tubi d'acqua



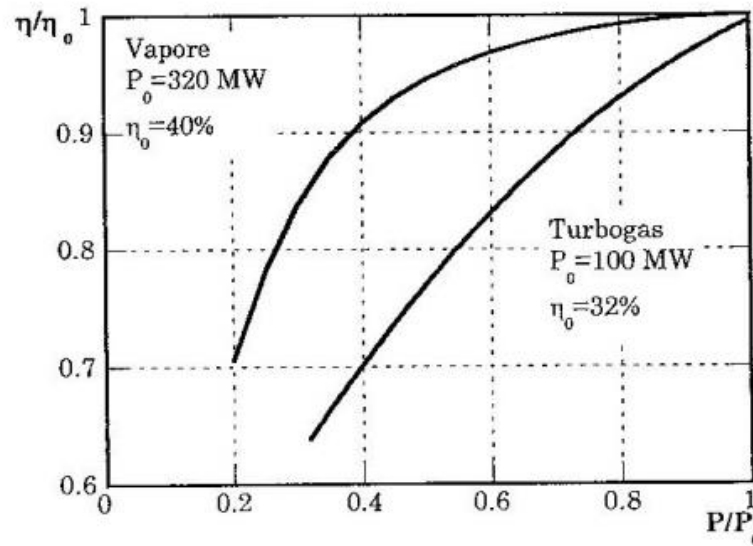
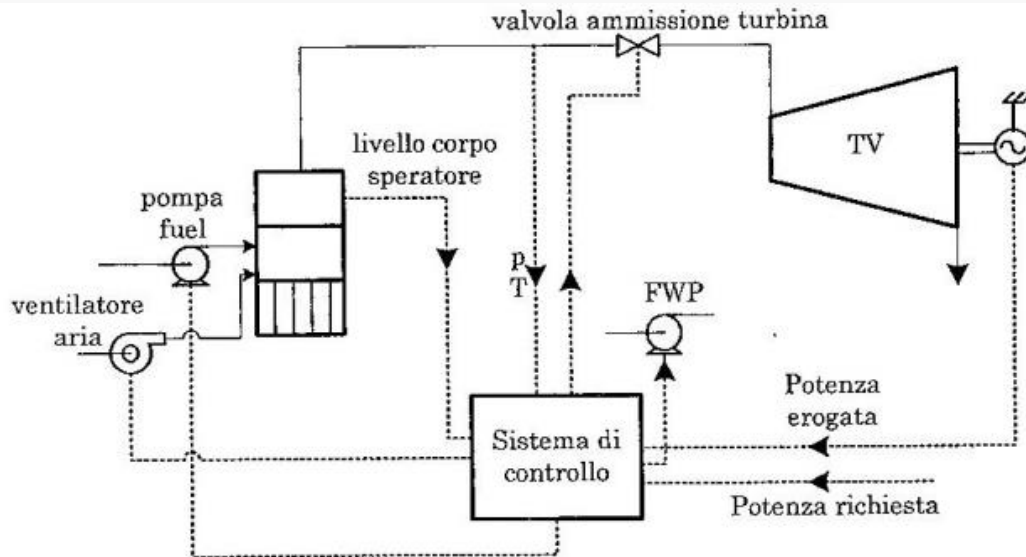
Componenti degli impianti a vapore



Turbina a vapore



Regolazione dell'impianto a vapore



Cicli Rankine a fluido organico (ORC - Organic Rankine Cycle)



Diagramma termodinamico $\{T,s\}$ del vapore d'acqua

Diagramma entropico:

temperatura T - °C

entropia s - kJ/(kg K)

Punto critico (H₂O):

temperatura: $T_{\text{crit.}}$ 374 °C

pressione: $p_{\text{crit.}}$ 22.1 MPa

volume massico:

$v_{\text{crit.}}$ 0.0032 m³/kg

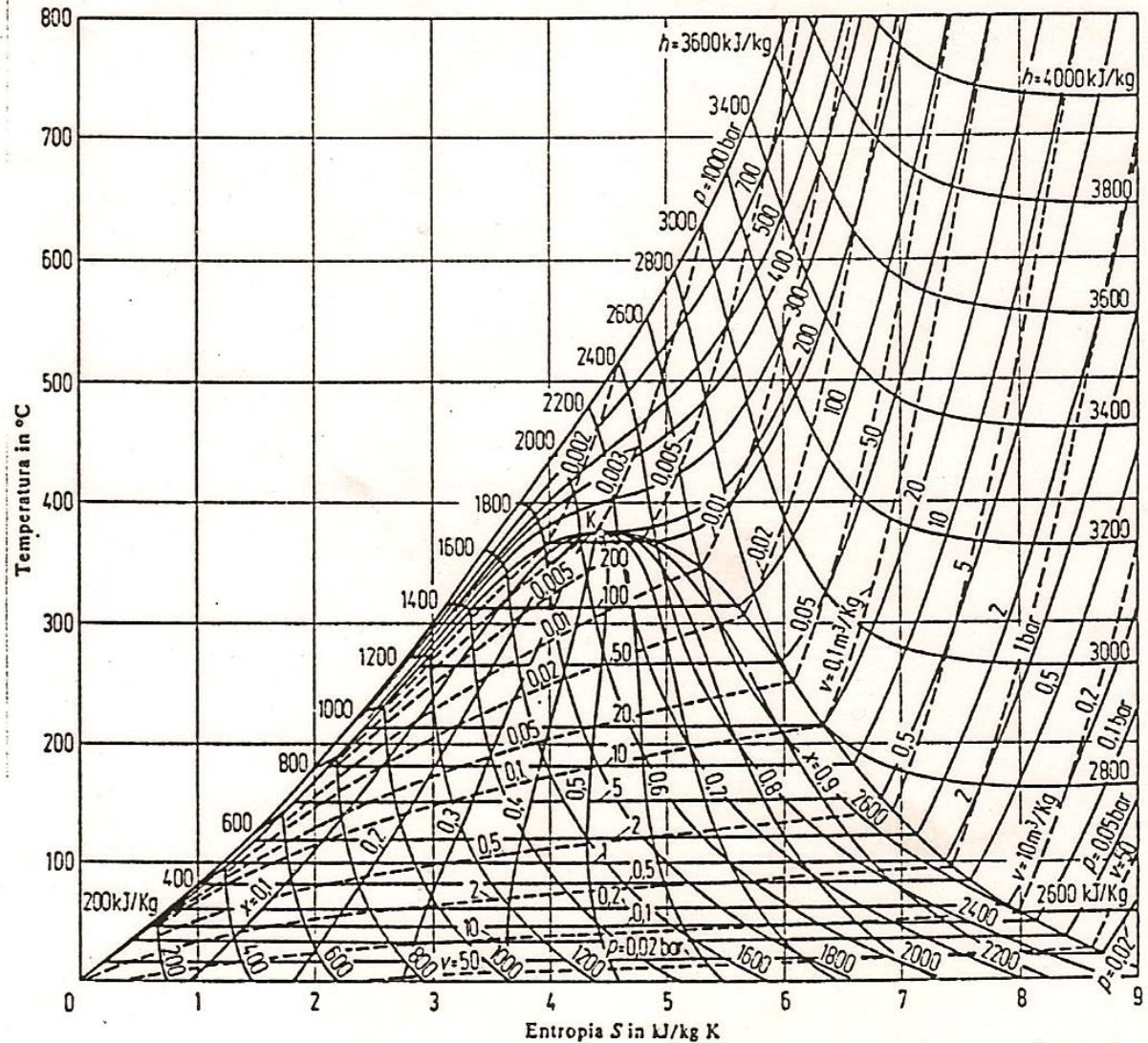


Diagramma T, s per il vapore d'acqua (Editori Springer e R. Oldenbourg)



Diagramma termodinamico {T,s} di alcuni fluidi organici

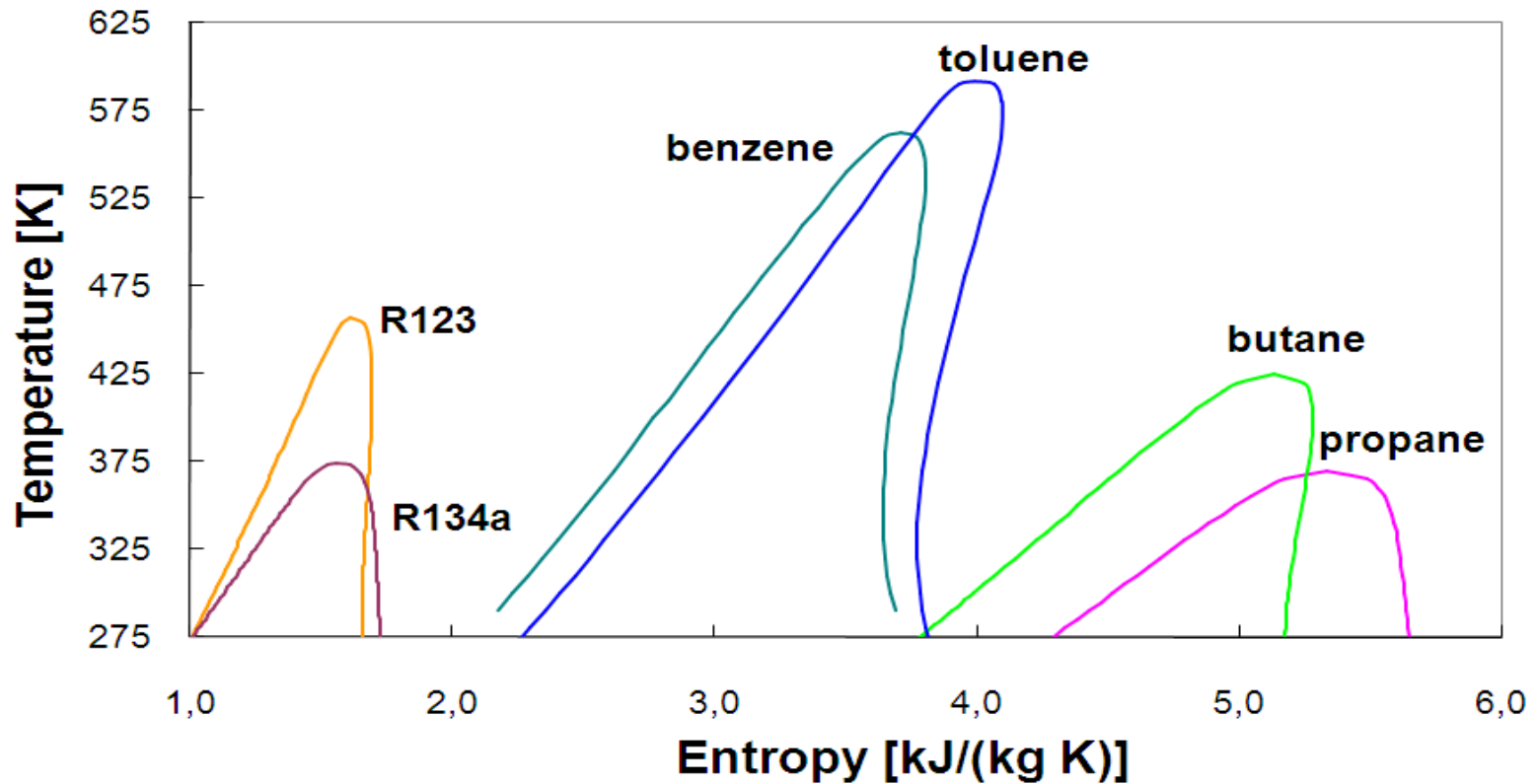
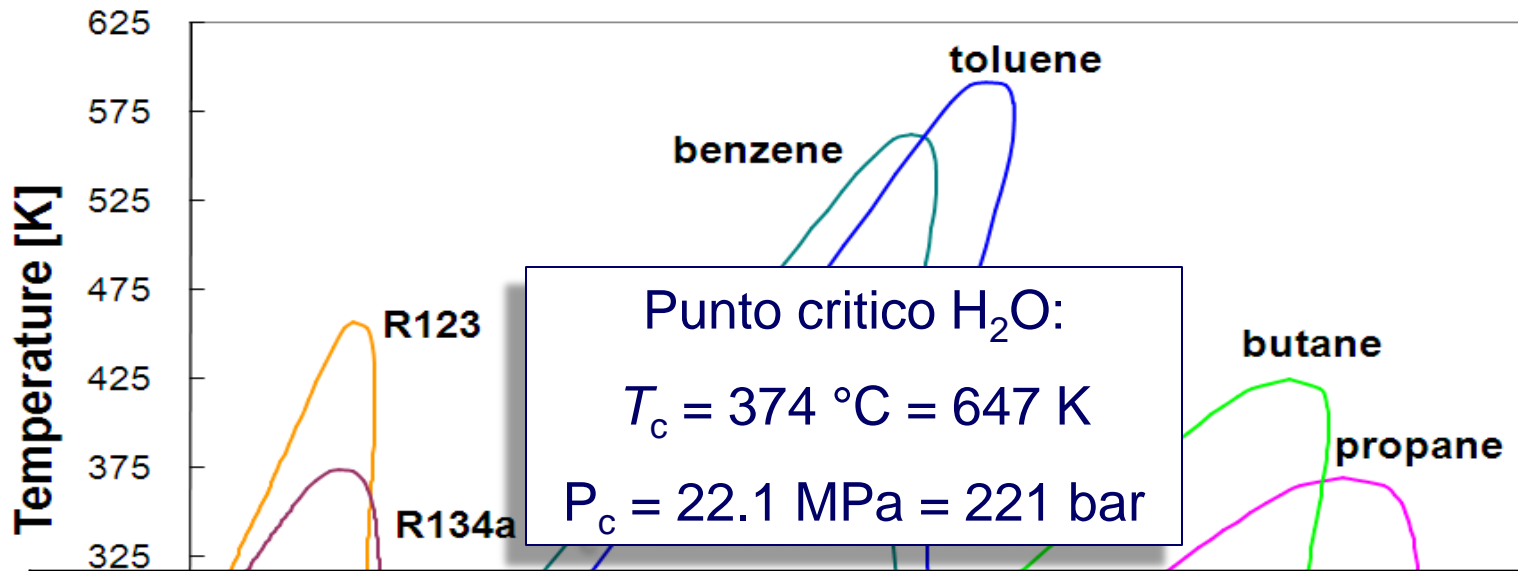


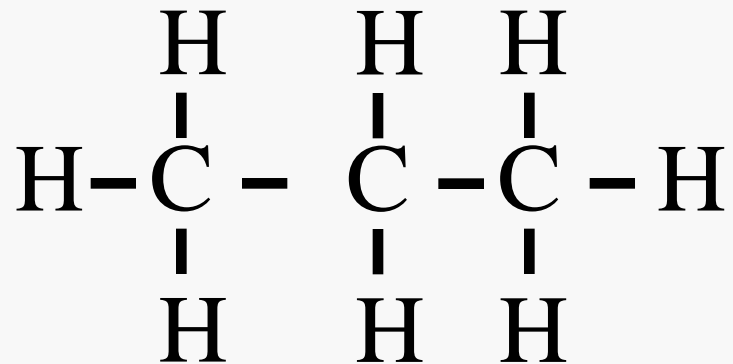
Diagramma termodinamico {T,s} di alcuni fluidi organici



nome	tipologia	MW [kg/kmol]	T_c [K]	p_c [bar]	v_c [m ³ /kmol]
Propano	alcano	44.1	369.8	42.5	0.203
Butano	alcano	58.1	425.16	38.0	0.255
Benzene	aromatico	78.1	562.2	49.0	0.212
Toluene	aromatico	92.1	591.8	41.1	0.316
R134a	alogenato	102.0	374.2	40.6	0.198
R123	alogenato	152.9	456.9	36.7	0.287



R-290 Propano C_3H_8



R-600 Butano C_4H_{10}

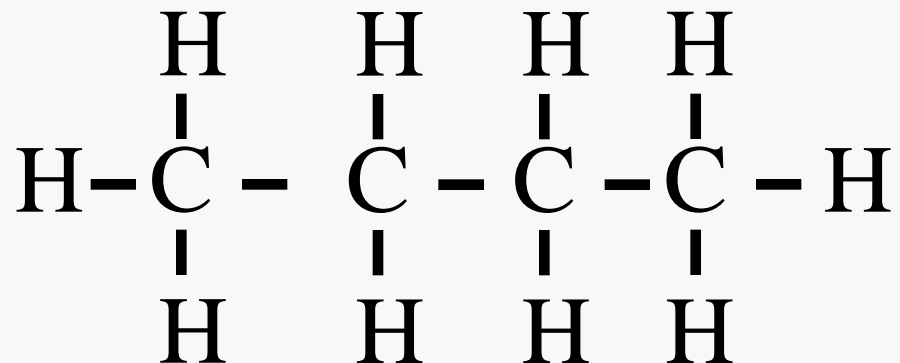


Diagramma termodinamico {T,s} di alcuni fluidi organici

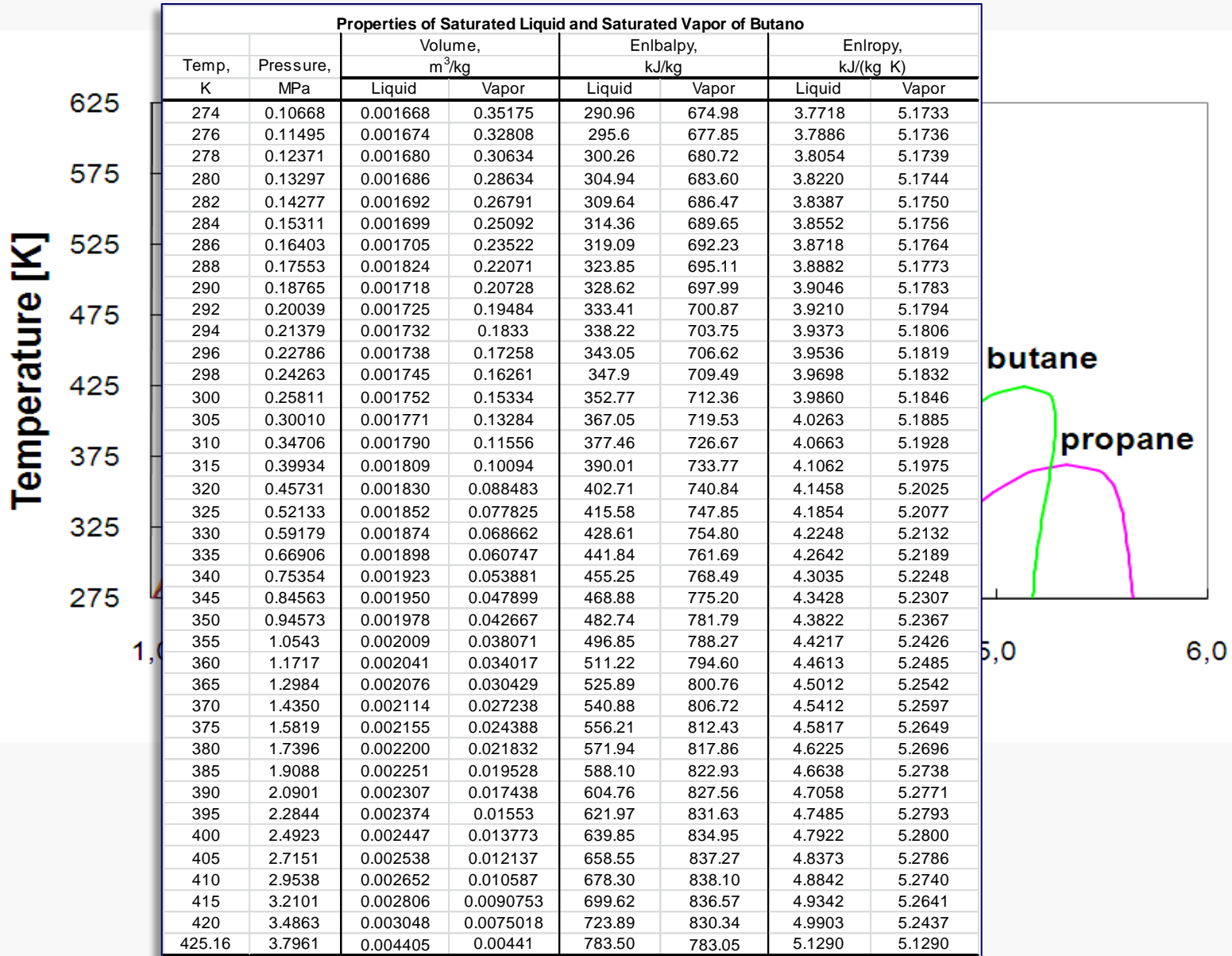
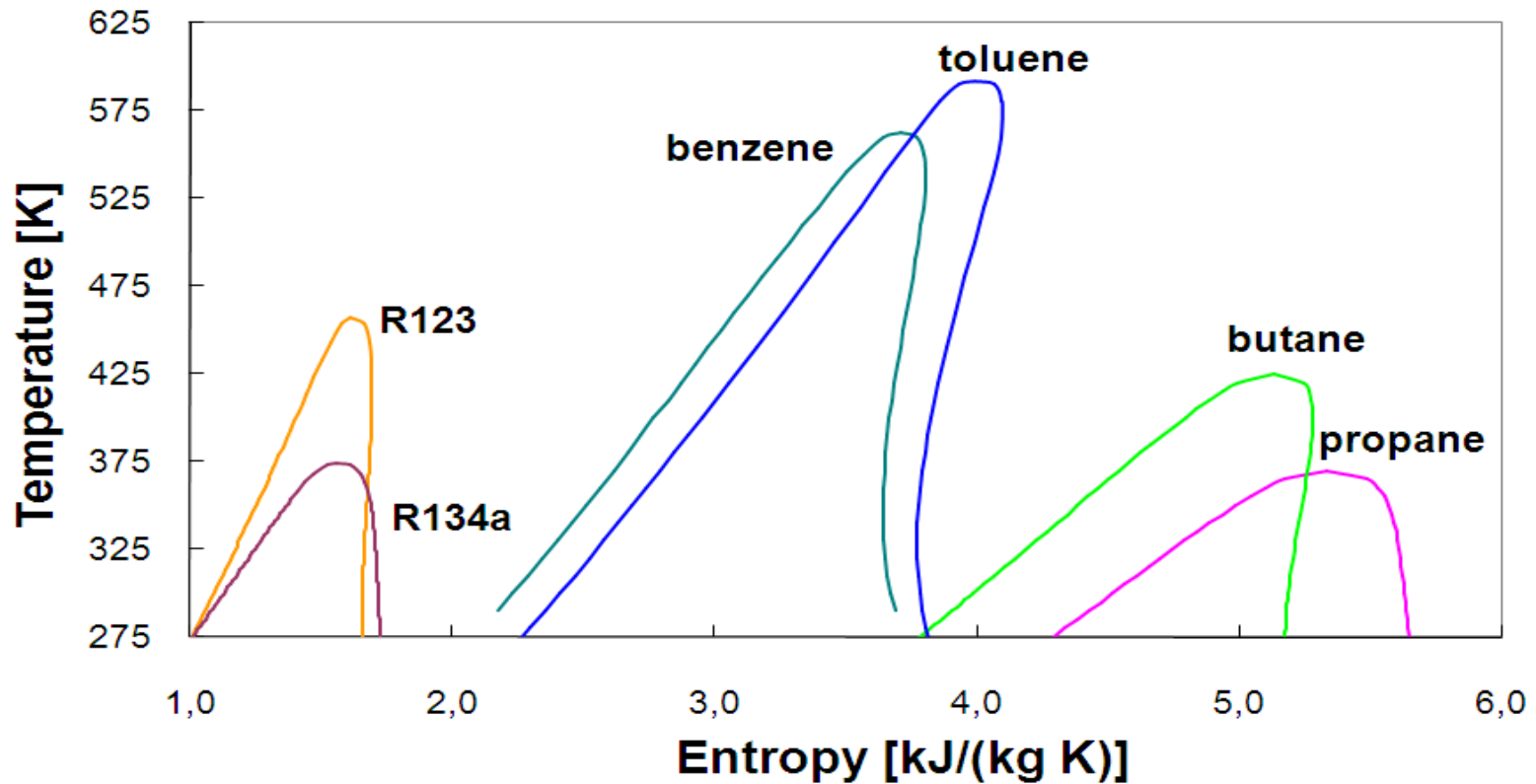
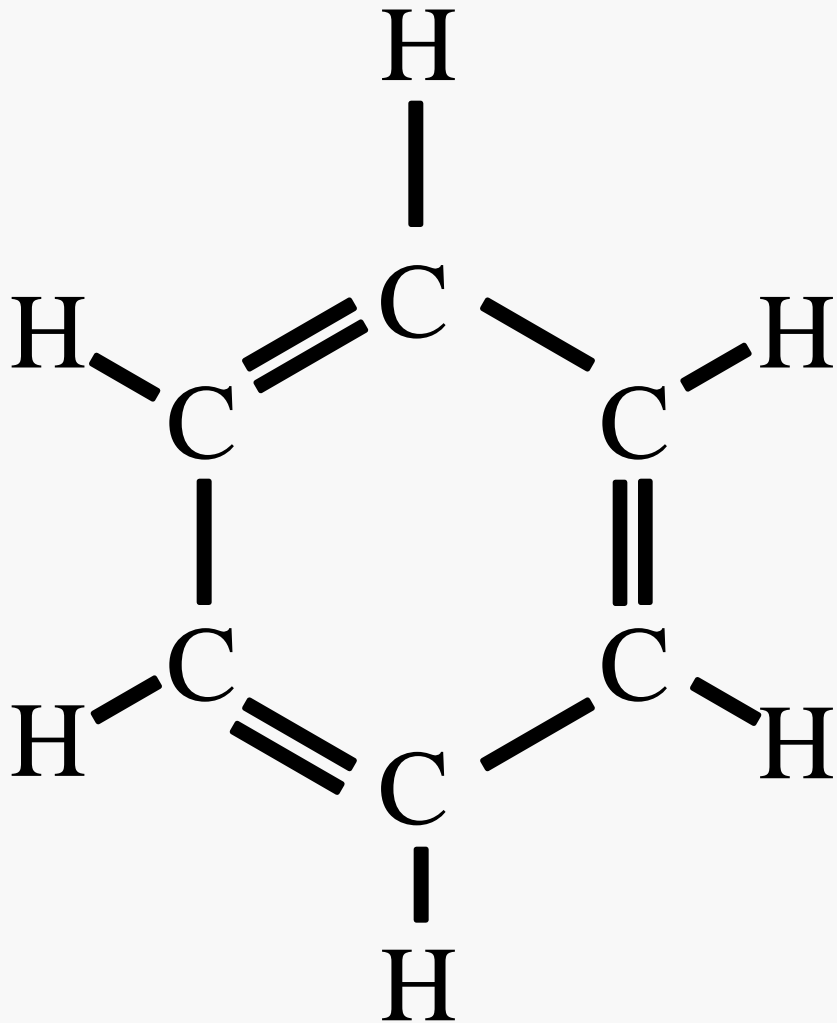


Diagramma termodinamico {T,s} di alcuni fluidi organici



Aromatici

Benzene



Toluene

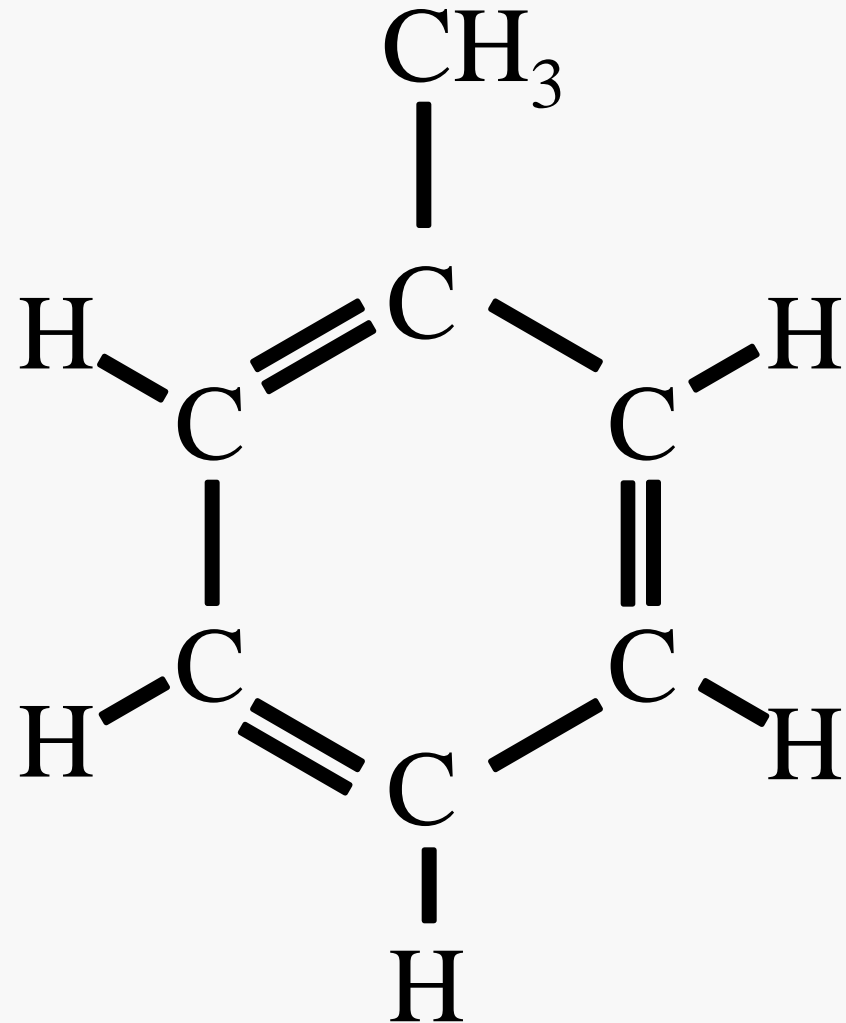


Diagramma termodinamico {T,s} di alcuni fluidi organici

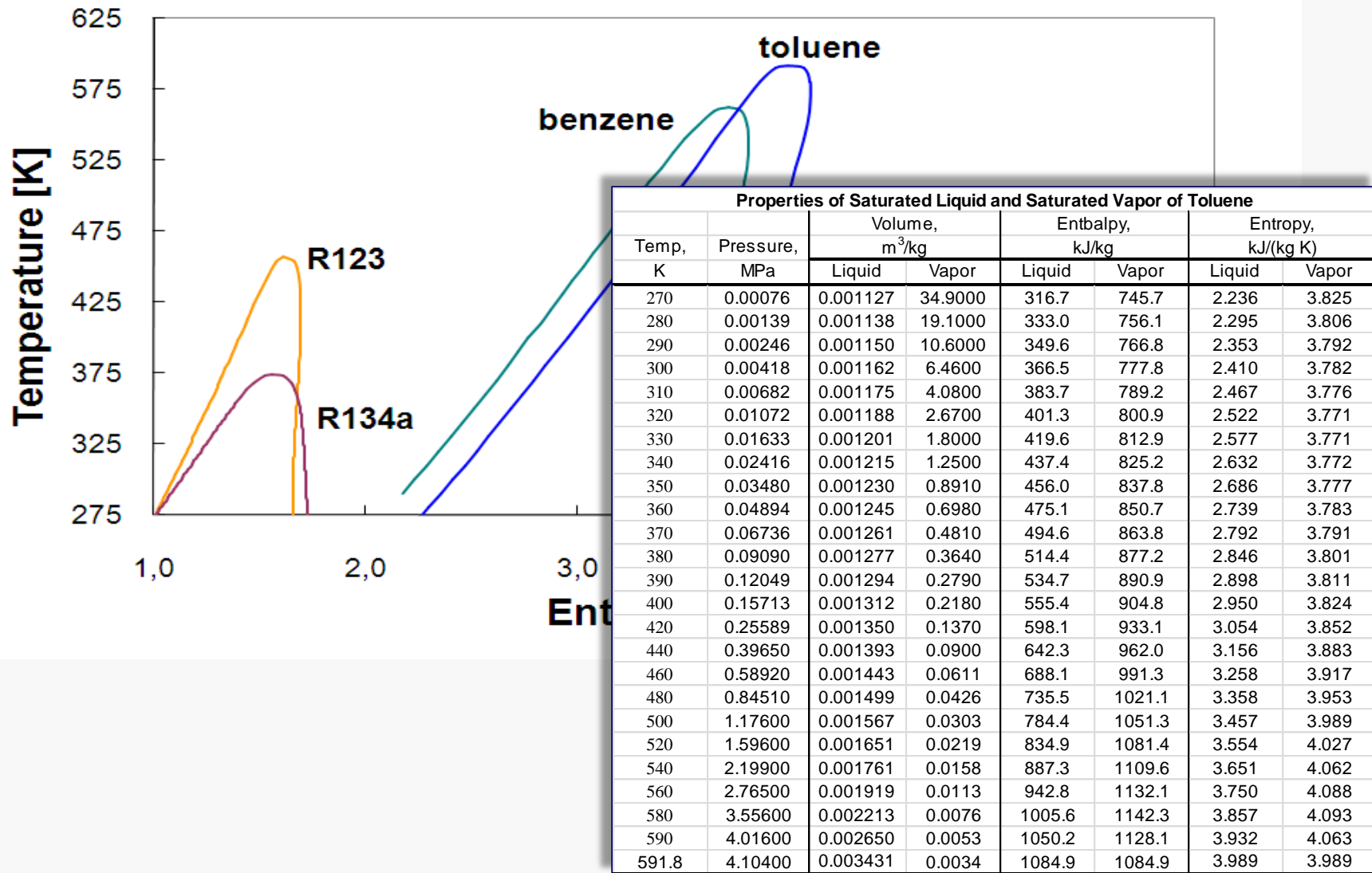
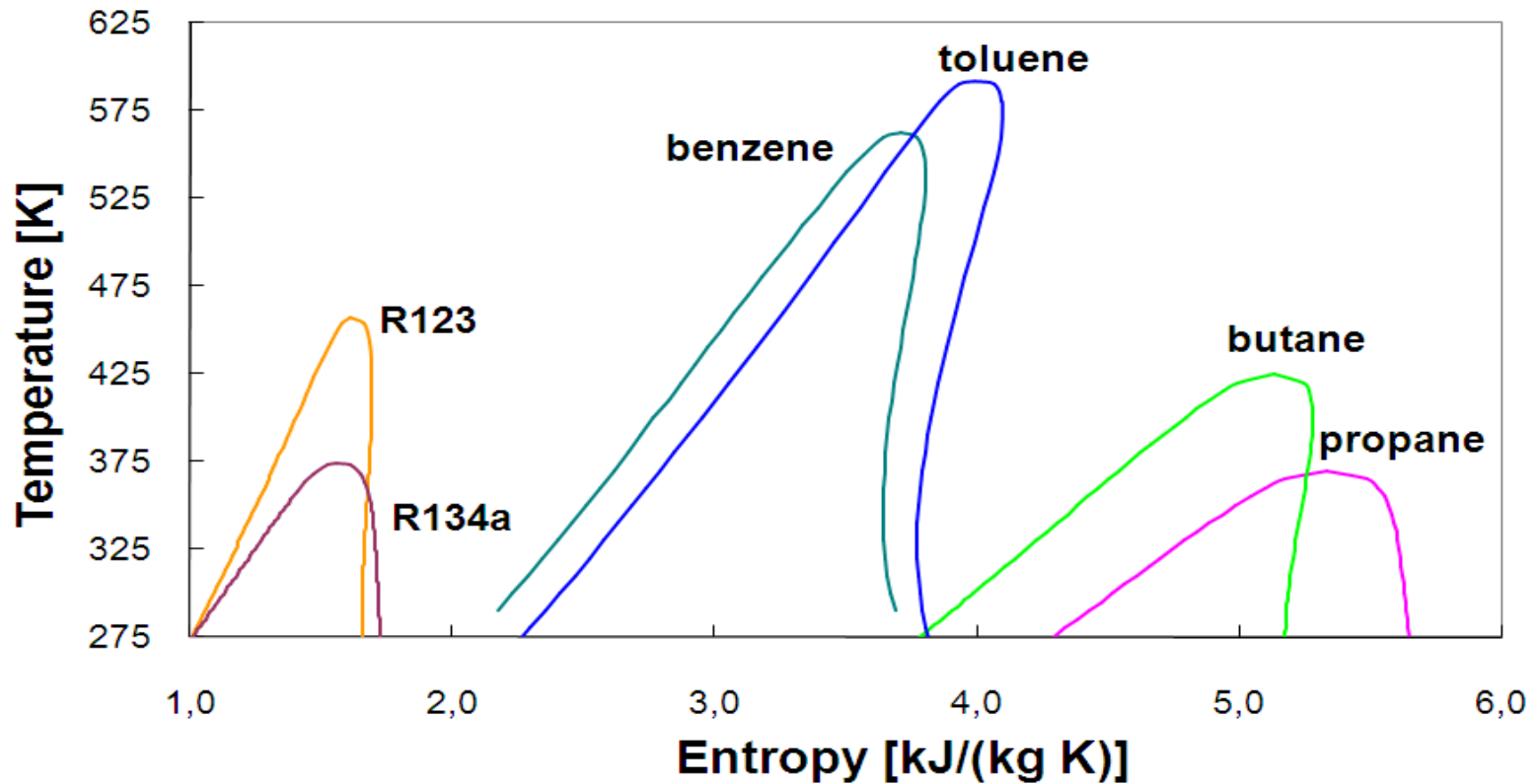
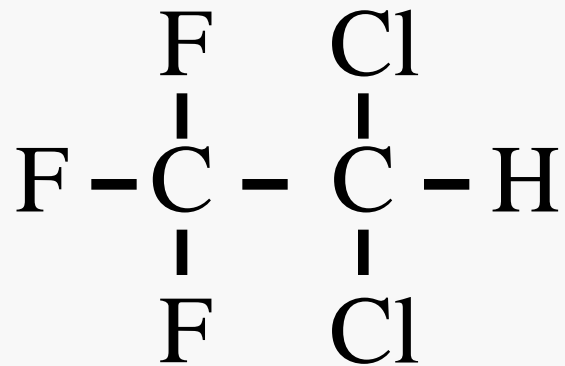


Diagramma termodinamico {T,s} di alcuni fluidi organici



Alogenati

R-123 2,2-dicloro-1,1,1-trifluoroetano $C_2HF_3Cl_2$



R-134a 1,1,1,2-tetrafluoroetano $C_2H_2F_4$

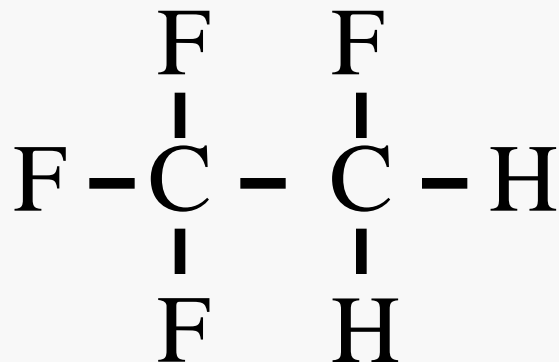
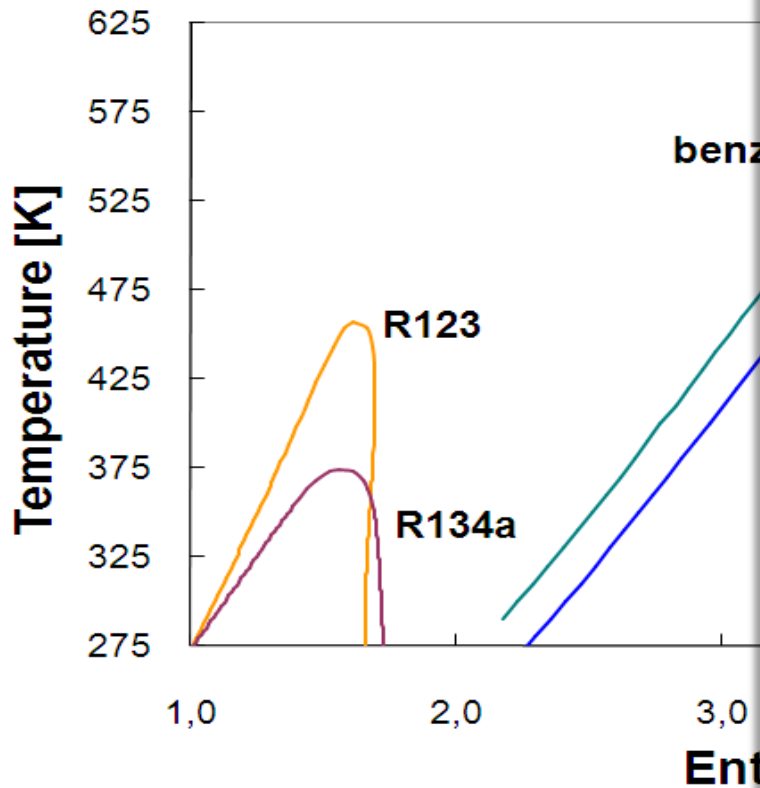


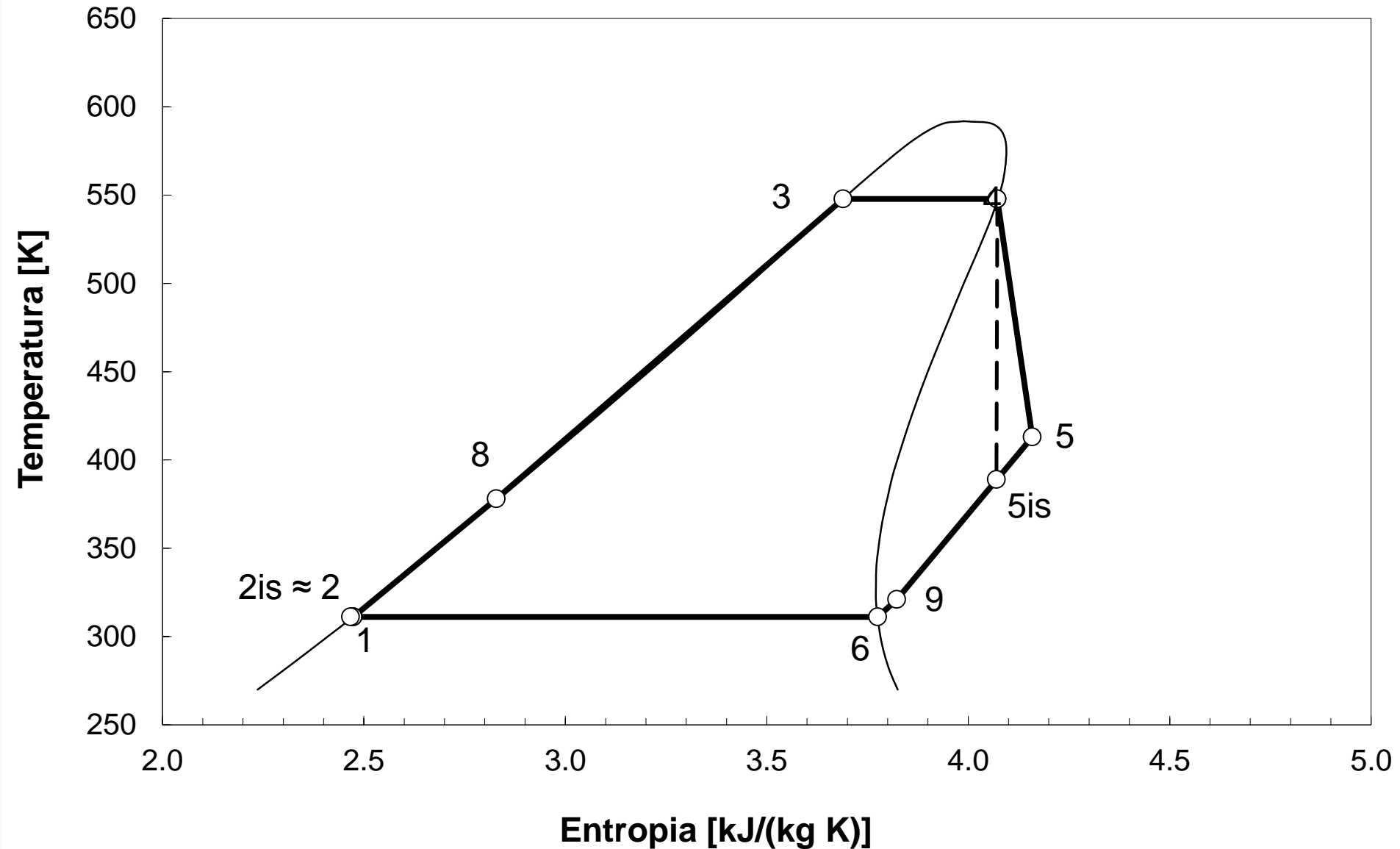
Diagramma termodinamico {T,s} di alcuni fluidi organici



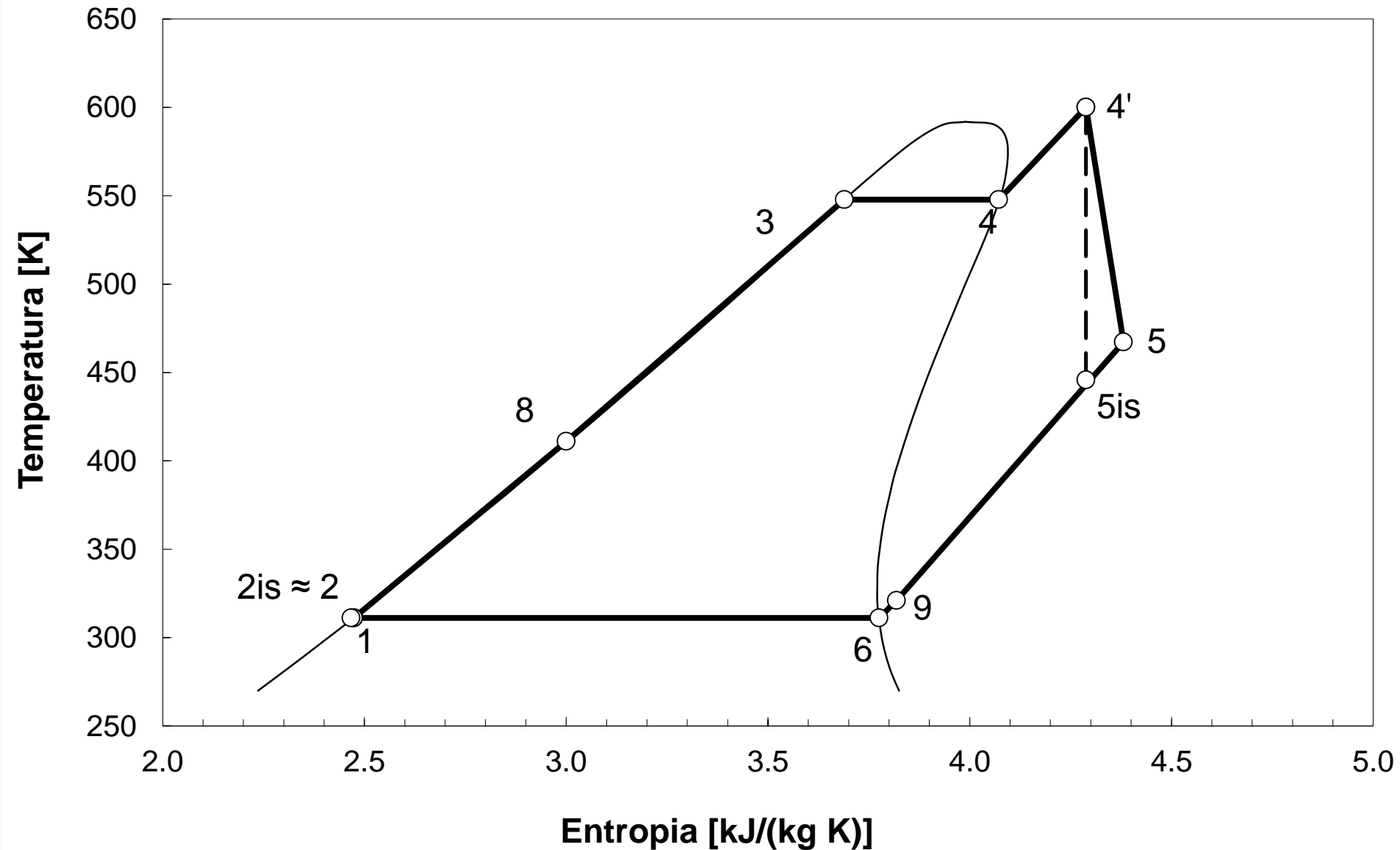
Properties of Saturated Liquid and Saturated Vapor of R134a							
Temp, K	Pressure, MPa	Volume, m ³ /kg		Enthalpy, kJ/kg		Entropy, kJ/(kg K)	
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor
273.15	0.2927	0.000773	0.06935	200.00	398.68	1.0000	1.7274
275.15	0.3145	0.000777	0.0647	202.68	399.84	1.0097	1.7263
277.15	0.3376	0.000781	0.06042	205.37	401.00	1.0194	1.7252
279.15	0.3619	0.000785	0.05648	208.08	402.14	1.0291	1.7242
281.15	0.3875	0.000789	0.05284	210.80	403.27	1.0387	1.7233
283.15	0.4145	0.000794	0.04948	213.53	404.40	1.0483	1.7224
285.15	0.4429	0.000798	0.04636	216.27	405.51	1.0579	1.7215
287.15	0.4728	0.000802	0.04348	219.03	406.61	1.0674	1.7207
289.15	0.5041	0.000807	0.04081	221.80	407.7	1.0770	1.7199
291.15	0.5371	0.000812	0.03833	224.59	408.78	1.0865	1.7191
293.15	0.5716	0.000816	0.03603	227.40	409.84	1.0960	1.7183
295.15	0.6078	0.000821	0.03388	230.21	410.89	1.1055	1.7176
297.15	0.6457	0.000826	0.03189	233.05	411.93	1.1149	1.7169
299.15	0.6853	0.000832	0.03003	235.90	412.95	1.1244	1.7162
301.15	0.7268	0.000837	0.02829	238.77	413.95	1.1338	1.7155
303.15	0.7701	0.000842	0.02667	241.65	414.94	1.1432	1.7149
305.15	0.8153	0.000848	0.02516	244.55	415.9	1.1527	1.7142
307.15	0.8625	0.000854	0.02374	247.47	416.85	1.1621	1.7135
309.15	0.9117	0.000860	0.02241	250.41	417.78	1.1715	1.7129
311.15	0.9630	0.000866	0.02116	253.37	418.69	1.1809	1.7122
313.15	1.0165	0.000872	0.01999	256.35	419.58	1.1903	1.7115
315.15	1.0721	0.000879	0.01890	259.35	420.4	1.1997	1.7108
317.15	1.1300	0.000886	0.01786	262.38	421.28	1.2091	1.7101
319.15	1.1901	0.000893	0.01689	265.42	422.09	1.2185	1.7094
321.15	1.2527	0.000900	0.01598	268.49	422.88	1.2279	1.7086
323.15	1.3177	0.000907	0.01511	271.59	423.63	1.2373	1.7078
325.15	1.3852	0.000915	0.01430	274.71	424.35	1.2468	1.7070
327.15	1.4553	0.000923	0.01353	277.86	425.03	1.2562	1.7061
329.15	1.5280	0.000932	0.01280	281.04	425.68	1.2657	1.7051
331.15	1.6033	0.000941	0.01212	284.25	426.29	1.2752	1.7041
333.15	1.6815	0.000950	0.01146	287.49	426.86	1.2847	1.7031
335.15	1.7625	0.000960	0.01085	290.77	427.37	1.2943	1.7019
337.15	1.8464	0.000970	0.01026	294.08	427.84	1.3039	1.7007
339.15	1.9334	0.000981	0.0097	297.44	428.25	1.3136	1.6993
341.15	2.0234	0.000992	0.00917	300.84	428.61	1.3234	1.6979
343.15	2.1165	0.001004	0.00867	304.29	428.89	1.3332	1.6963
345.15	2.2130	0.001017	0.00818	307.79	429.10	1.3430	1.6945
347.15	2.3127	0.001031	0.00772	311.34	429.23	1.3530	1.6926
349.15	2.4159	0.001045	0.00728	314.96	429.27	1.3631	1.6905
351.15	2.5227	0.001061	0.00686	318.65	429.20	1.3733	1.6881
353.15	2.6331	0.001078	0.00646	322.41	429.02	1.3837	1.6855
355.15	2.7475	0.001096	0.00608	326.24	428.73	1.3943	1.6826
358.15	2.9259	0.001128	0.0055	332.27	427.91	1.4105	1.6775
363.15	3.2445	0.001195	0.00461	343.01	425.48	1.4392	1.6663
368.15	3.5916	0.001296	0.00374	355.43	420.60	1.4720	1.6490
373.15	3.9721	0.001546	0.00265	374.02	407.08	1.5207	1.6093
374.18	4.0560	0.001948	0.00195	389.79	389.79	1.5593	1.5593



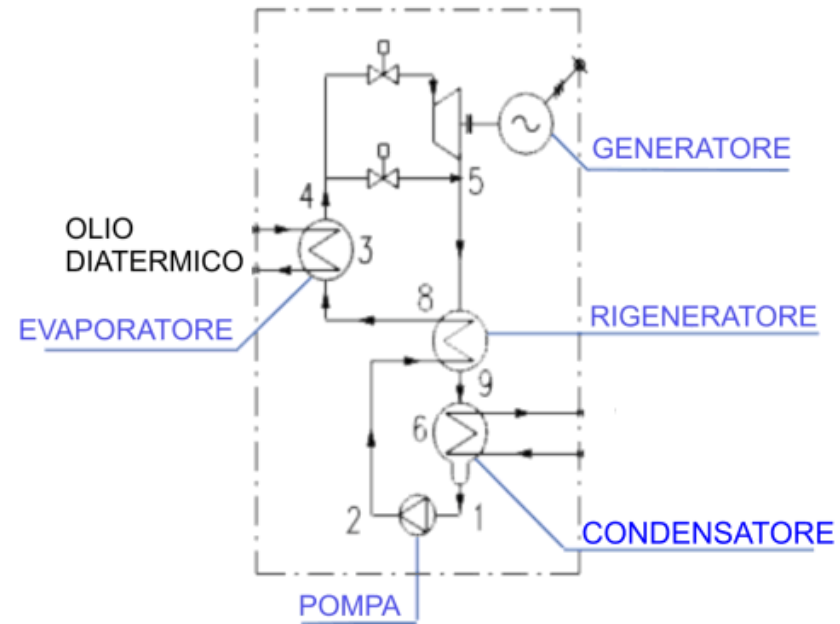
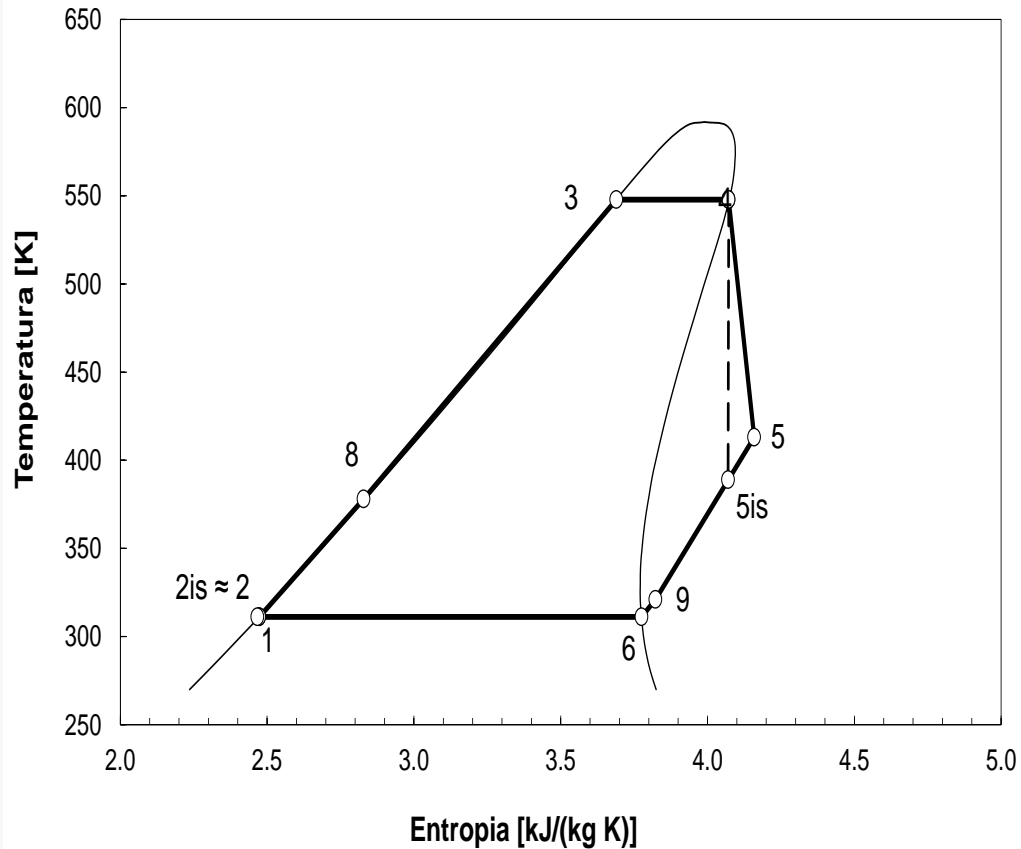
Cicli termodinamici



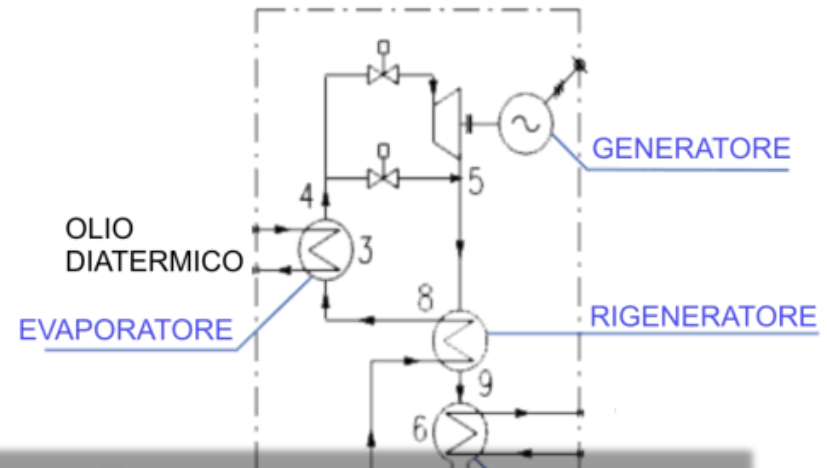
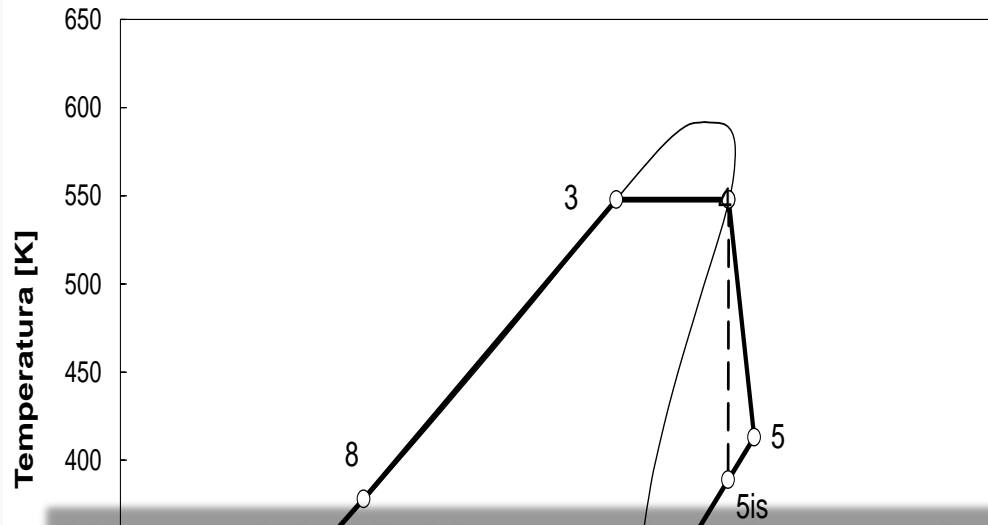
Cicli termodinamici



Ciclo termodinamico e circuito termico



Ciclo termodinamico e circuito termico

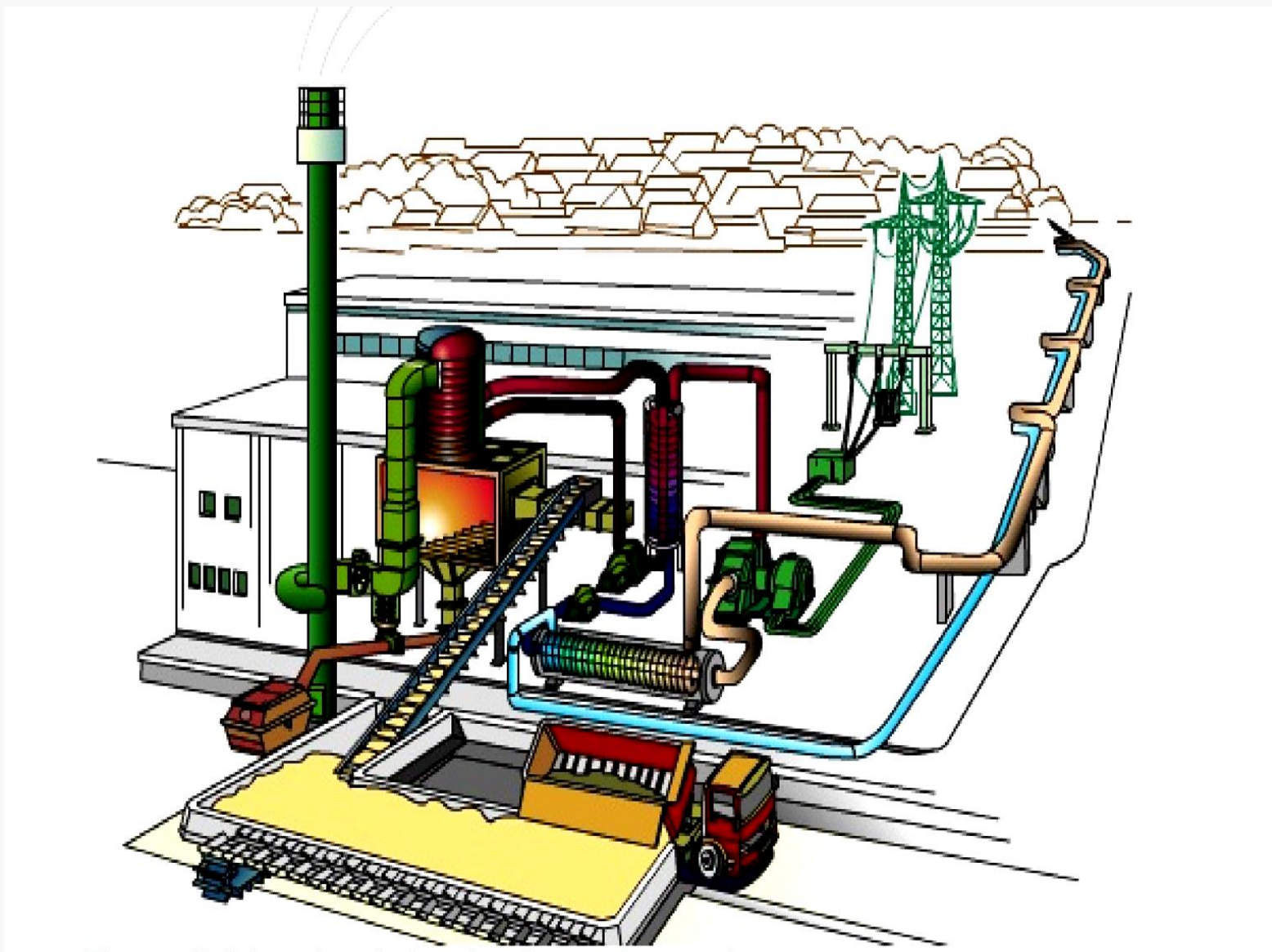


Vantaggi del fluido organico rispetto al vapor d'acqua

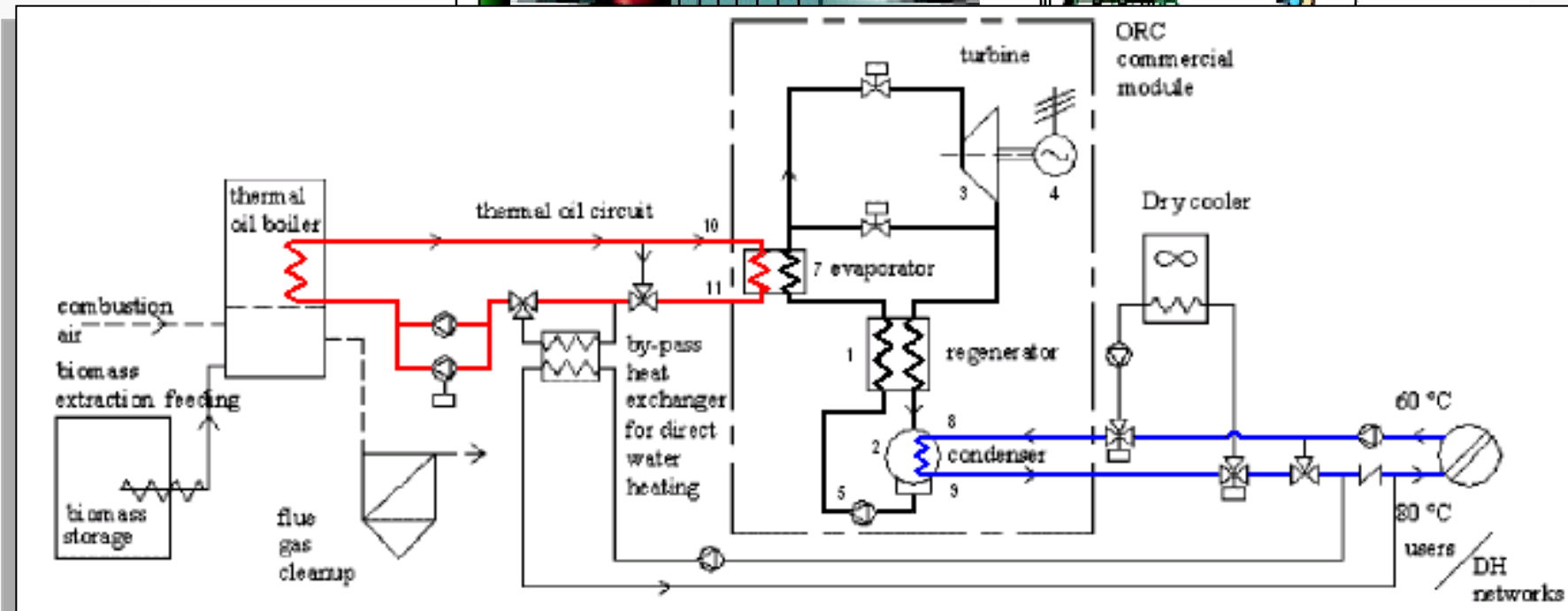
- ✓ Possibilità di sfruttare sorgenti di calore a bassa temperatura (100 ÷ 400 °C)
- ✓ Basse pressioni di vaporizzazione, anche per condizioni prossime a quelle critiche
- ✓ Modesti salti entalpici da sfruttare ed elevati pesi molecolari del fluido di lavoro, con conseguente possibilità di utilizzo di turbine con basso numero di stadi (anche uno solo) e dalle velocità di rotazione ridotte (accoppiamento diretto al generatore elettrico)
- ✓ Tempi di avviamento rapidi



ORC - Esempi

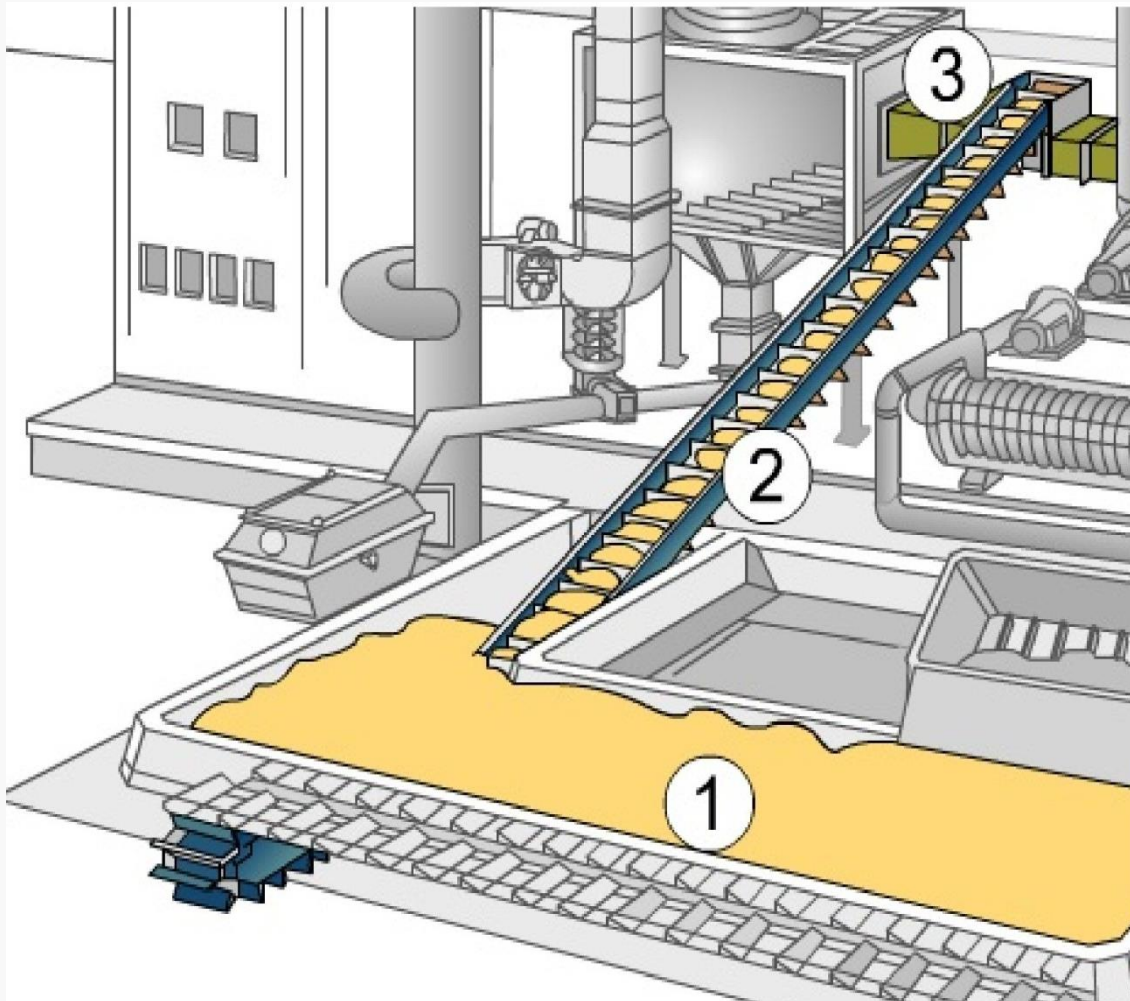


ORC - Esempi



ORC - Esempi

Sistema automatico di alimentazione del combustibile



1. Silos/bacino di raccolta



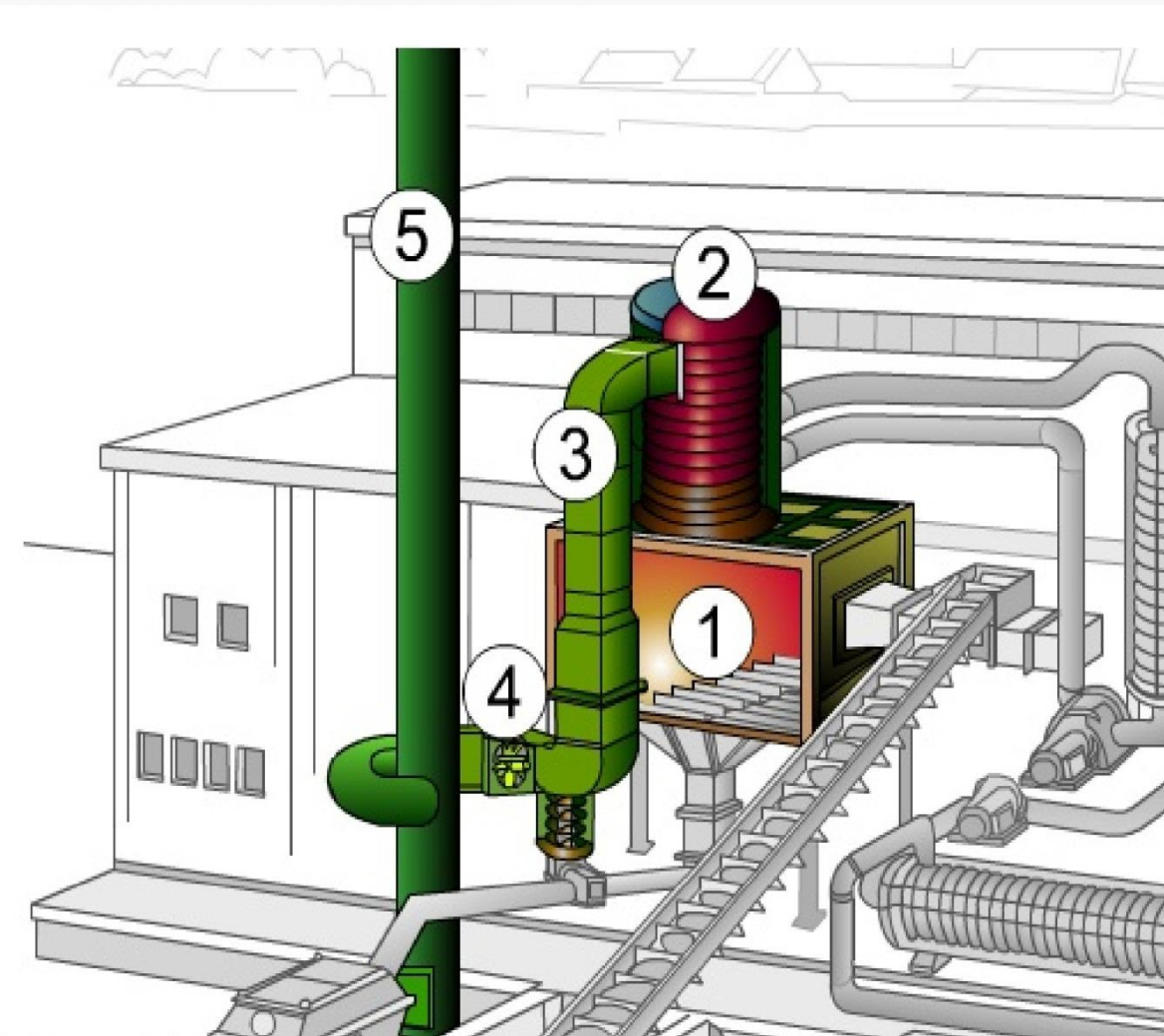
2. Rullo trasportatore



3. Iniettore



Caldaia per biomassa ad olio diatermico



**1. Caldaia a griglia mobile
o a insuflaggio a vortice**



2. Recuperatore



3. Condotto di scarico



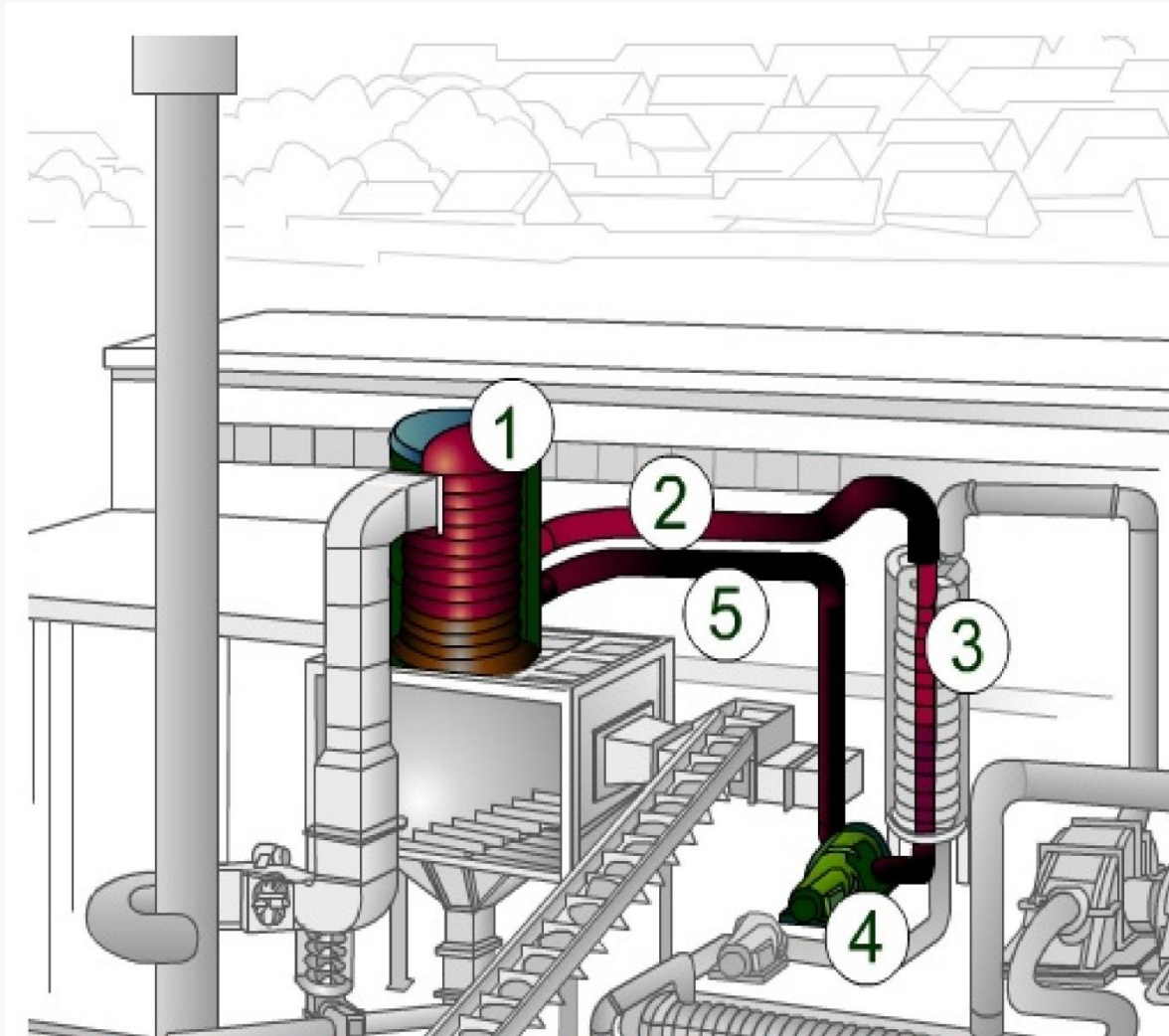
**4. Filtro ciclone e
Ventilatore**



5. Camino

ORC - Esempi

Circuito primario - olio diatermico



1. Recuperatore



**2. Andata olio diatermico
(300-350°C)**



3. Evaporatore



4. Pompa

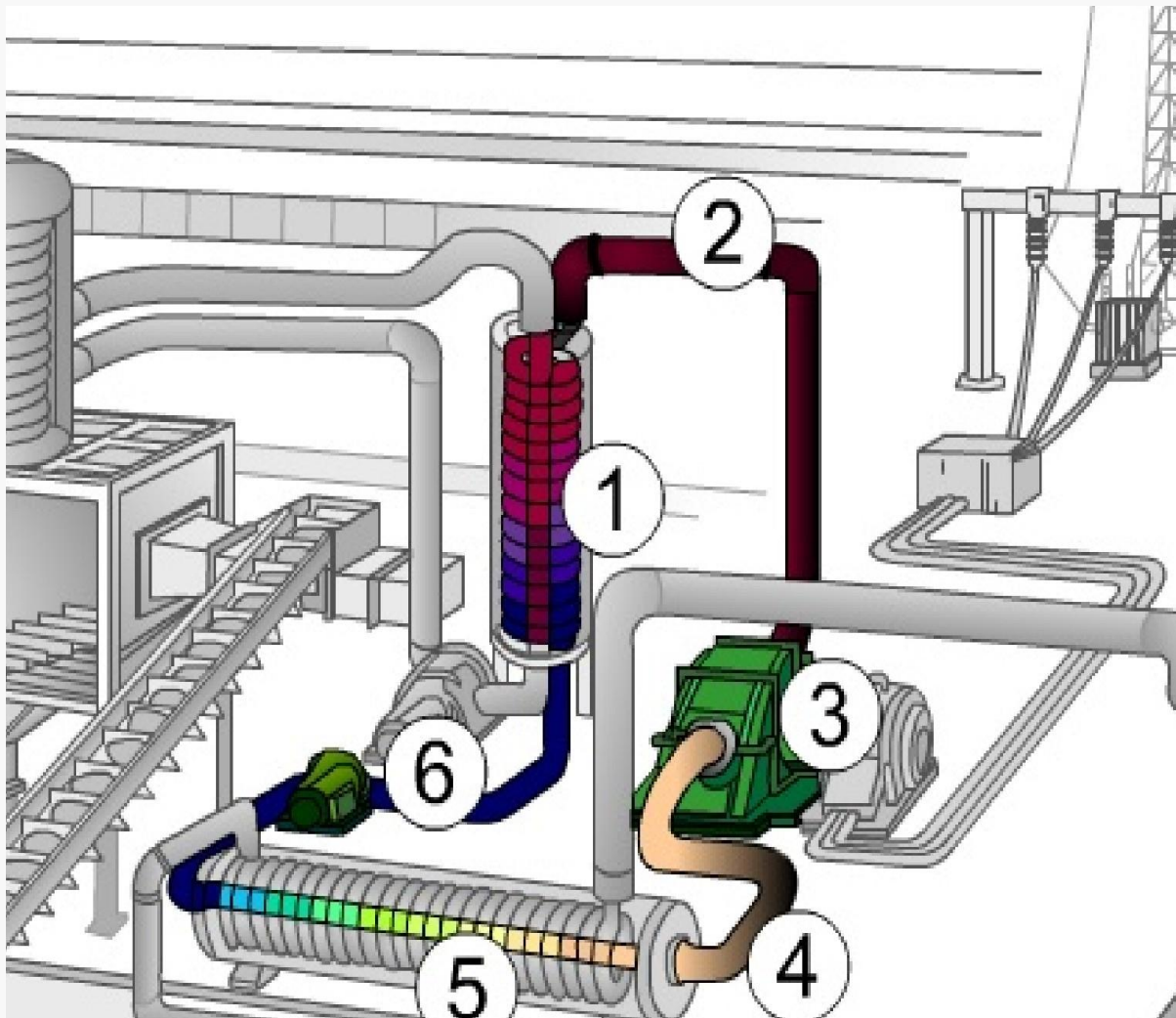


**5. Ritorno
olio diatermico**



ORC - Esempi

Circuito secondario (modulo ORC) - fluido organico



1. Evaporatore



**2. Mandata vapore
Fluido organico
(250-300°C)**



3. Turbogeneratore



**4. Scarico vapore fluido
organico (90°C)**



5. Condensatore



6. Pompa



ORC - Esempi

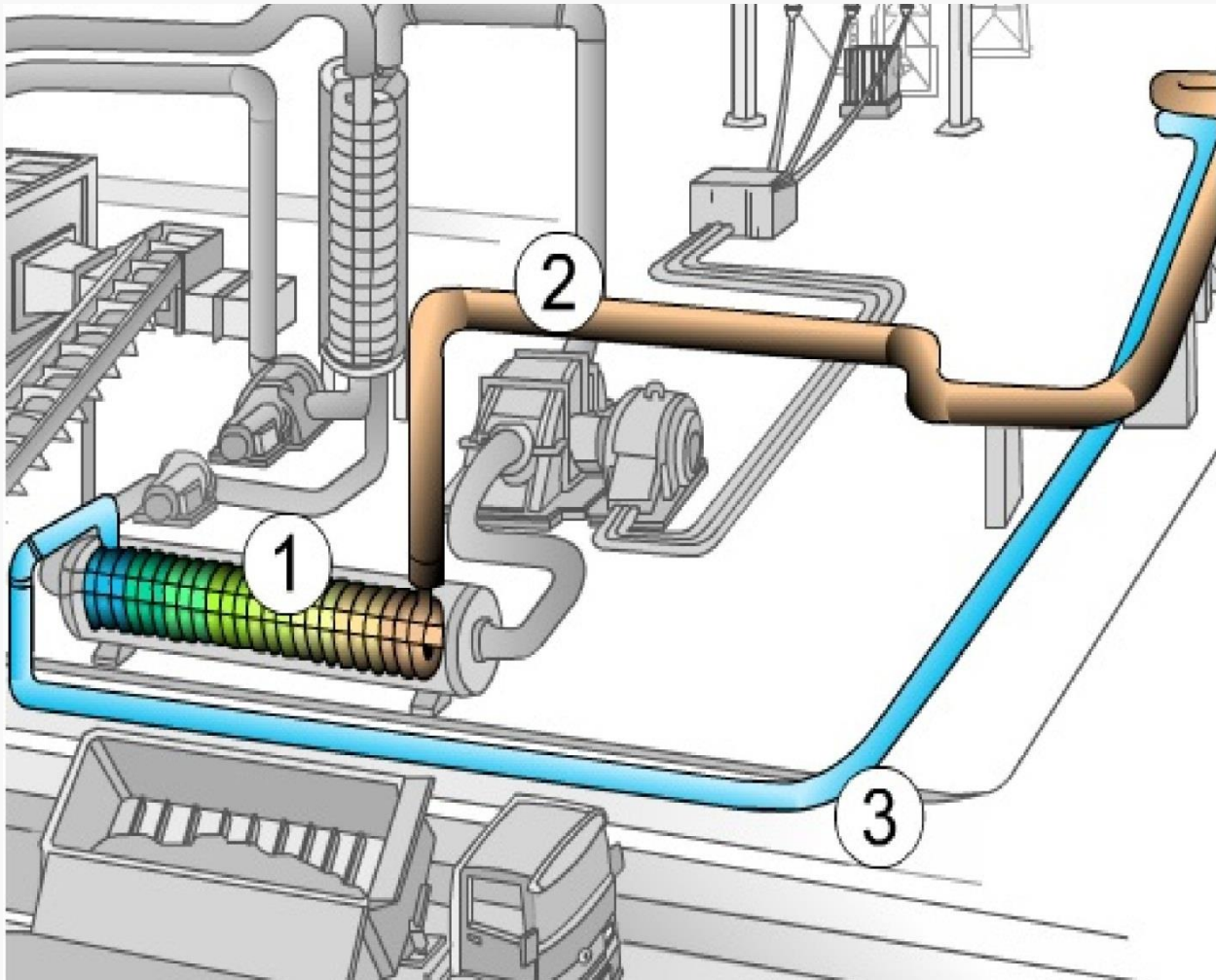
Circuito secondario (modulo ORC) - fluido organico



- | | | |
|------------------------|-----------------------------------|---------------------------------|
| 1 Economizzatore | 5 Pompa | 9 Uscita acqua di condensazione |
| 2 Condensatore | 6 Pre-riscaldatore | 10 Ingresso olio diatermico |
| 3 Turbina | 7 Evaporatore | 11 Uscita olio diatermico |
| 4 Generatore elettrico | 8 Ingresso acqua di condensazione | |



Circuito dell'acqua di raffreddamento



1. Condensatore



**2. Acqua calda alle
utenze (80-90°C)**



**3. Acqua fredda
(60°C)**

Moduli ORC

Taglie Standard e prestazioni tipiche di Impianti CHP (cogenerativi) con split*

		TURBODEN 4 CHP - split	TURBODEN 6 CHP - split	TURBODEN 7 CHP - split	TURBODEN 10 CHP - split	TURBODEN 14 CHP - split	TURBODEN 18 CHP - split	TURBODEN 22 CHP - split
INPUT - olio diatermico								
temperatura nominale circuito alta temperatura (in/out)	°C	310/250	310/250	310/250	310/250	310/250	312/252	312/252
potenza termica circuito alta temperatura	KW	2100	2965	3485	4690	6130	8935	10975
temperatura nominale circuito bassa temperatura (in/out)	°C	250/130	250/130	250/130	250/130	250/130	252/132	252/132
potenza termica circuito bassa temperatura	KW	200	275	330	450	585	855	1045
potenza termica totale in ingresso	KW	2300	3240	3815	5140	6715	9790	12020
OUTPUT - acqua calda								
temperatura acqua calda (in/out)	°C	60/80	60/80	60/80	60/80	60/80	60/90	60/90
potenza termica all'acqua	KW	1844	2600	3060	4100	5350	7850	9630
PRESTAZIONI								
potenza elettrica attiva lorda	KW	424	617	727	1001	1317	1862	2282
efficienza elettrica lorda		0.184	0.19	0.191	0.194	0.196	0.19	0.189
autoconsumi elettrici	KW	24	30	38	51	62	87	107
potenza elettrica attiva netta	KW	400	587	689	950	1255	1775	2175
efficienza elettrica netta		0.174	0.181	0.181	0.184	0.186	0.181	0.181
generatore elettrico		asincrono trifase B.T. 400V	asincrono trifase B.T. 400V	asincrono trifase B.T. 400V	asincrono trifase B.T. 400V	asincrono trifase B.T. 400V	asincrono trifase B.T. 660V	asincrono trifase B.T. 660V
configurazione impianto		single skid	single skid	single skid	single skid	multiple skid	multiple skid	multiple skid
consumo biomassa **	kg/h	1005	1416	1667	2247	2935	4279	5254

* Il sistema split Turboden permette di massimizzare la produzione elettrica a pari consumo biomassa.

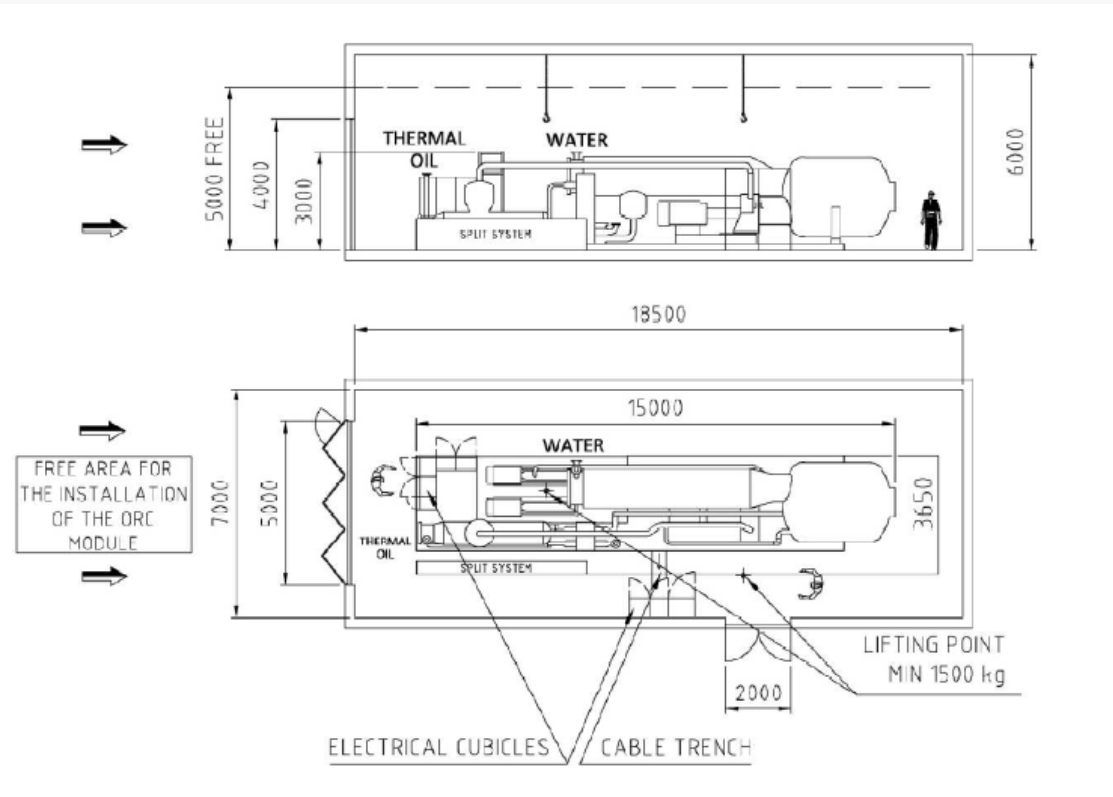
** Assumendo potere calorifico della biomassa=2,6 kWh/kg ed efficienza della caldaia=0,88. La caldaia ad olio diatermico non è compresa nello scopo di fornitura Turboden.

Costo: 900 ÷ 2500 Euro/kW_e



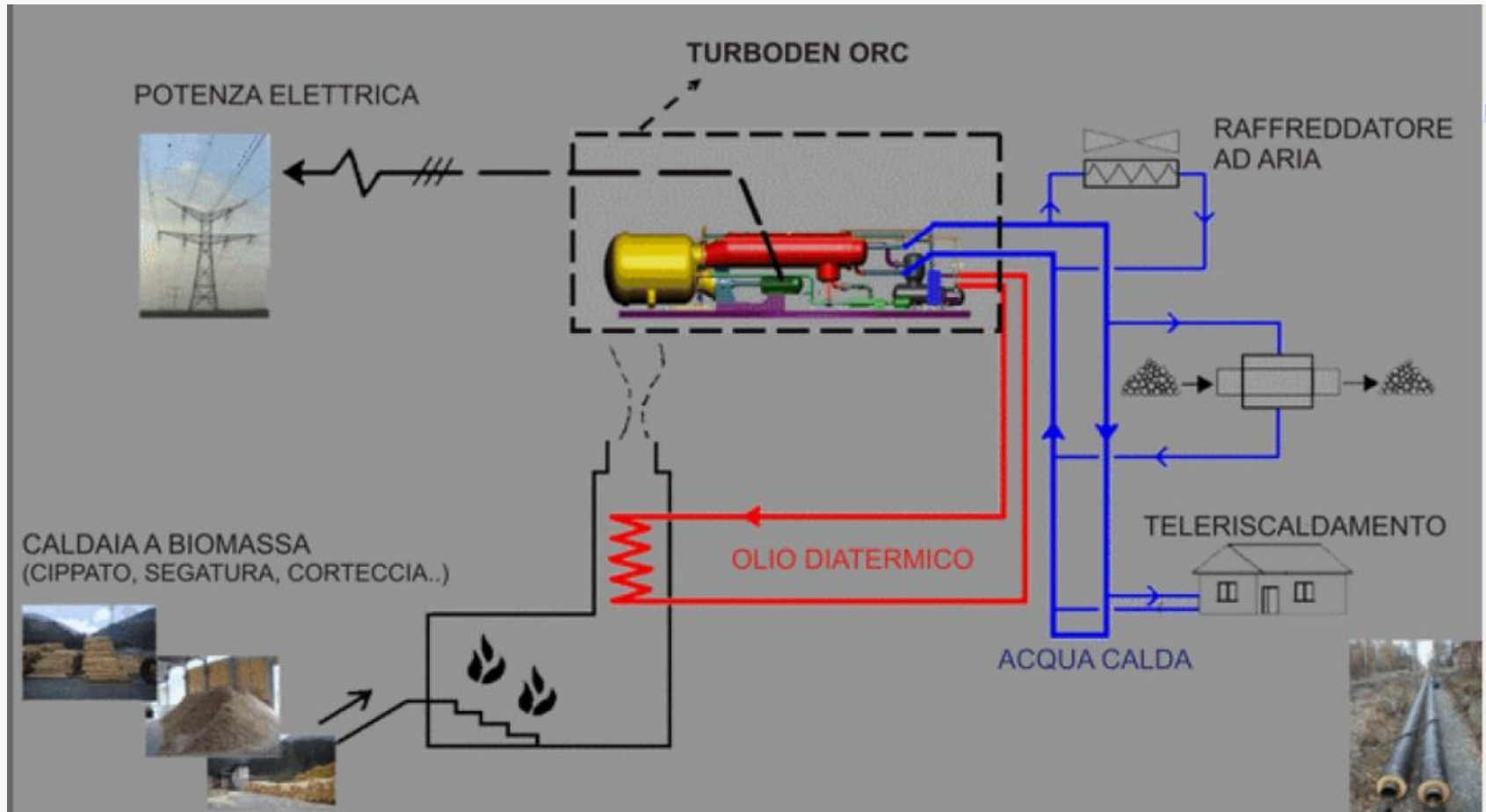
Moduli ORC

		TURBODEN 4 CHP - split
INPUT - olio diatermico		
temperatura nominale circuito alta temperatura (in/out)	°C	310/250
potenza termica circuito alta temperatura	KW	2100
temperatura nominale circuito bassa temperatura (in/out)	°C	250/130
potenza termica circuito bassa temperatura	KW	200
potenza termica totale in ingresso	KW	2300
OUTPUT - acqua calda		
temperatura acqua calda (in/out)	°C	60/80
potenza termica all'acqua	KW	1844
PRESTAZIONI		
potenza elettrica attiva lorda	KW	424
efficienza elettrica lorda		0.184
autoconsumi elettrici	KW	24
potenza elettrica attiva netta	KW	400
efficienza elettrica netta		0.174
generatore elettrico		asincrono trifase B.T. 400V
configurazione impianto		single skid
consumo biomassa **	kg/h	1005



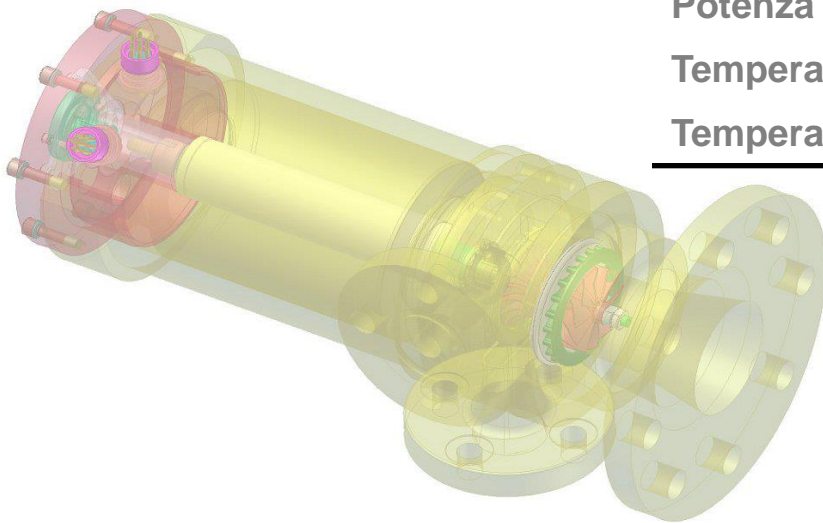
Applicazioni ORC

- ✓ Può essere conveniente soprattutto con biomassa solida e syngas
- ✓ Possibilità di recupero di calore scaricato da motori (ciclo combinato)



ORC di piccola taglia

- ✓ Recentemente proposti ORC di taglie inferiori a 200 kW



FreePower FP120

Potenza termica ingresso	kW	742
Potenza elettrica lorda	kW	130
Potenza elettrica netta	kW	120
Rendimento elettrico netto	%	16
Temperatura IN	°C	280
Temperatura OUT	°C	136
Potenza termica scaricata	kW	612
Temperatura acqua per cogen	°C	64
Temperatura fumi	°C	457

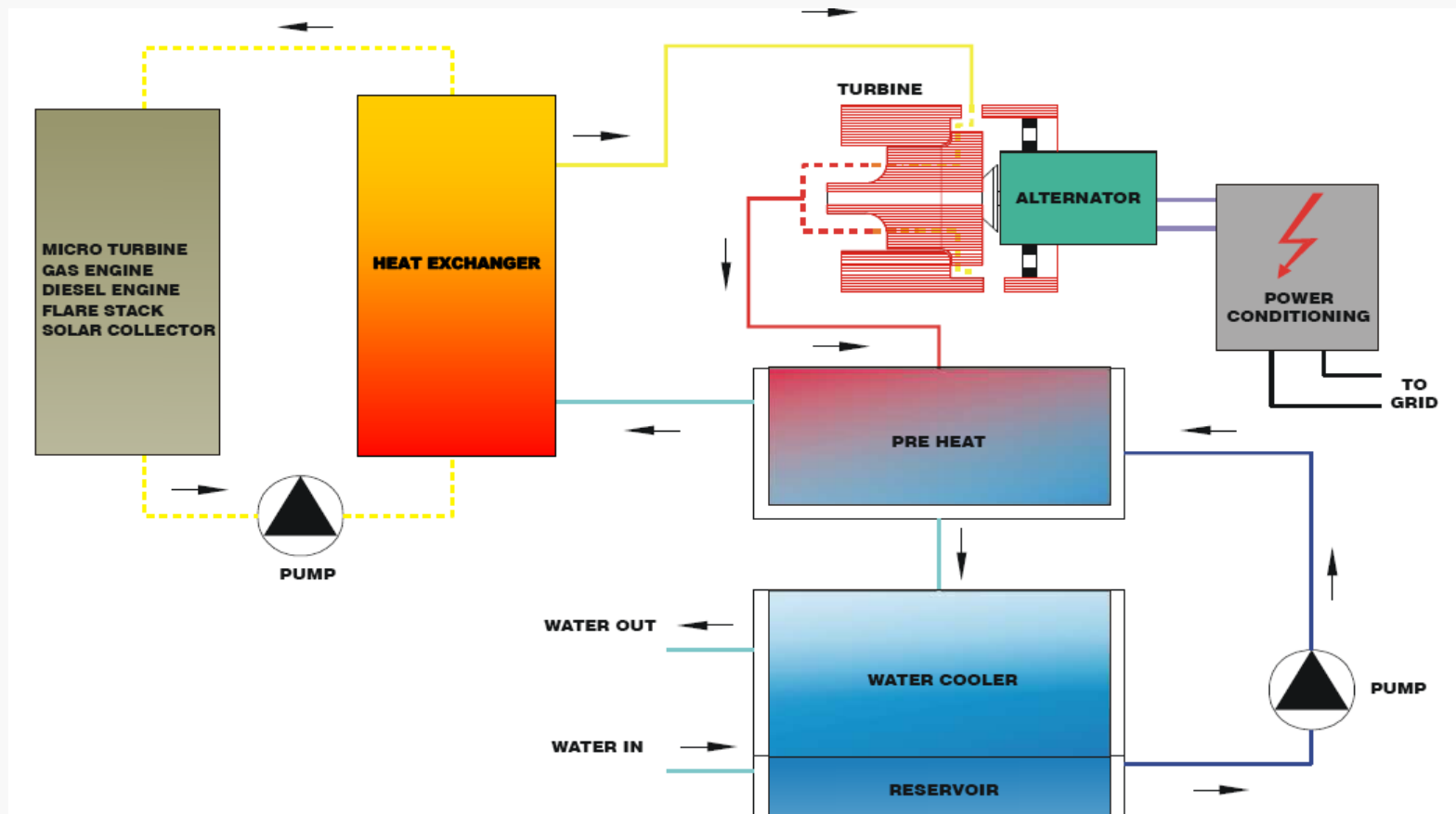


ORC di piccola taglia

- ✓ Recentemente proposti ORC di taglie inferiori a 200 kW

Dimensioni package: 3.9 x 2.2 x 1.3 m

Peso package : 3000 kg



ORC di piccola taglia

- ✓ Recentemente proposti ORC di taglie inferiori a 200 kW



Potenza termica ingresso acqua	kW	542
Potenza elettrica lorda	kW	N/A
Potenza elettrica netta	kW	50
Rendimento elettrico netto	%	9
Temperatura IN	°C	82-121



Slow energy - Green Machine

Potenza termica ingresso fumi	kW	592
Potenza elettrica lorda	kW	N/A
Potenza elettrica netta	kW	50
Rendimento elettrico netto	%	8.4
Temperatura fumi	°C	350

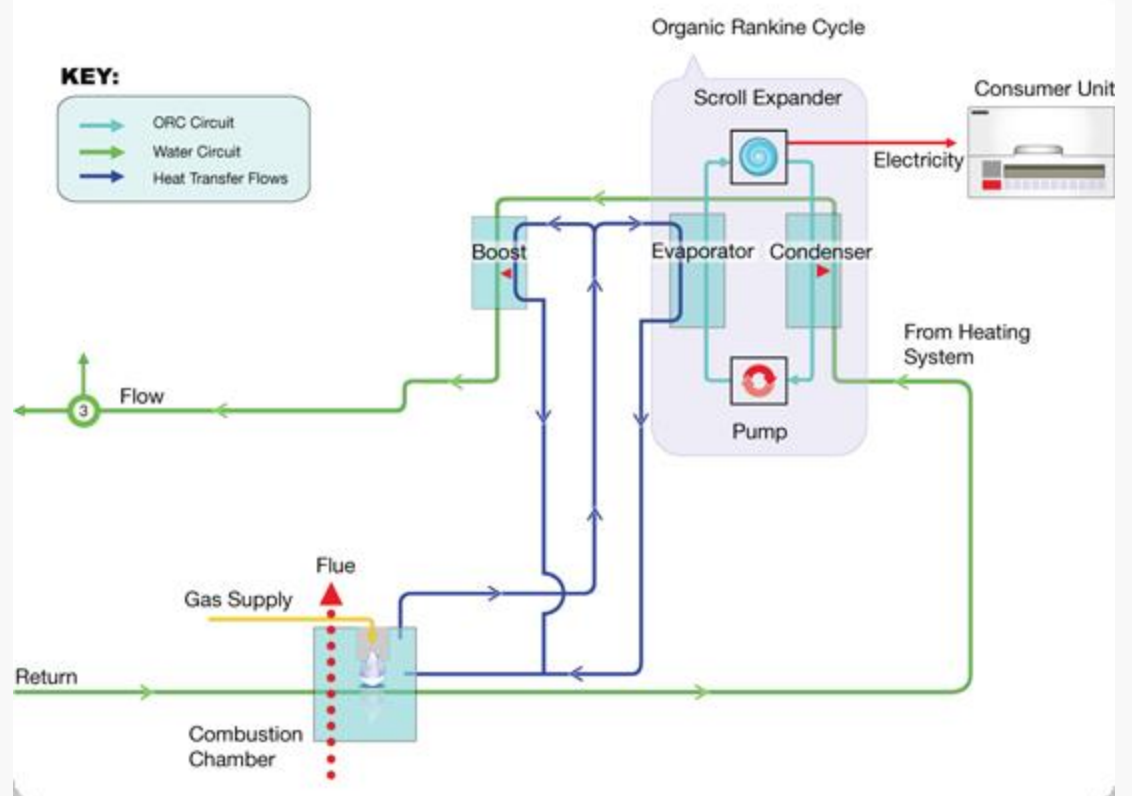
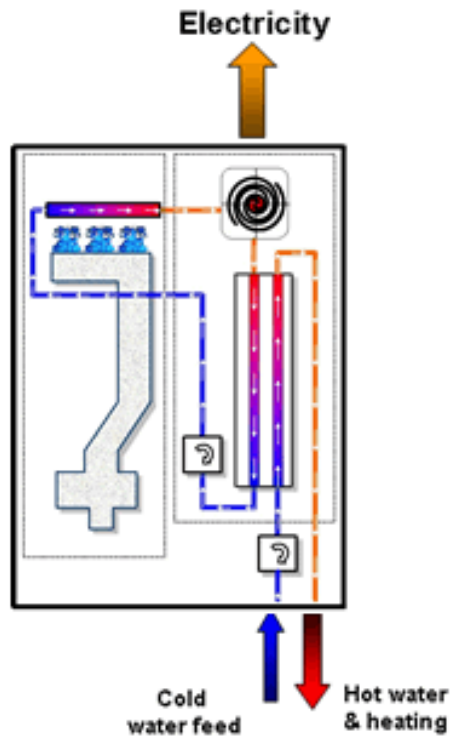
Temperatura fumi: 200 °C – 500 °C



Micro cicli Rankine

Genlec - Energetix (UK)

- ORC
- espansore tipo scroll
- $P_e = 1 \text{ kW}_e$, $P_{th} = 10 \text{ kW}_{th}$



Micro cicli Rankine

Cogen Microsystem (Australia)

- H₂O
- espansore tipo scroll
- $P_e = 2.5 - 10 \text{ kW}_e$
- $P_{th} = 11 - 44 \text{ kW}_{th}$

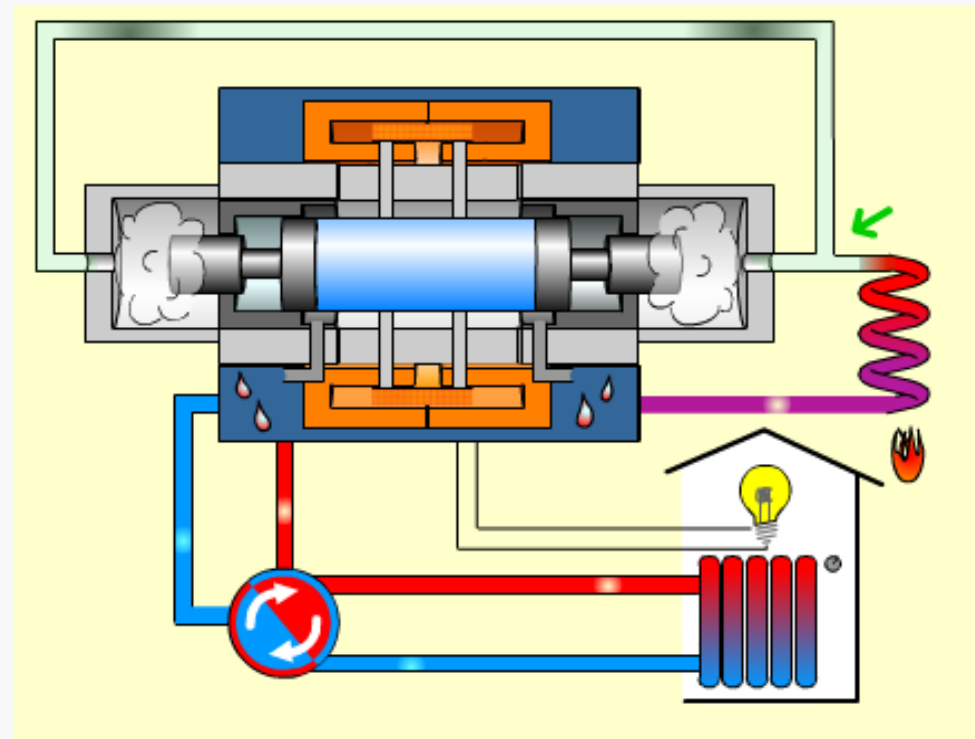


Micro cicli Rankine

Otag (Germania)

- H₂O
- espansore volumetrico
- $P_e = 2.1 \text{ kW}_e$, $P_{th} = 16 \text{ kW}_{th}$
- In commercio dal 2006

www.otag.de



Turbogas



Diagramma termodinamico {h,s} dell'aria

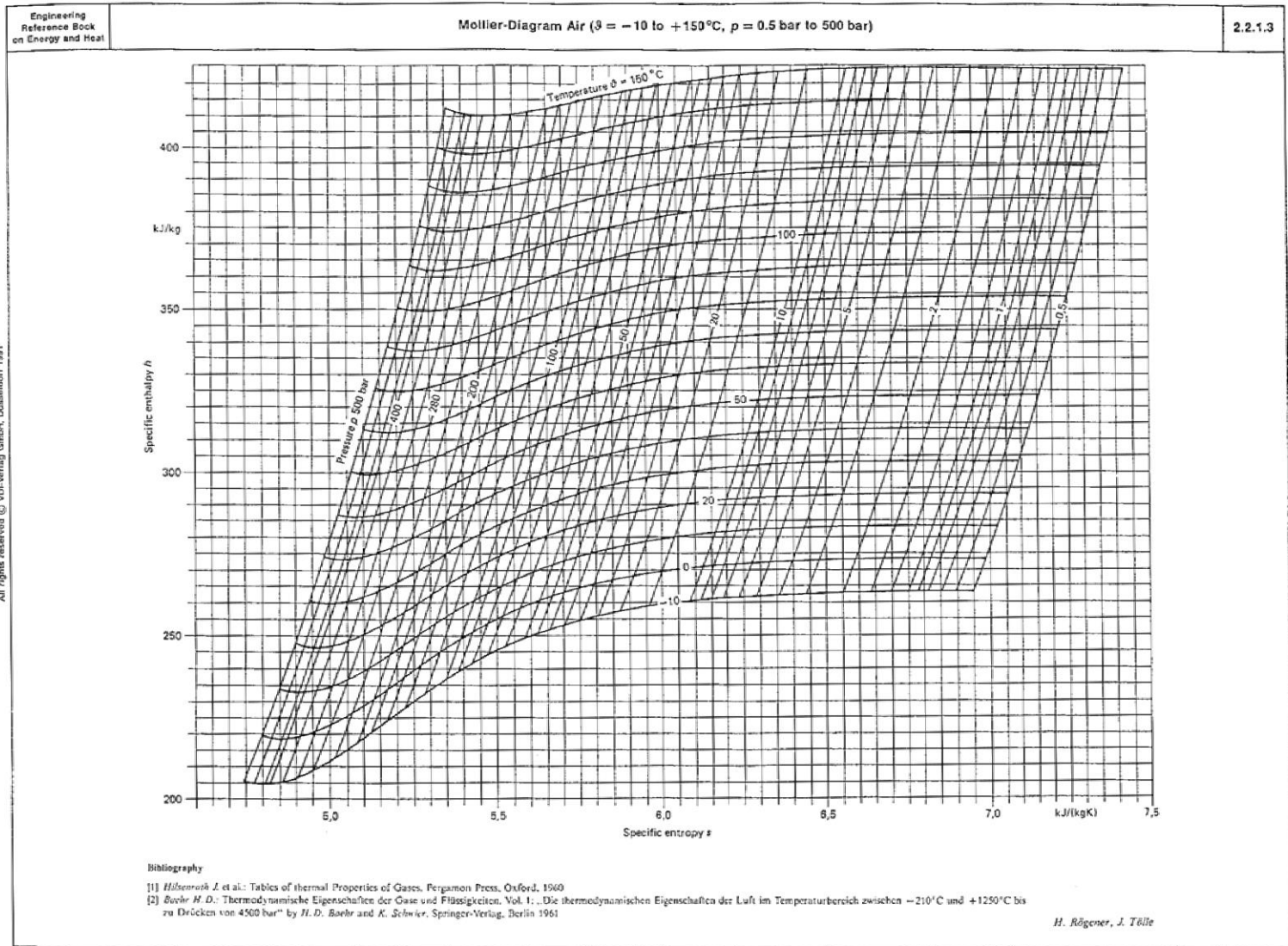
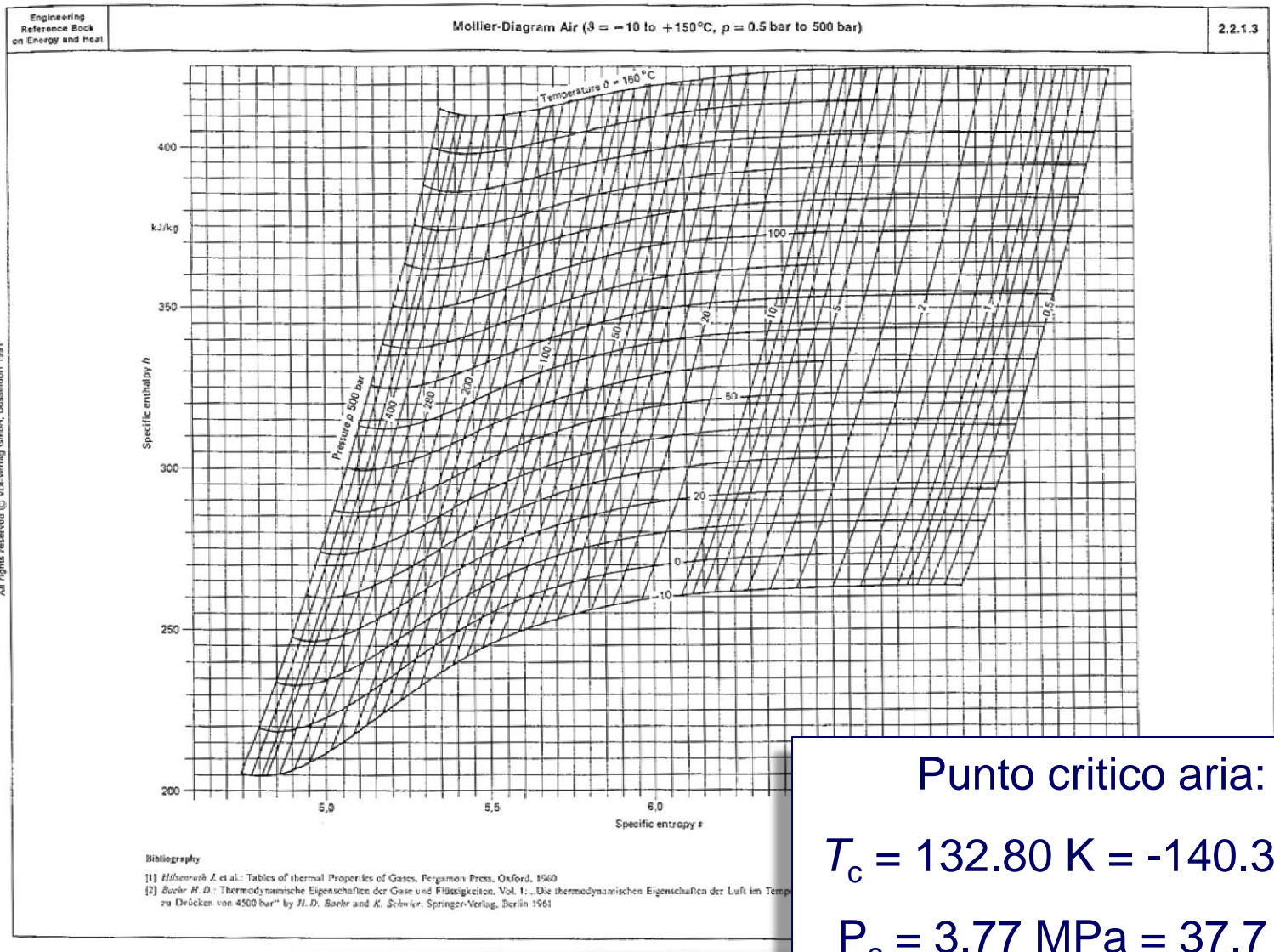


Diagramma termodinamico {h,s} dell'aria



Punto critico aria:

$$T_c = 132.80 \text{ K} = -140.35 \text{ }^\circ\text{C}$$

$$P_c = 3.77 \text{ MPa} = 37.7 \text{ bar}$$

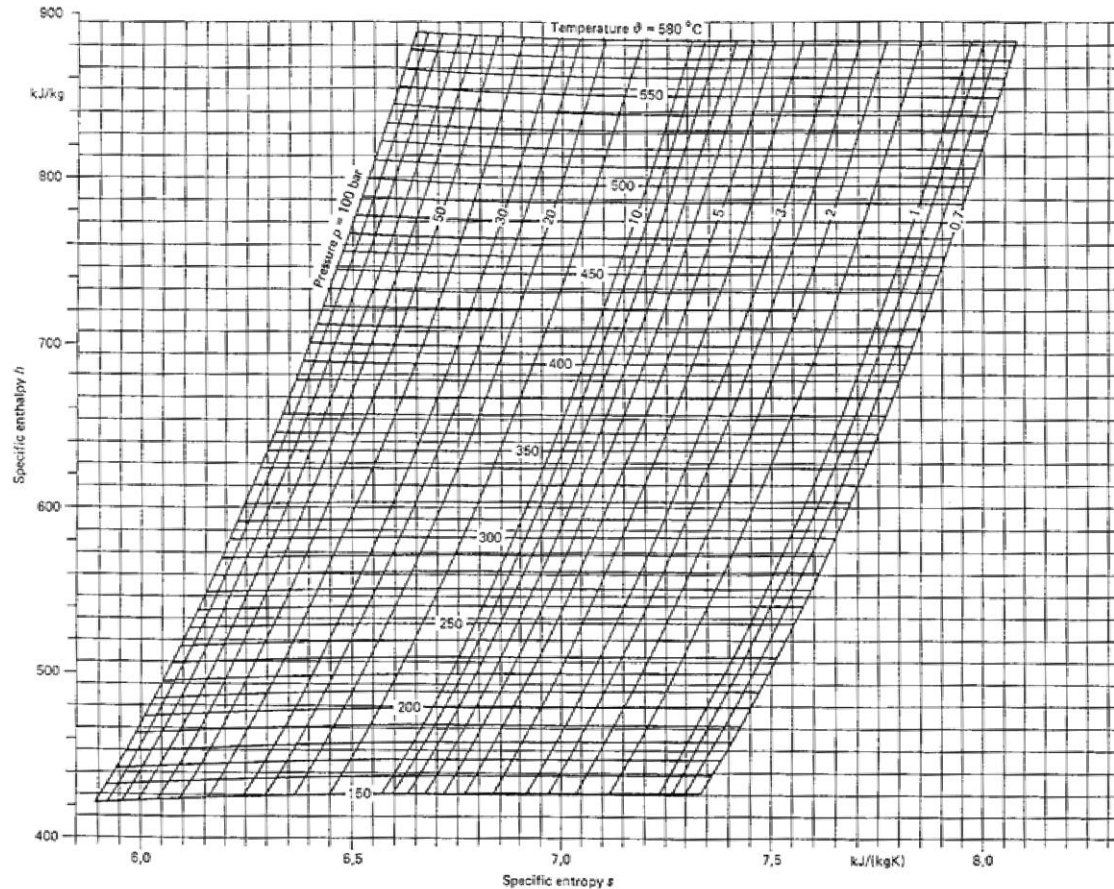


Diagramma termodinamico {h,s} dell'aria

Engineering
Reference Book
on Energy and Heat

Mollier-Diagram Air ($\vartheta = 150$ to 580°C , $p = 0.7$ bar to 100 bar)

2.2.1.2



Bibliography

- [1] Hilsenrath J. et al.: Tables of thermal Properties of Gases, Pergamon Press, Oxford, 1960
- [2] Beehr H. D.: Thermodynamische Eigenschaften der Gase und Flüssigkeiten. Vol. 1: „Die thermodynamischen Eigenschaften der Luft im Temperaturbereich zwischen -210°C und $+1250^\circ\text{C}$ bis zu Drücken von 4500 bar“ by H. D. Beehr and K. Schwiier, Springer-Verlag, Berlin 1961

H. Rögner, J. Töfle

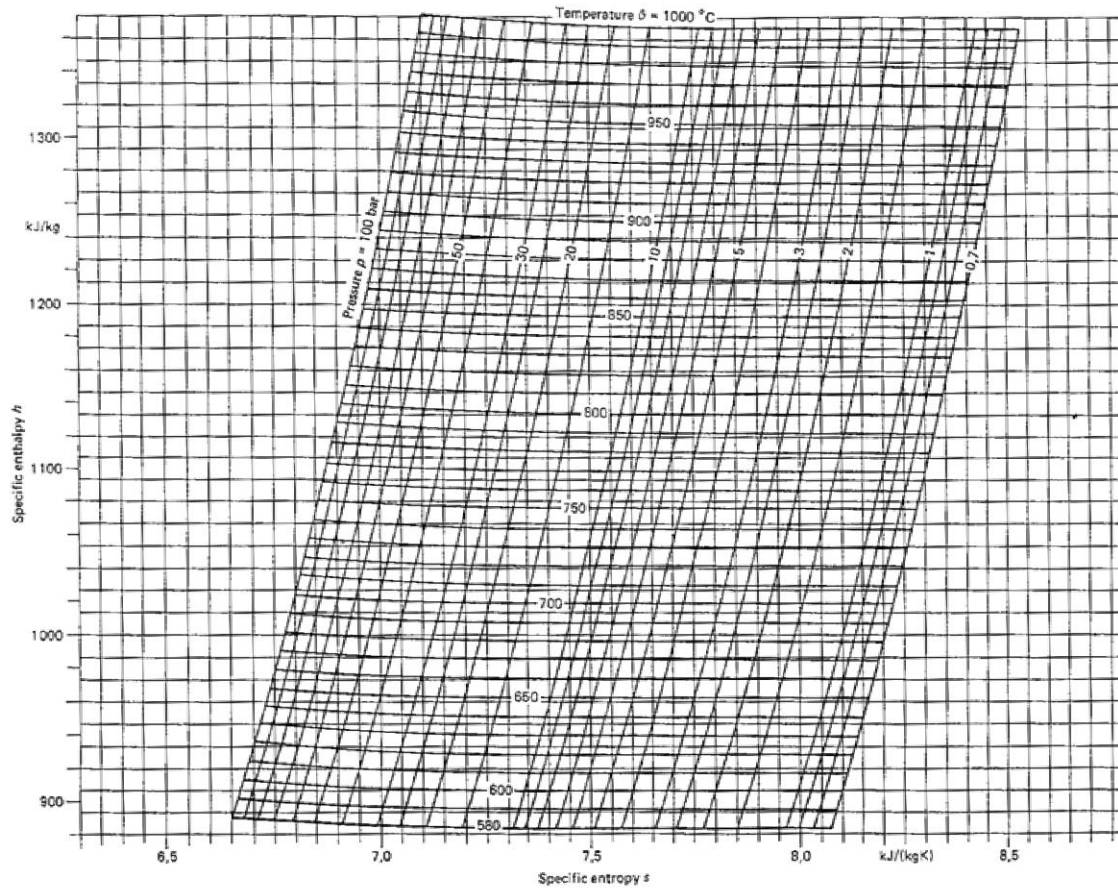


Diagramma termodinamico {h,s} dell'aria

Engineering
Reference Book
on Energy and Heat

Mollier-Diagram Air ($\beta = 580$ to 1000 °C, $p = 0.7$ bar to 100 bar)

2.2.1.1



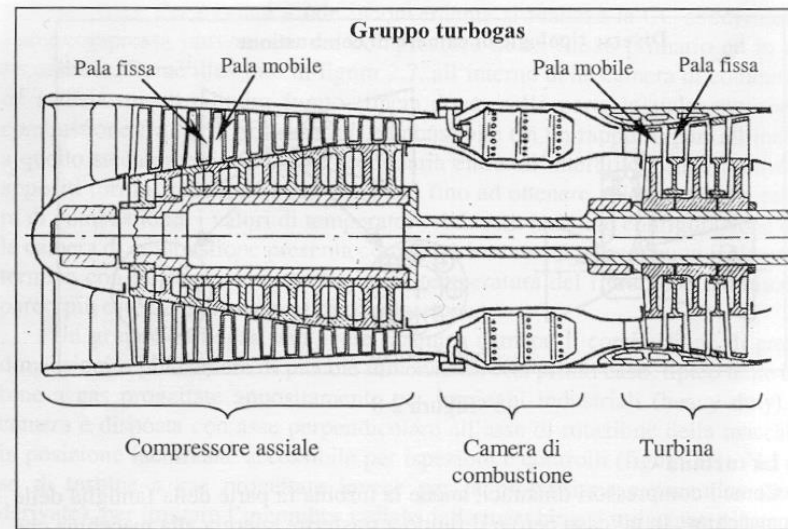
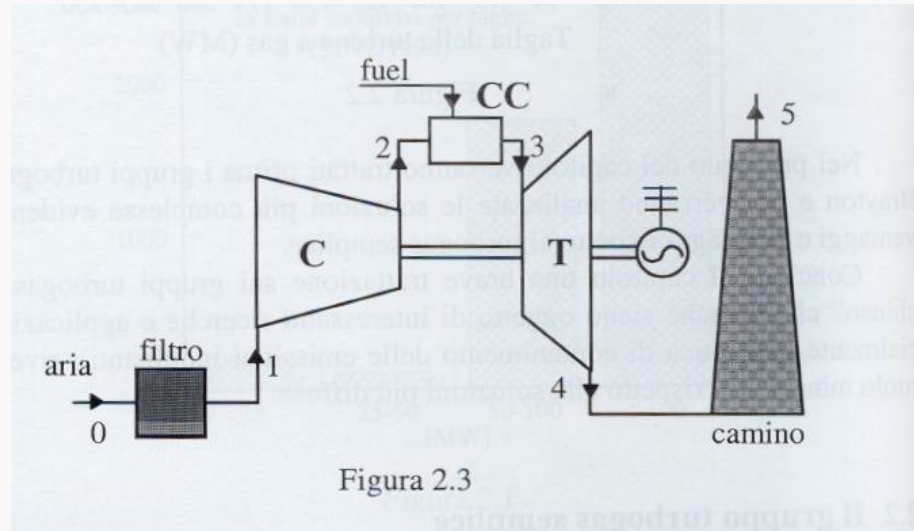
Bibliography

- [1] Hilsenrath J. et al.: Tables of thermal Properties of Gases, Pergamon Press, Oxford, 1960
- [2] Baer H. D.: Thermodynamische Eigenschaften der Gase und Flüssigkeiten. Vol. 1: „Die thermodynamischen Eigenschaften der Luft im Temperaturbereich zwischen -210 °C und $+1250$ °C bis zu Drücken von 4500 bar“ by H. D. Baer and K. Schrier, Springer-Verlag, Berlin 1961

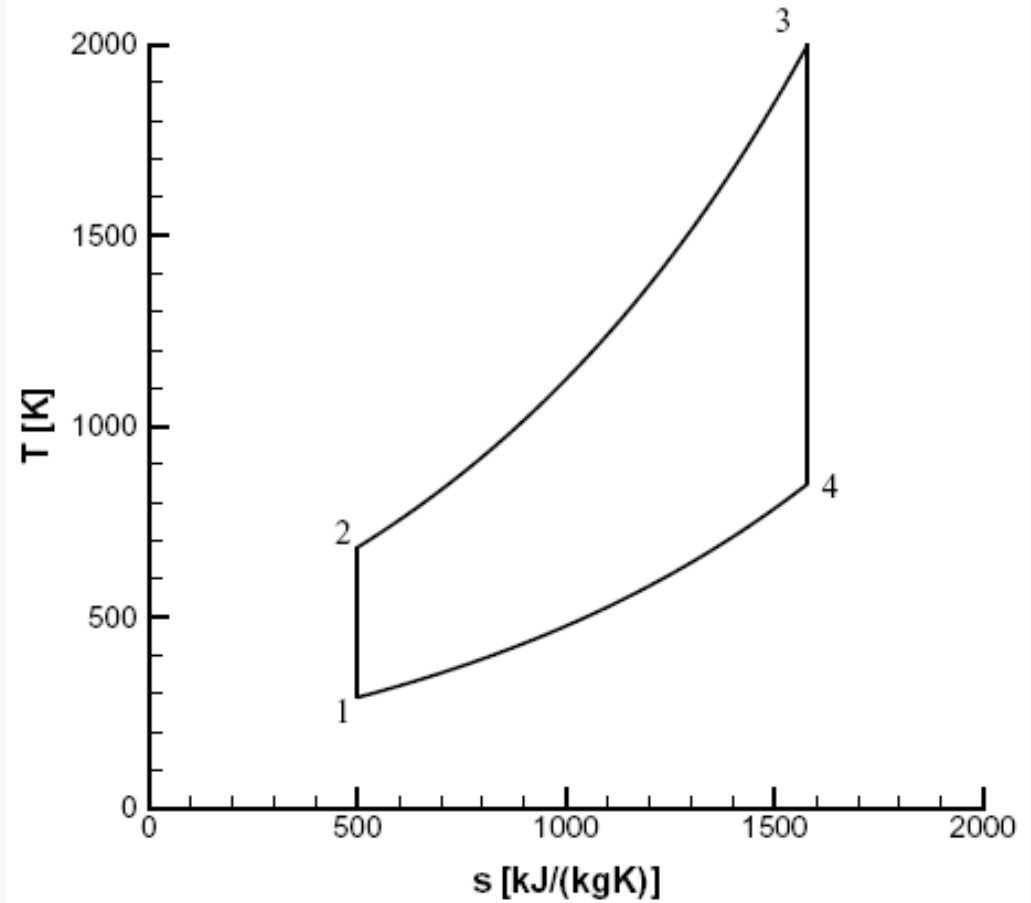
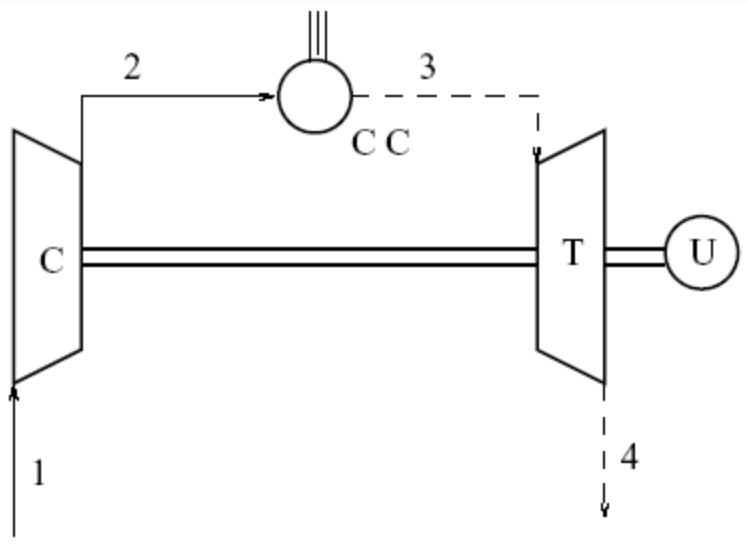
H. Rögner, J. Tülle



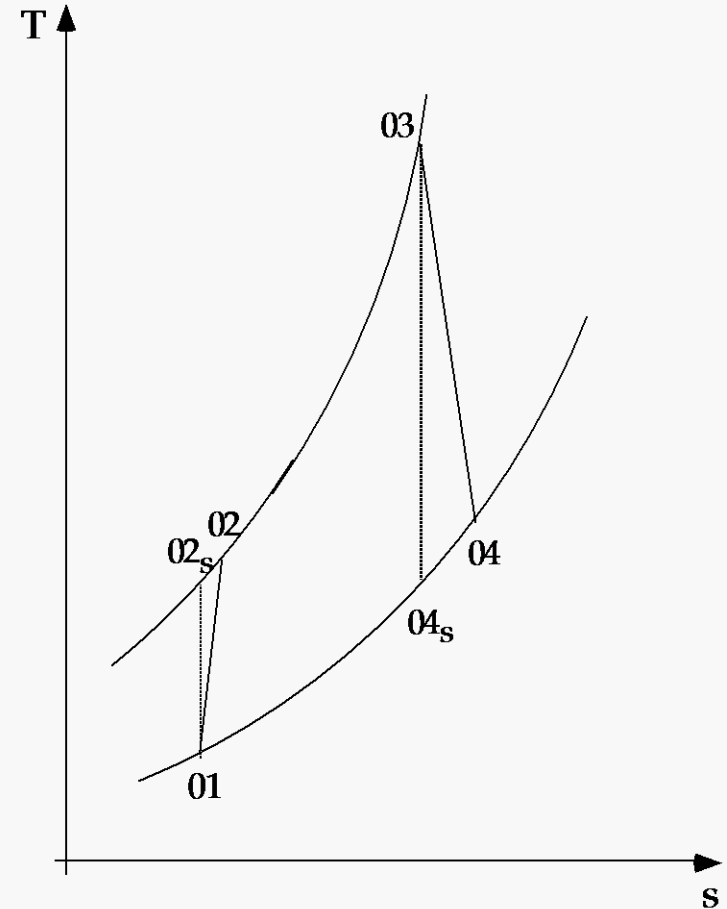
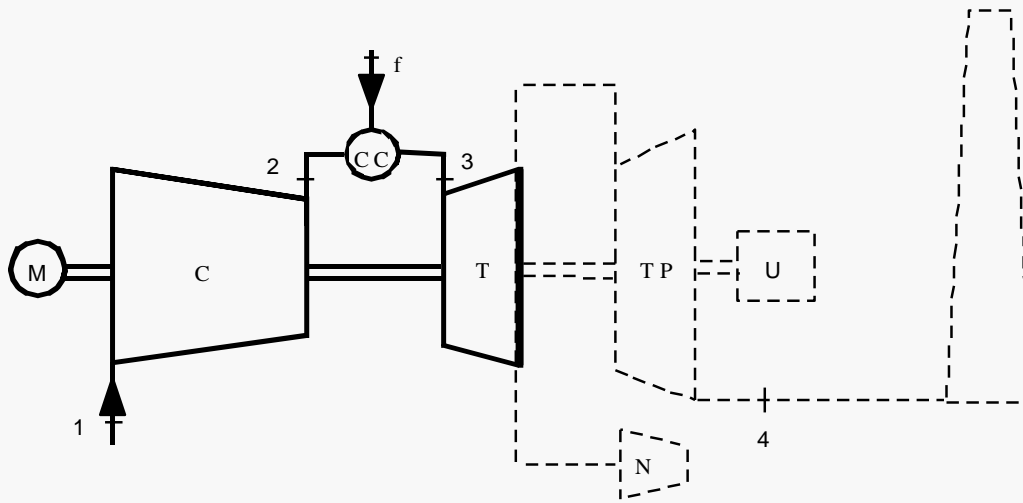
Schema di una turbina a gas



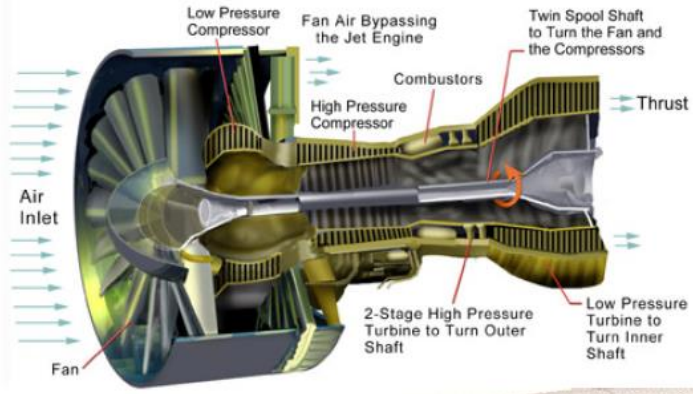
Ciclo turbogas semplice ideale



Ciclo turbogas semplice reale

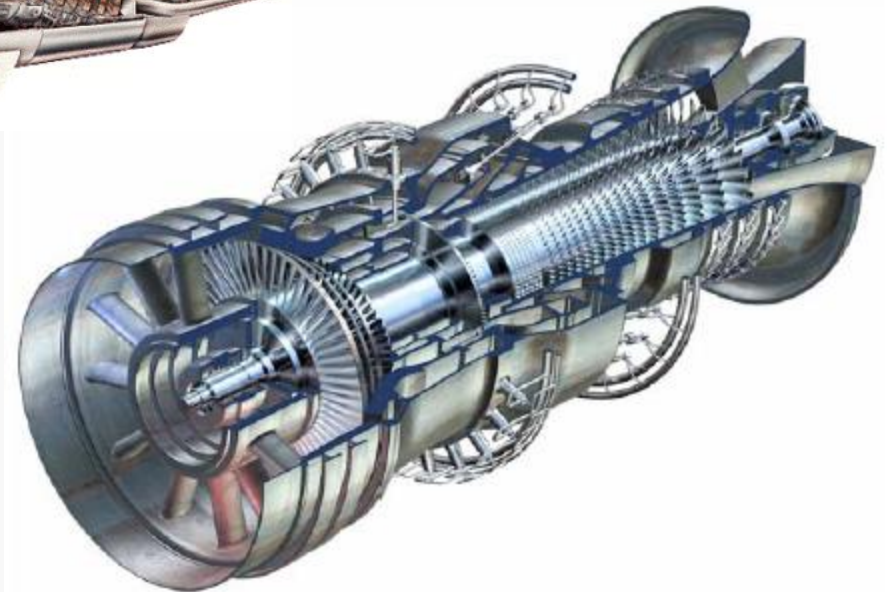
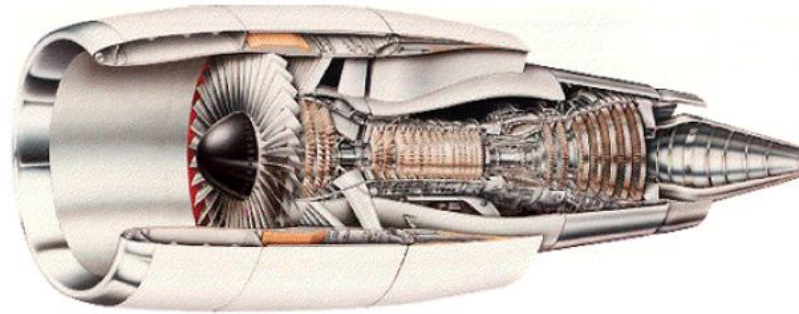


Immagini di turbine a gas reali



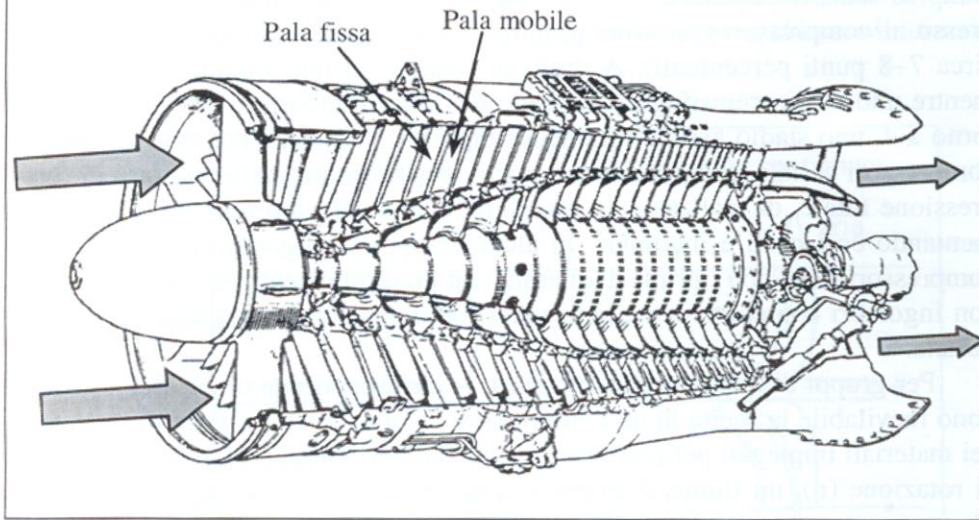
High by-pass ratio

Low by-pass ratio

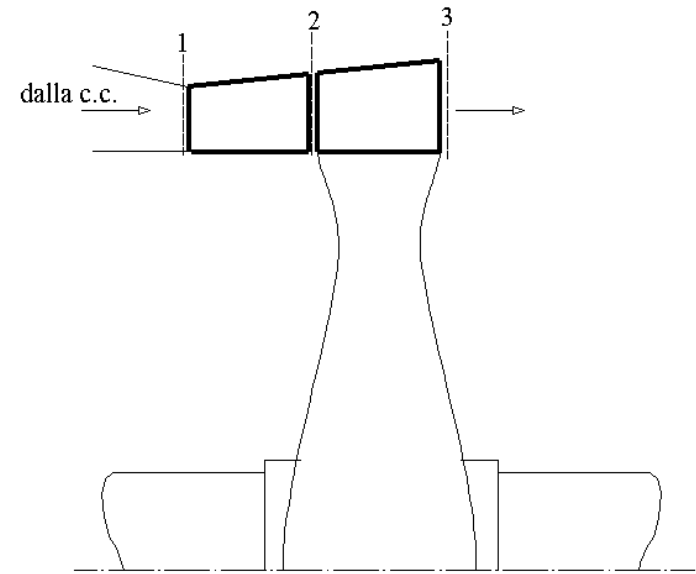
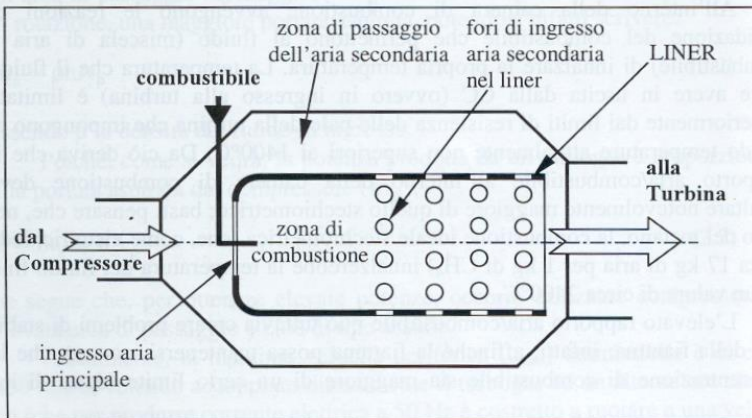
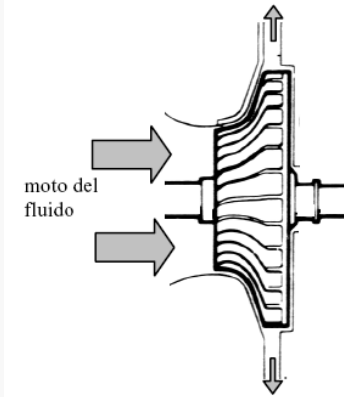


Componenti delle turbine a gas

Compressore assiale

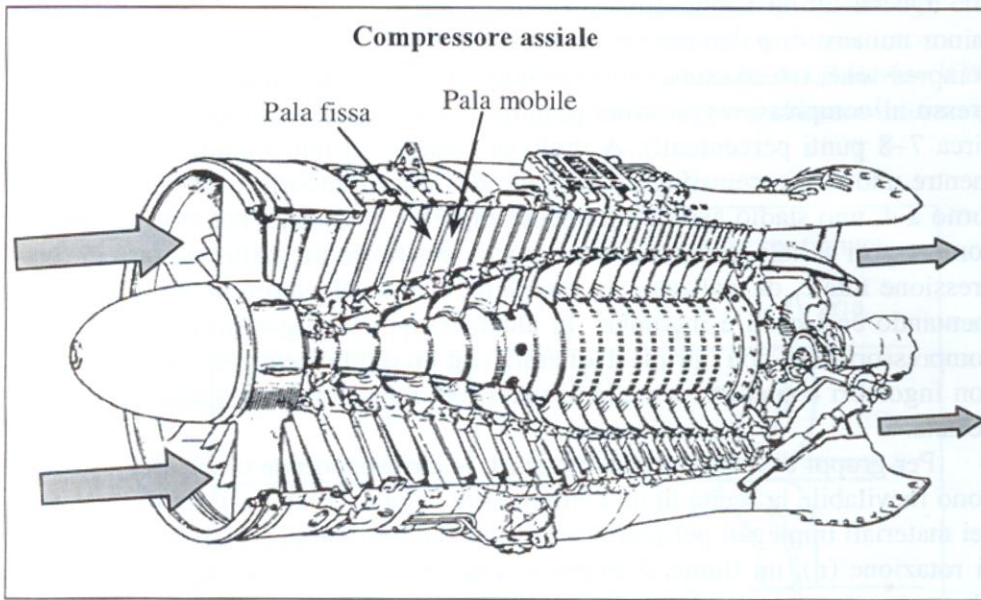


Compressore centrifugo

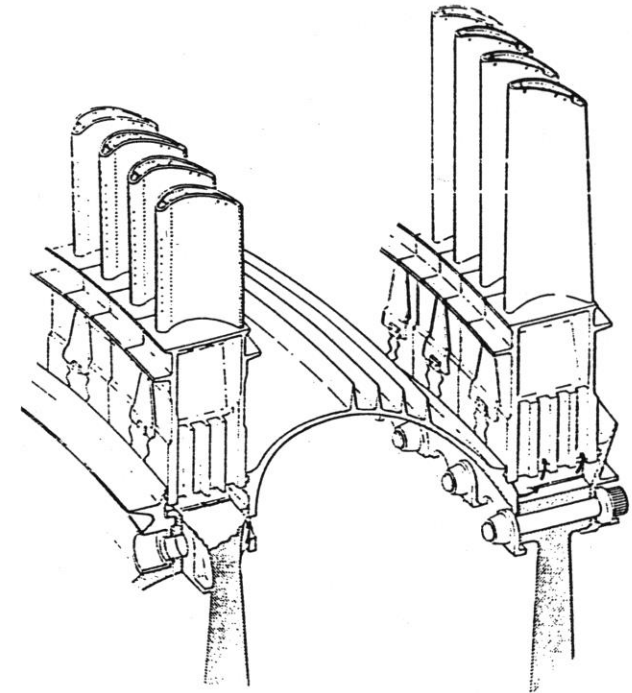
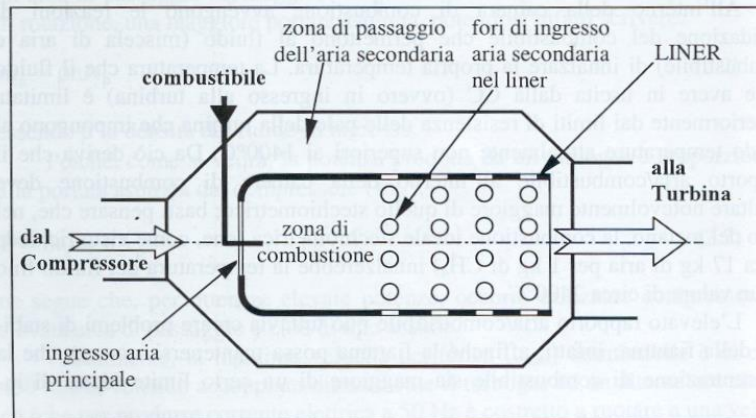
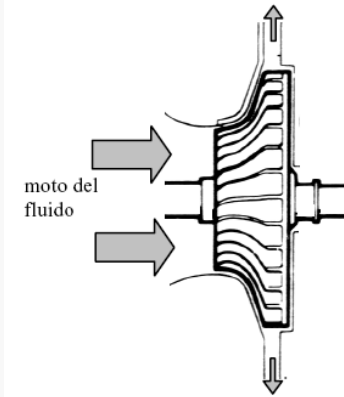


Componenti delle turbine a gas

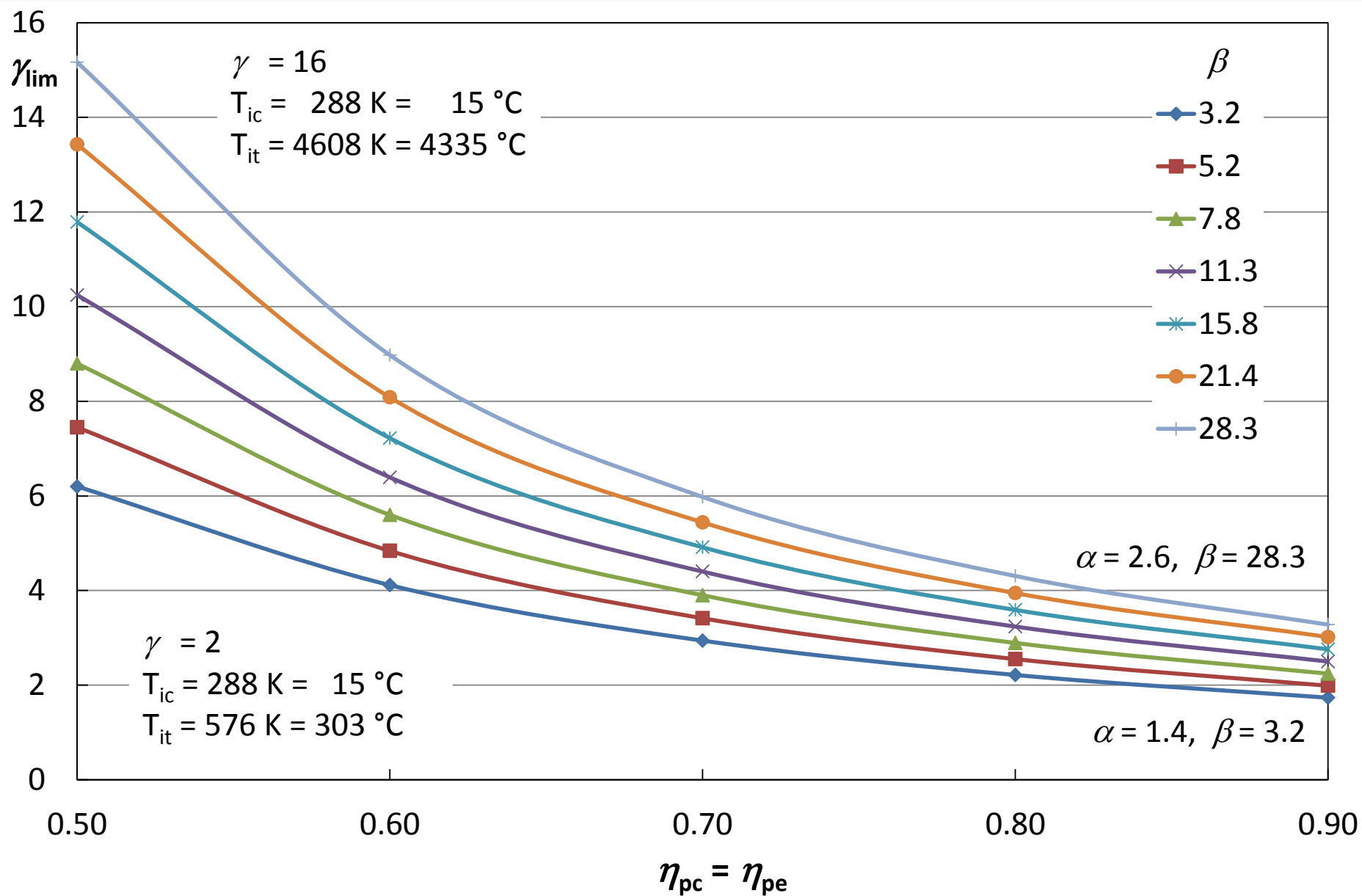
Compressore assiale



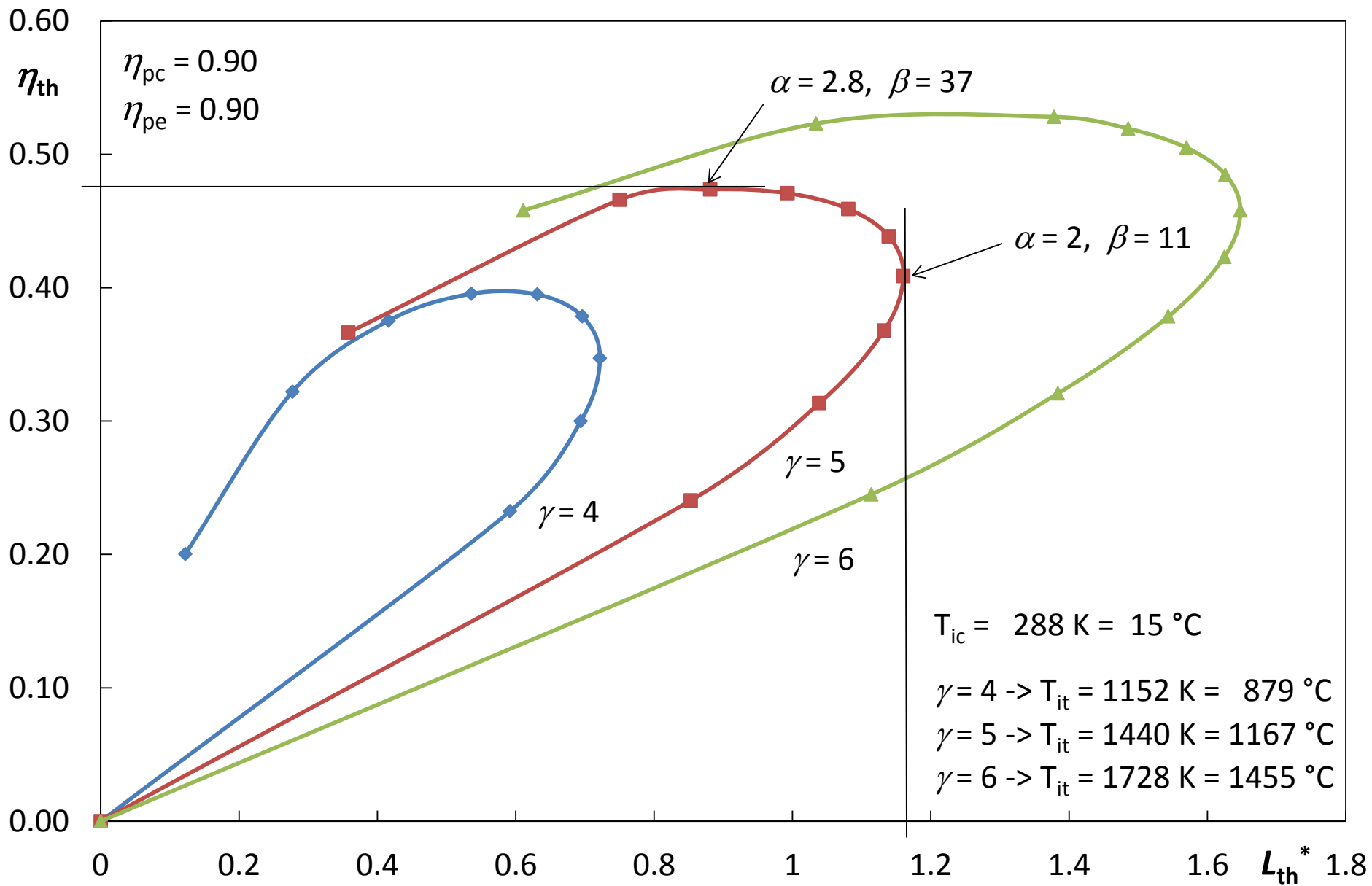
Compressore centrifugo



Ciclo turbogas semplice reale - γ_{lim} per l'autosufficienza



Ciclo turbogas semplice reale - $\eta_{th} \equiv f(L_{th})$



Prestazione del ciclo semplice

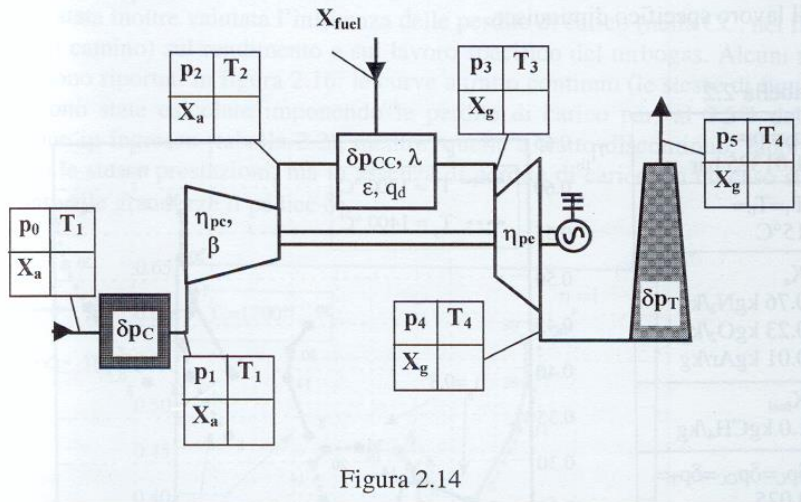
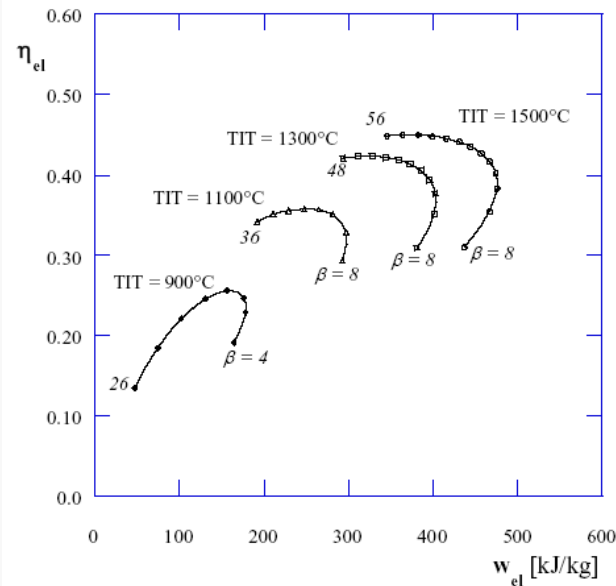
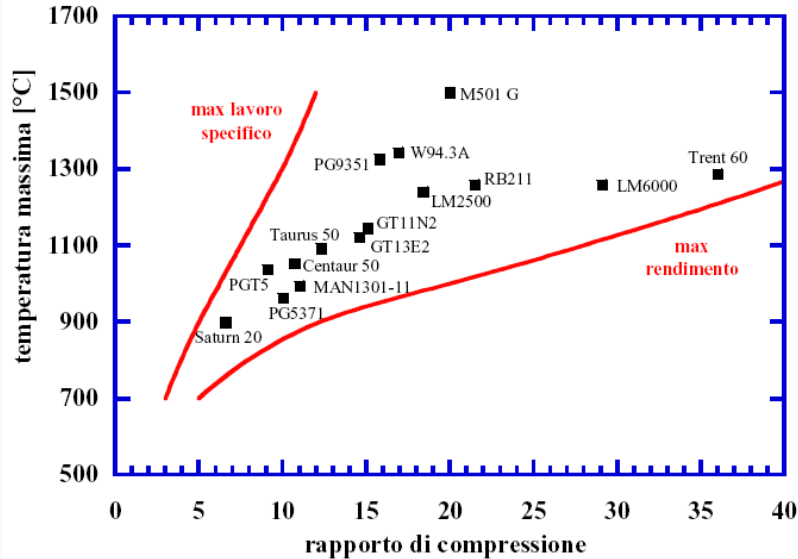
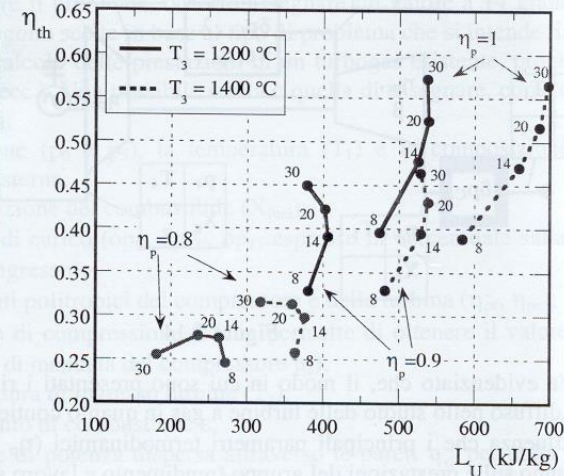


Tabella 2.2

$p_0 = p_5 =$ 1.01325 bar
$T_1 = T_0 =$ 15°C
X_a 0.76 kgN ₂ /kg 0.23 kgO ₂ /kg 0.01 kgAr/kg
X_{fuel} 1.0 kgCH ₄ /kg
$\delta p_c = \delta p_{cc} = \delta p_T =$ 0.025
$q_a = 0$ e quindi $\eta_{cc} = \epsilon = 0.99$



Temperatura massima di una turbina a gas

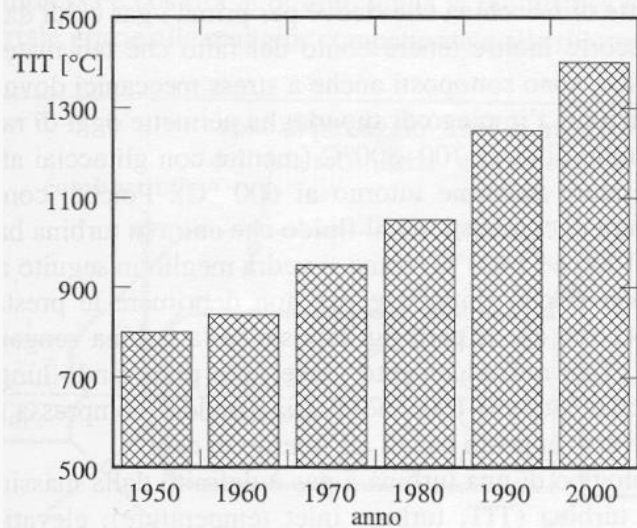
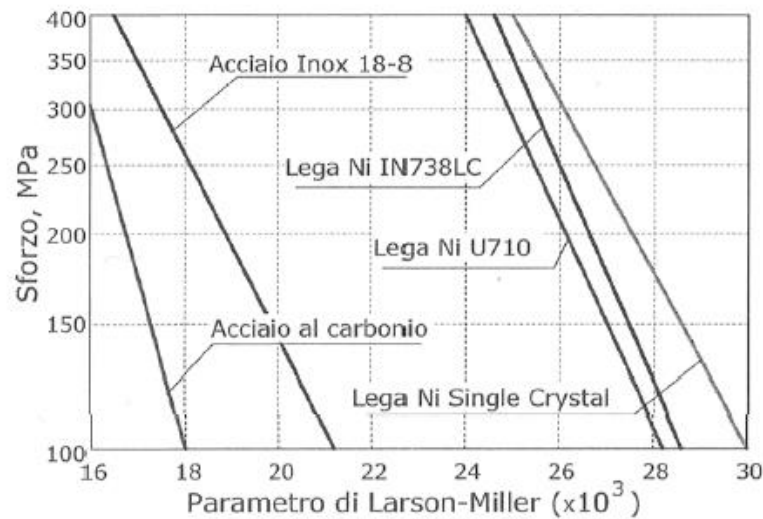
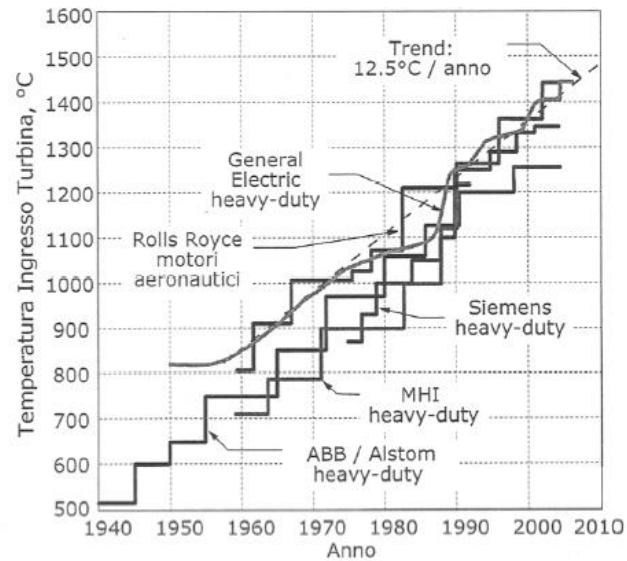
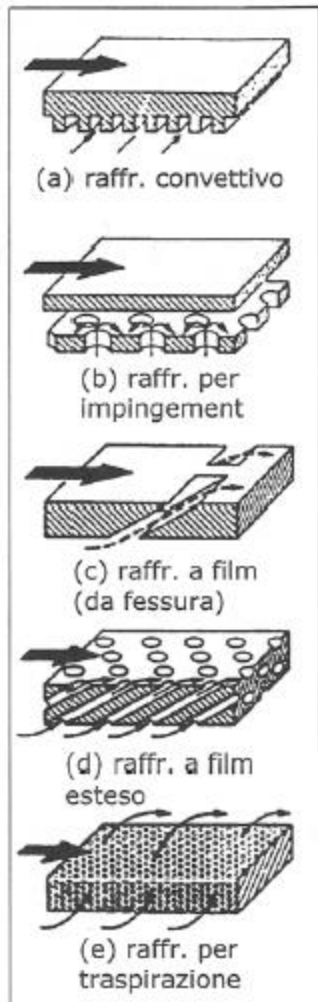


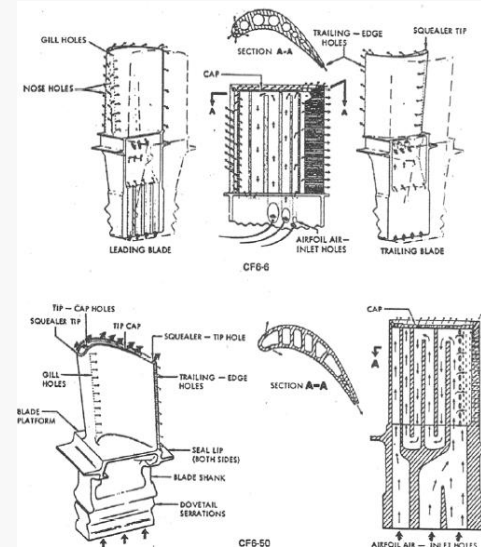
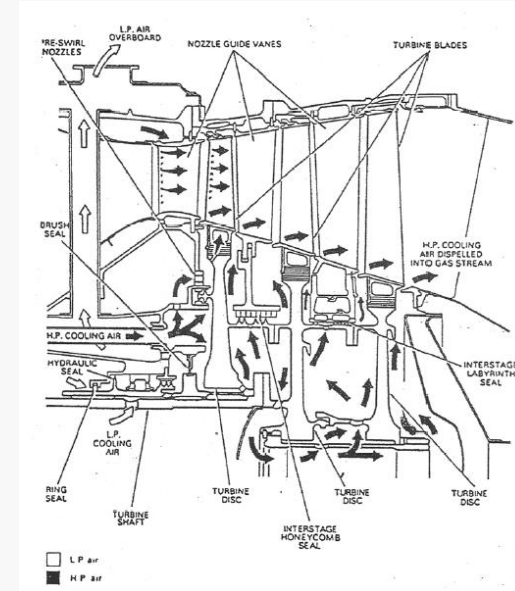
Figura 2.10



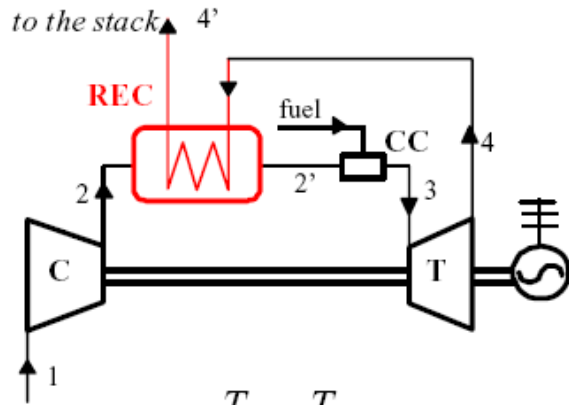
Raffreddamento delle pale della turbina



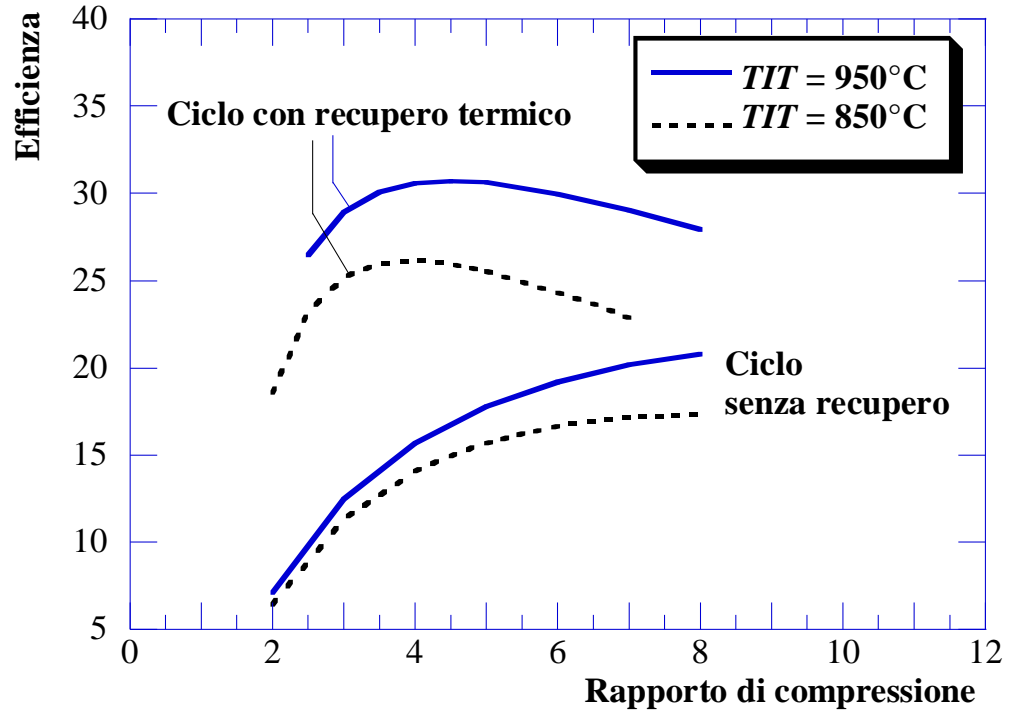
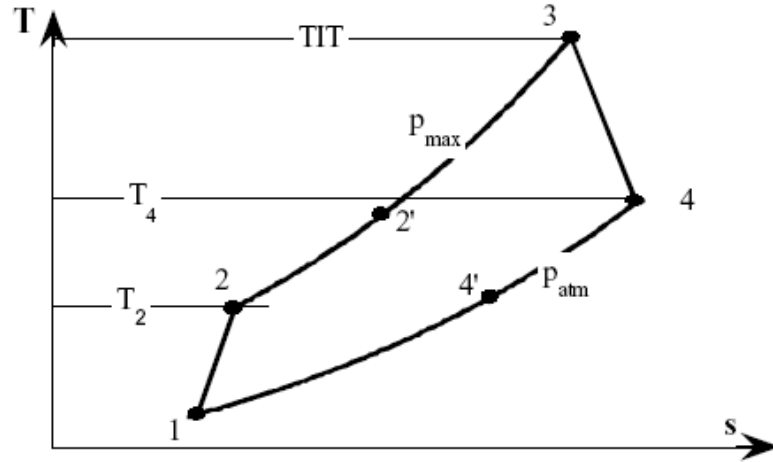
	Palettatura refrigerata a convezione interna e film
	Ugello primo stadio con raffreddamento a convezione interna, impingement e film
	Ugello primo stadio con raffreddamento a convezione interna, impingement e film
	Pala primo stadio rotorio con raffreddamento a convezione interna (con canali multipassaggio e turbolenziatori) e film



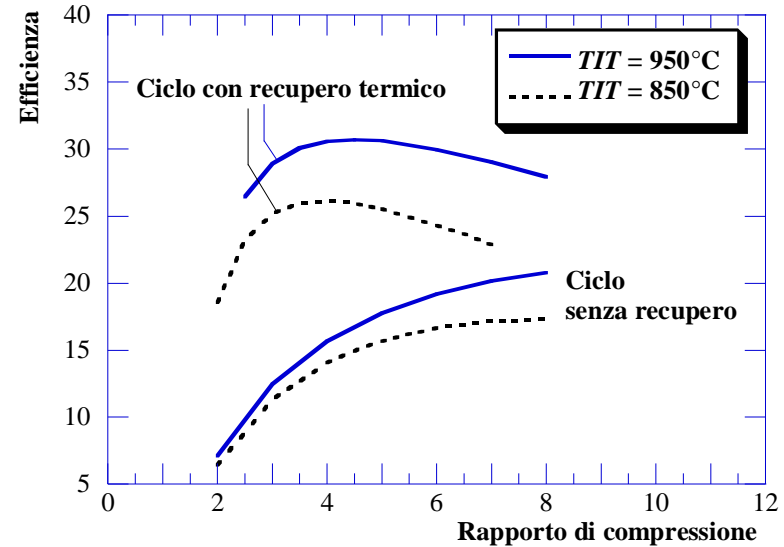
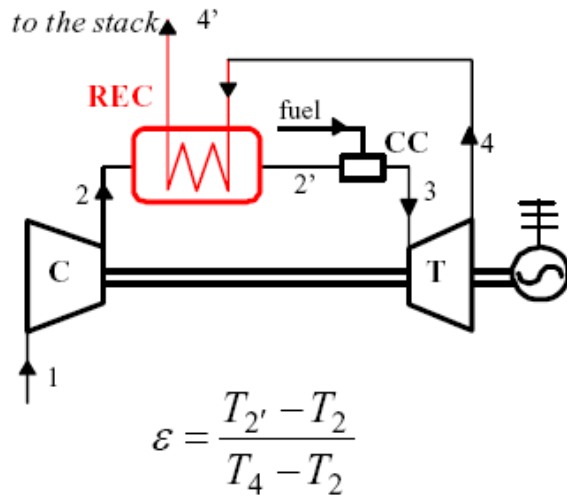
Cicli complessi – rigenerazione (R)



$$\varepsilon = \frac{T_{2'} - T_2}{T_4 - T_2}$$



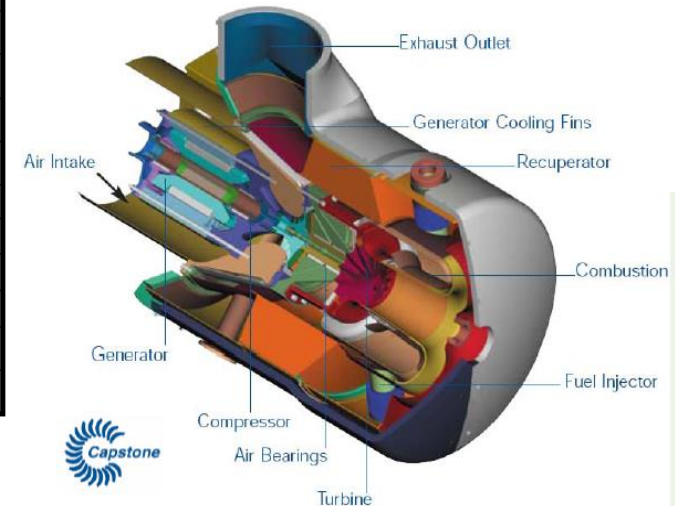
Cicli complessi – rigenerazione (R)



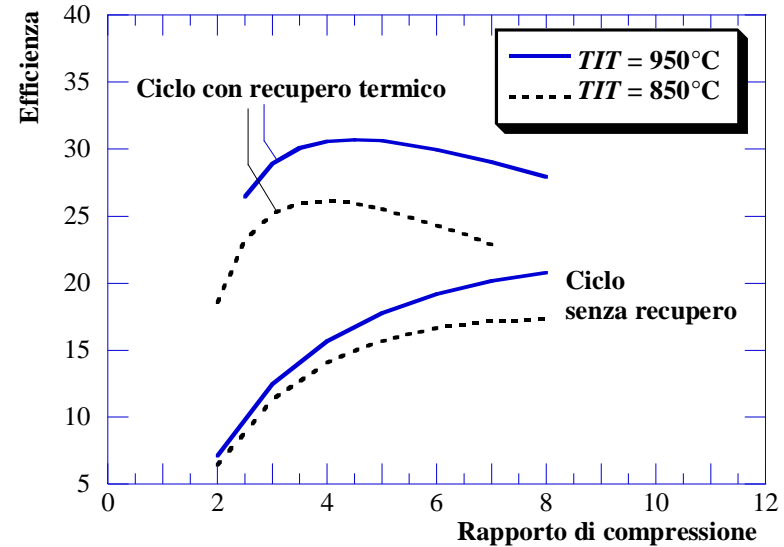
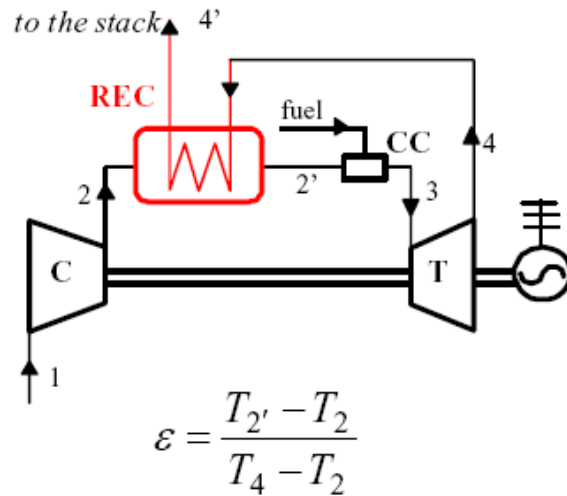
manufacturer	model	year	shafts	Power [kW]	Eff. (%)	HR [Btu/kWh]	PR	TIT [°C]	exit T [°C]	m _{air} [kg/s]	comment
GE	MS3002R / M3142R (J)	1952	2	10832	34.4	9905	7.3	960	370	53	mech.drive retired ?
GE	M5322R (B)	1972	2	23872	36.0	9478	8.2	960	352	114	mech.drive retired ?
GE	MS5002R / M5352R (C)	1987	2	26558	36.4	9374	8.7	960	367	121	mech.drive
MAN Turbo AG	THM 1203 R	1979	2	5130	31.4	10877	7.6	910	-	35.2	
MAN Turbo AG	THM 1304-10 R	1980	2	9030	34.8	9791	10	975	-	44.9	
Capston	C30	1998	1	30	26	13100	4	850	275	0.31	MTG
Capston	C60	2000	1	60	28	12200	4	850	305	0.49	MTG
Turbec	T100	2000	1	105	30	-	4.5	900	-	0.8	MTG, CHP
Kawasaki	S7A-01	2001	1	677	24.2	14077	7.6	-	476	4	CHP
SOLAR	Mercury 50	1998	1	4200	38.5	8863	9	1163	516	18.8	retired 2000, reintroduced
PRATT & WHITNEY	ST5 R	2002	2	395	32.7	10435	8.1	-	365	2.22	from helic. engine

- Piccole taglie (MTG & 10-25 MW)
- Rendimenti fino 38,5%
- PR ridotti: 4-10
- TIT limitate, MTG non raffreddate

Capston C60



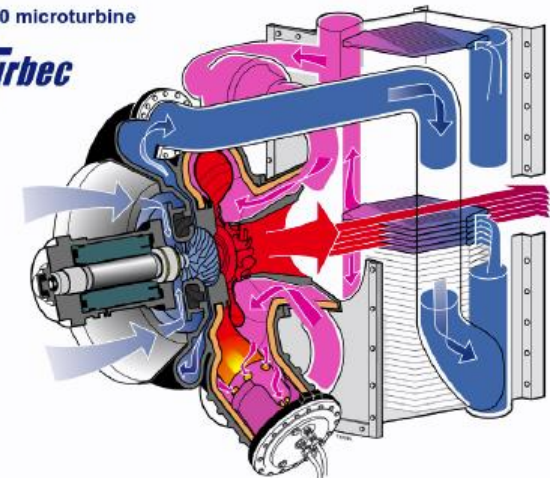
Cicli complessi – rigenerazione (R)



manufacturer	model	year	shafts	Power [kW]	Eff. (%)	HR [Btu/kWh]	PR	TIT [°C]	exit T [°C]	m _{air} [kg/s]	comment
GE	MS3002R / M3142R (J)	1952	2	10832	34.4	9905	7.3	960	370	53	mech.drive retired ?
GE	M5322R (B)	1972	2	23872	36.0	9478	8.2	960	352	114	mech.drive retired ?
GE	MS5002R / M5352R (C)	1987	2	26558	36.4	9374	8.7	960	367	121	mech.drive
MAN Turbo AG	THM 1203 R	1979	2	5130	31.4	10877	7.6	910	-	35.2	
MAN Turbo AG	THM 1304-10 R	1980	2	9030	34.8	9791	10	975	-	44.9	
Capston	C30	1998	1	30	26	13100	4	850	275	0.31	MTG
Capston	C60	2000	1	60	28	12200	4	850	305	0.49	MTG
Turbec	T100	2000	1	105	30	-	4.5	900	-	0.8	MTG, CHP
Kawasaki	S7A-01	2001	1	677	24.2	14077	7.6	-	476	4	CHP
SOLAR	Mercury 50	1998	1	4200	38.5	8863	9	1163	516	18.8	retired 2000, reintroduced
PRATT & WHITNEY	ST5 R	2002	2	395	32.7	10435	8.1	-	365	2.22	from helic. engine

T100 microturbine

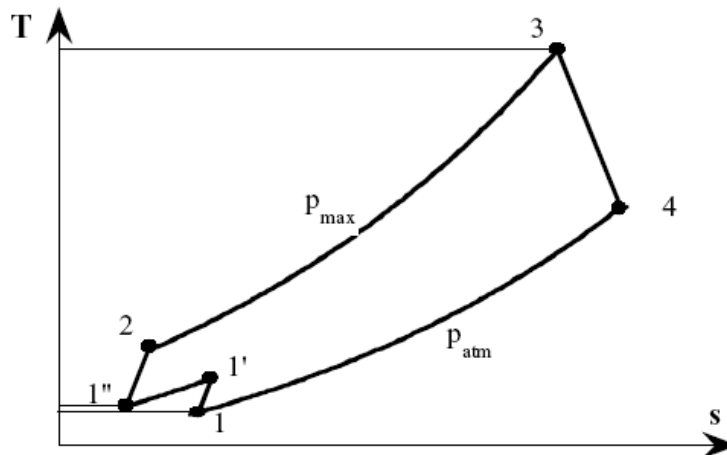
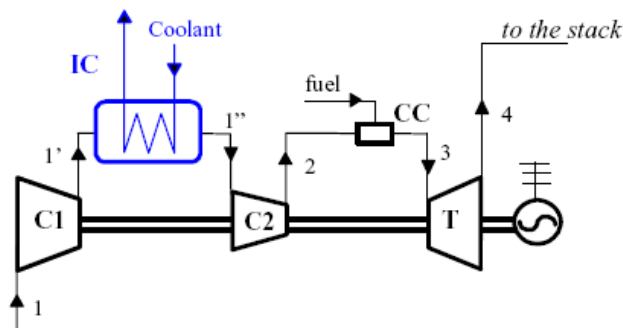
turbec



- Piccole taglie (MTG & 10-25 MW)
- Rendimenti fino 38,5%
- PR ridotti: 4-10
- TIT limitate, MTG non raffreddate



Cicli complessi – compressione interrefrigerata (IC)



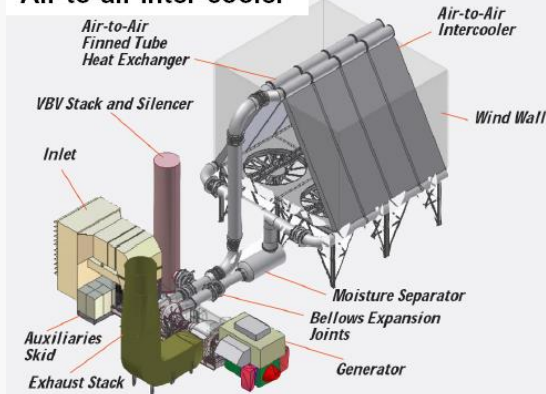
Parametri chiave:

- ✓ PR intermedio e totale (β_1, β)
- ✓ Temperatura di interrefrigerazione ($T_{1''}$)
- ✓ Temperatura fluido refrigerante (T_{cool})

Rolls-Royce WR-21 (ICR)

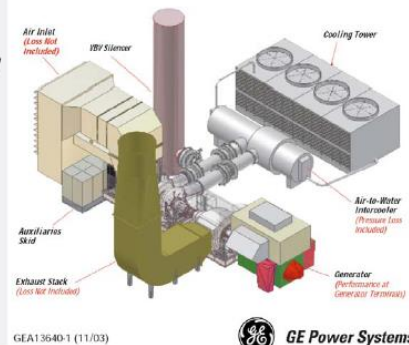


Air-to-air inter-cooler



- ✓ dimensioni
- ✓ consumi energetici

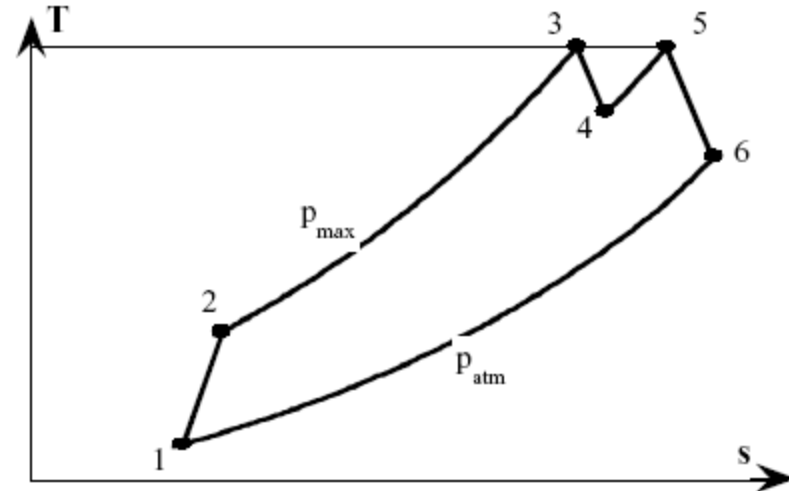
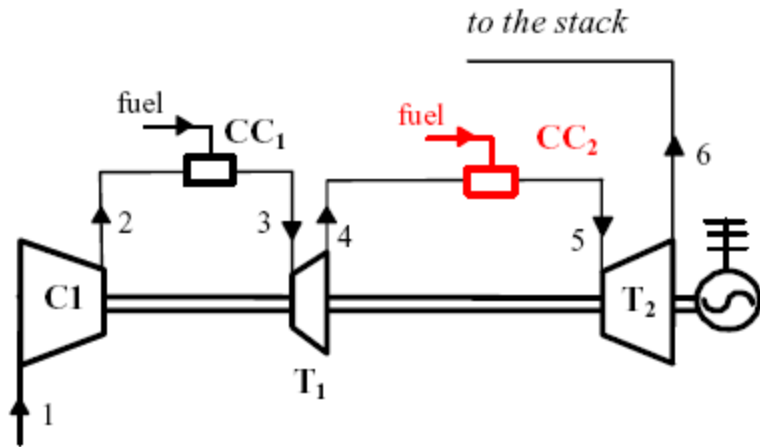
water-to-air inter-cooler



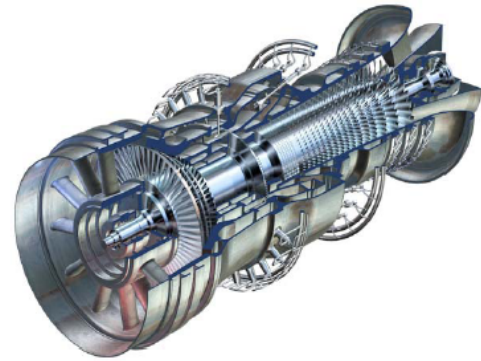
- ✓ Richiede disponibilità di acqua



Cicli turbogas complessi – espansione interriscaldata (RH)



ALSTOM GT24-26 (RH)

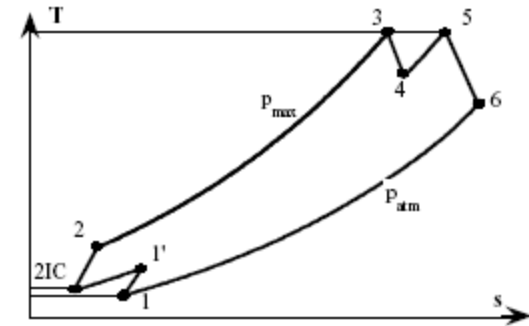
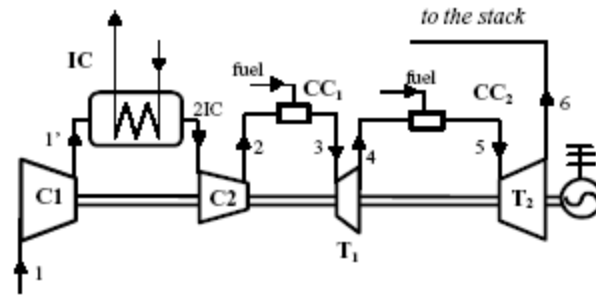


		GT24	GT26
Power output	MW	171	263
LHV efficiency	%	37.5	38.2
Shaft speed	rpm	3600	3000
Compressor pressure ratio	-	32	32
Discharge temperature	°C	615	615
Exit gas mass flow	kg/s	410	600
NOx Emission	ppmvd (15%O ₂)	<25	<25
CO Emission	ppmvd (15%O ₂)	<10	<10

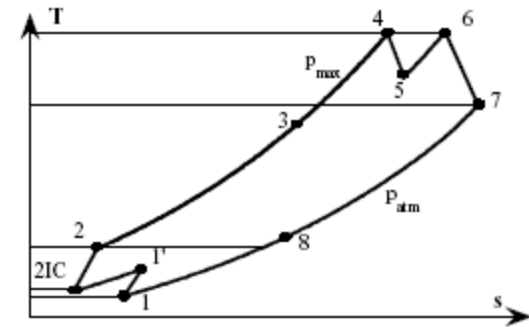
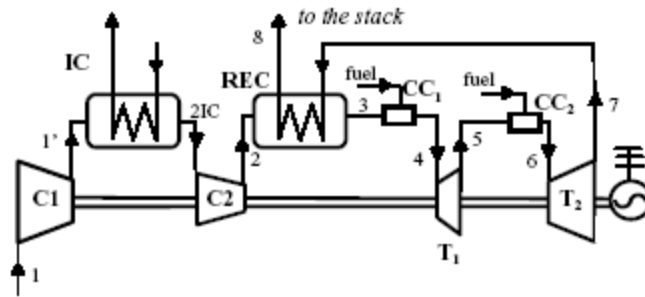


Cicli turbogas complessi – altri

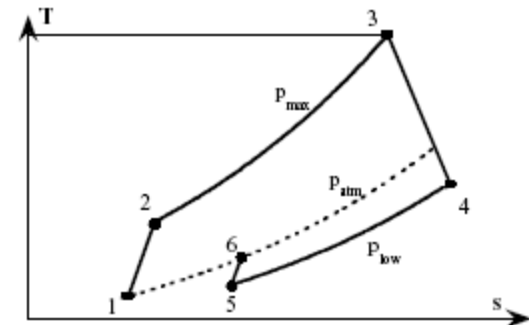
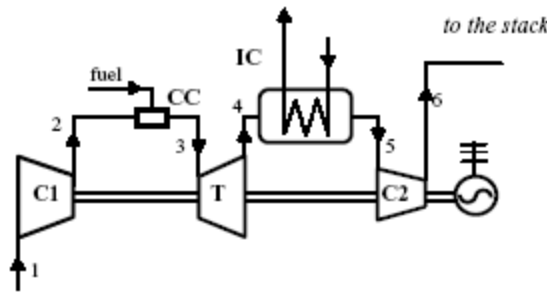
ICRH



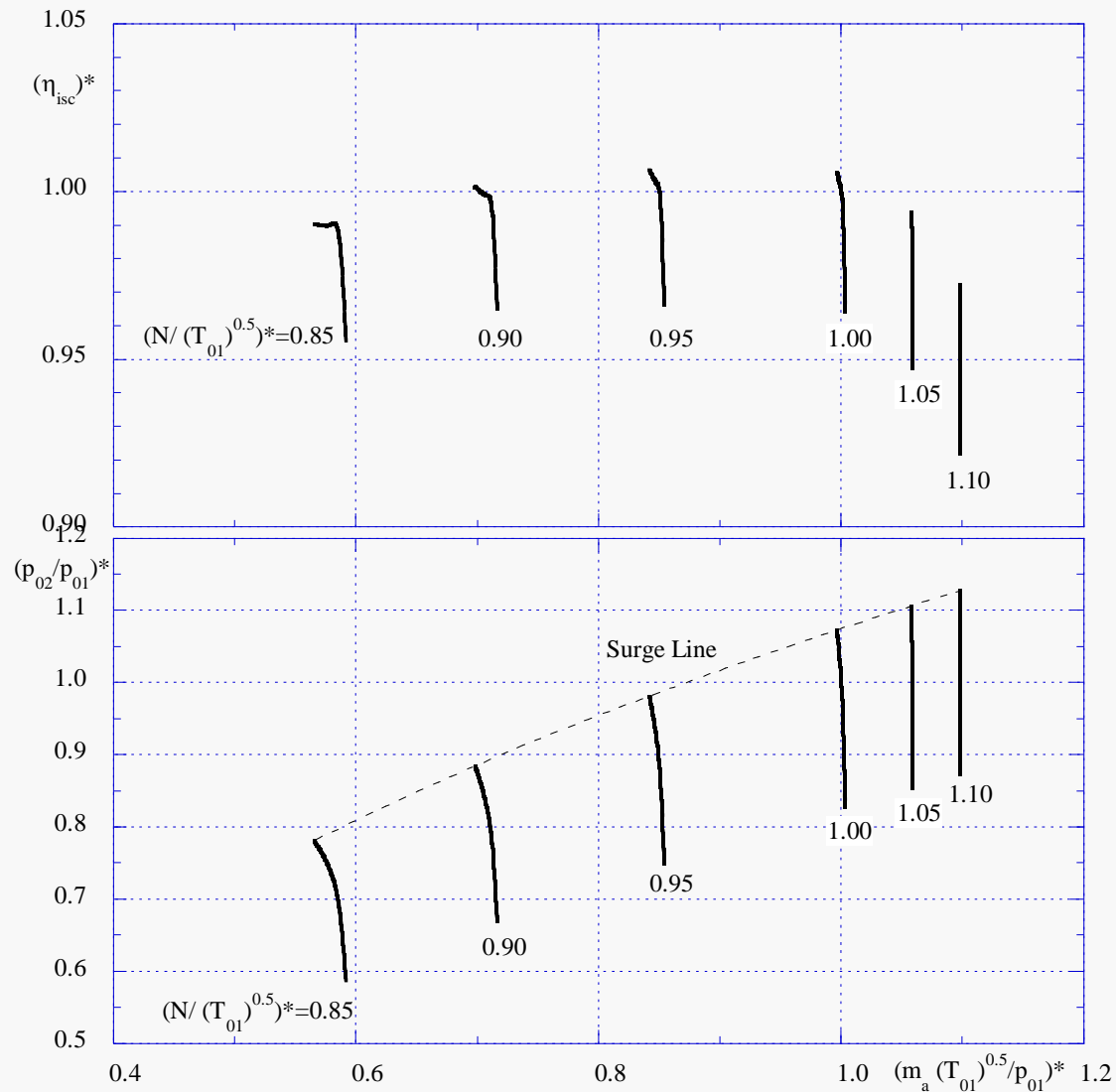
ICRHR



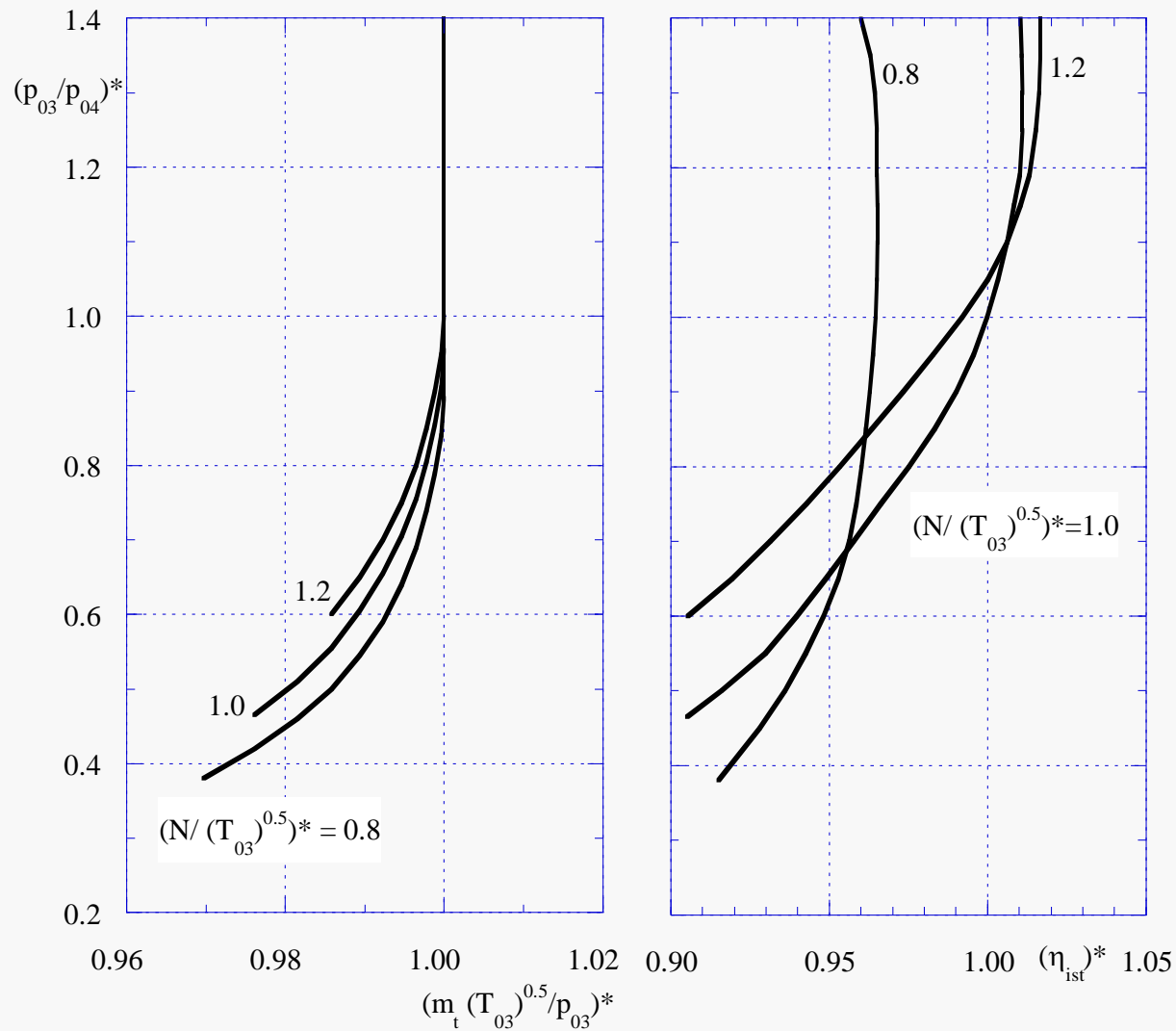
BAGT



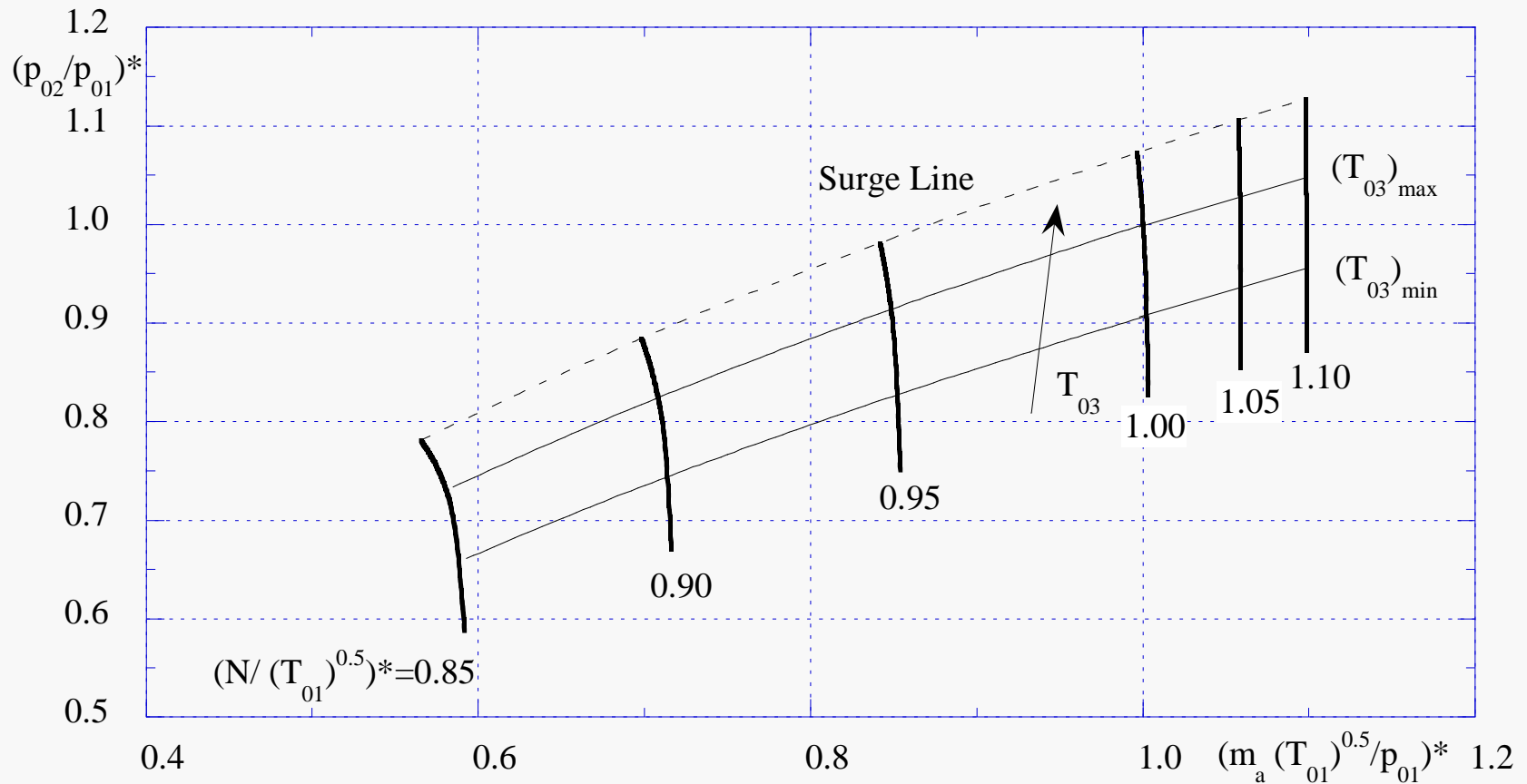
Mappe di prestazione del compressore



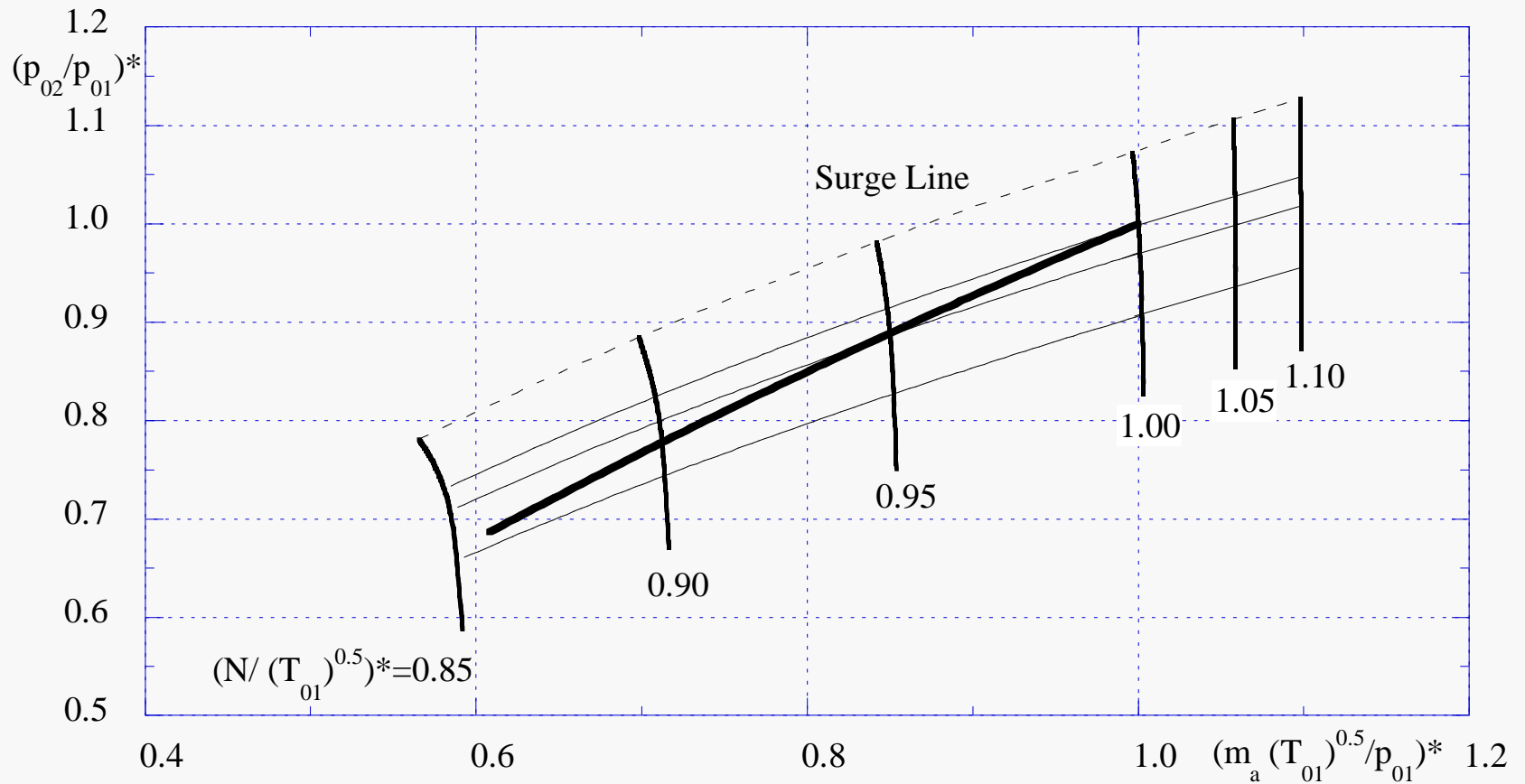
Mappe di prestazione della turbina



Accoppiamento compressore-turbina



Accoppiamento compressore-turbina



Influenza del punto di funzionamento (potenza utile)

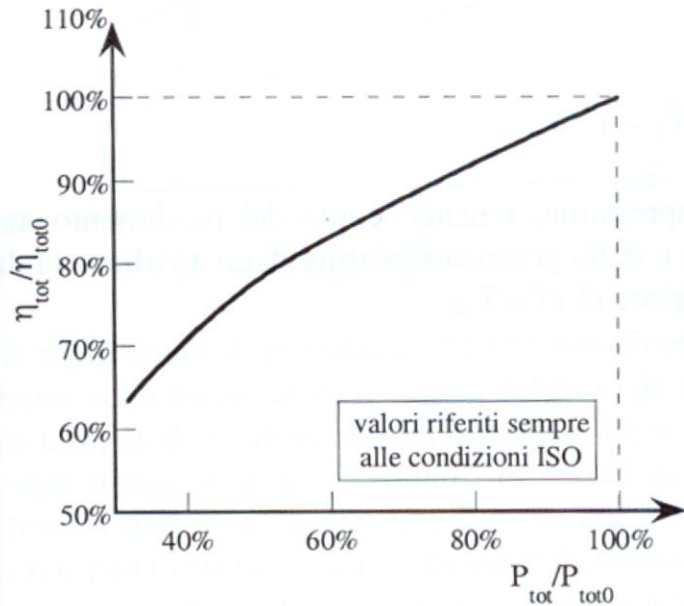
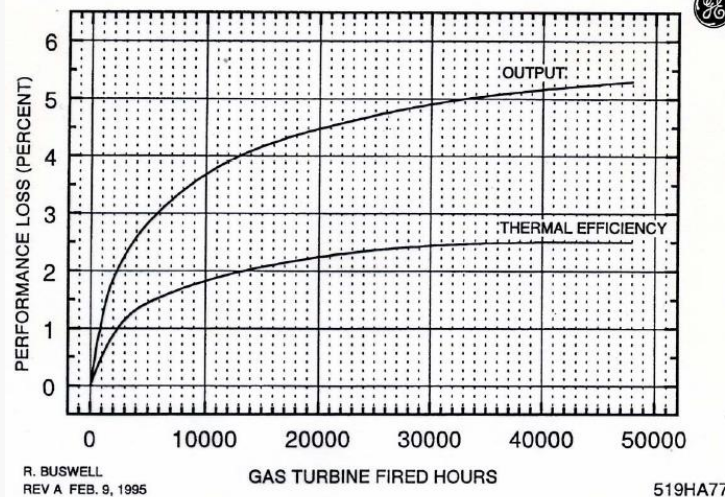
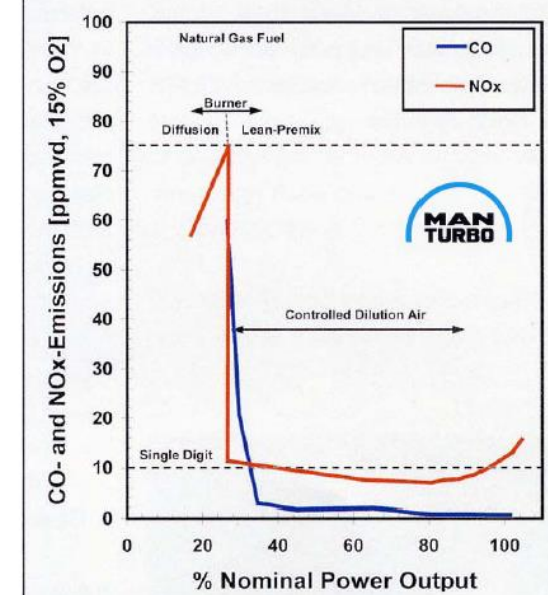
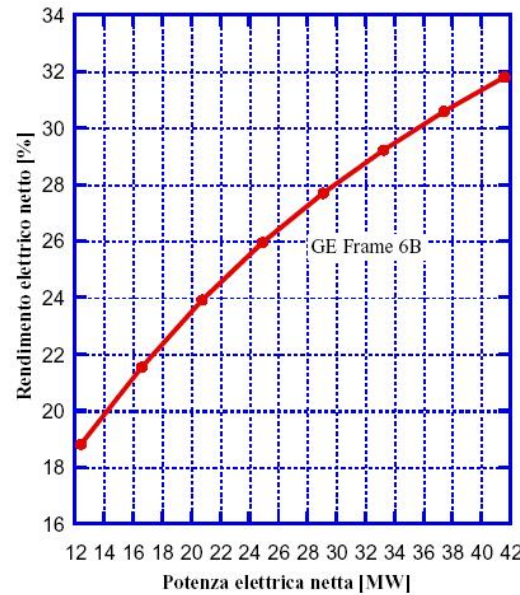


Figura 2.27

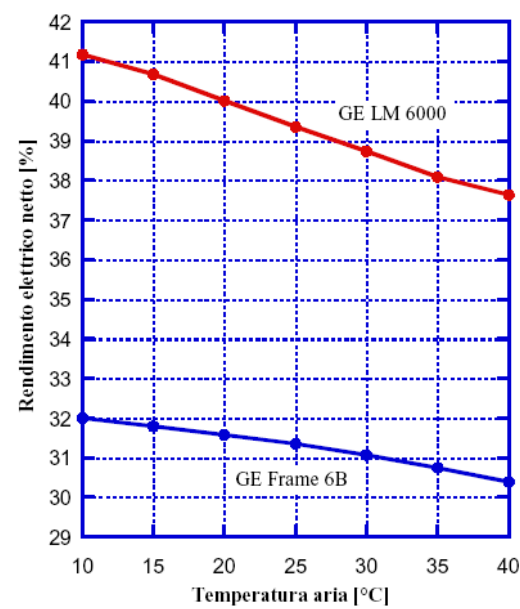
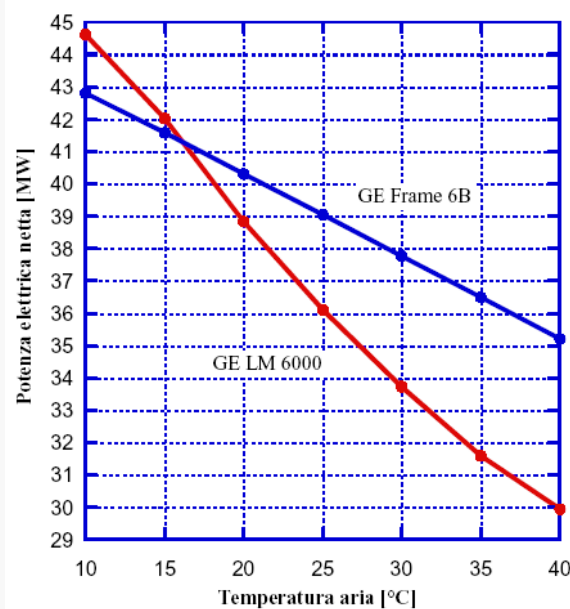
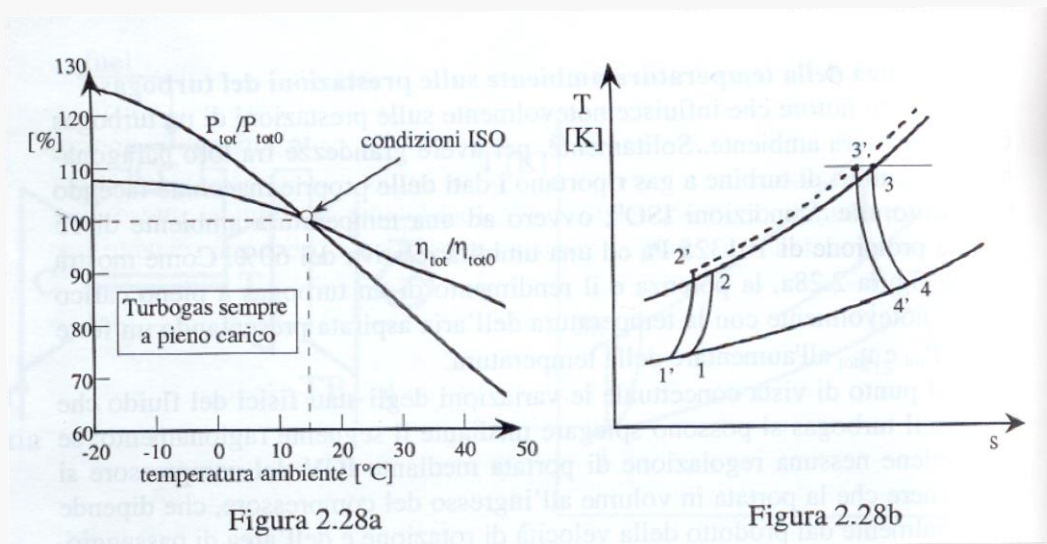


R. BUSWELL
REV A FEB. 9, 1995

519HA772



Influenza della temperatura ambiente



Turbine a gas sul mercato

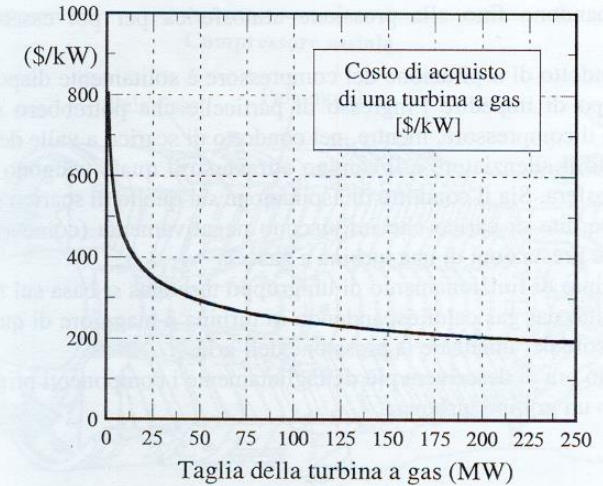
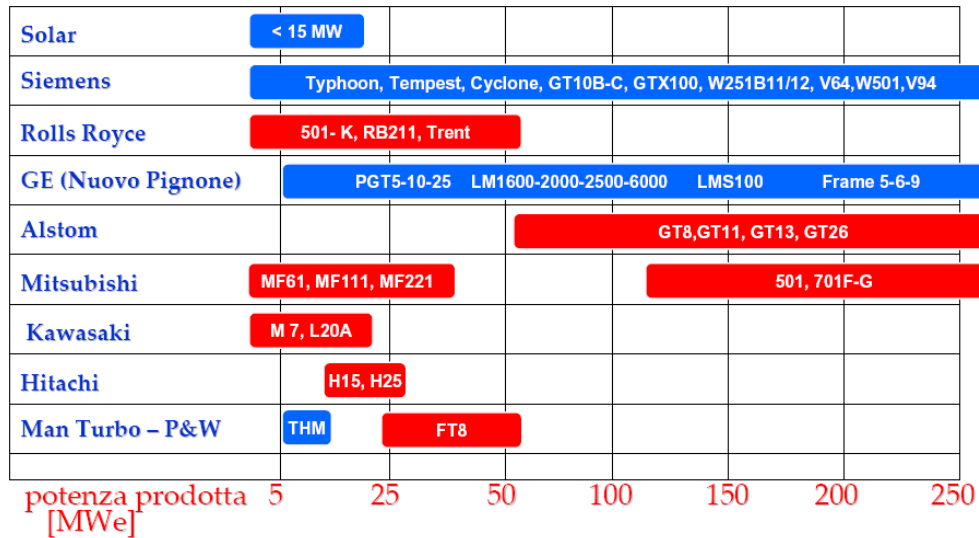


Figura 2.2

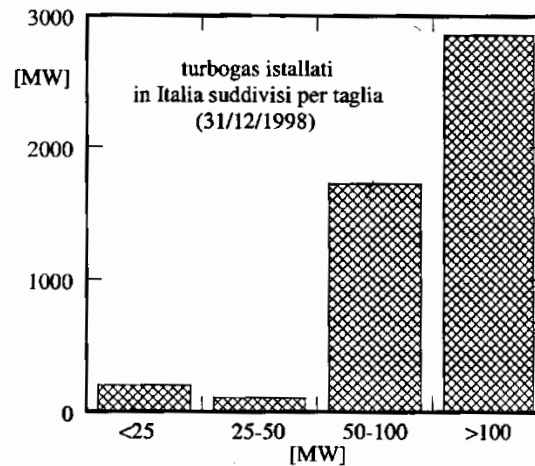
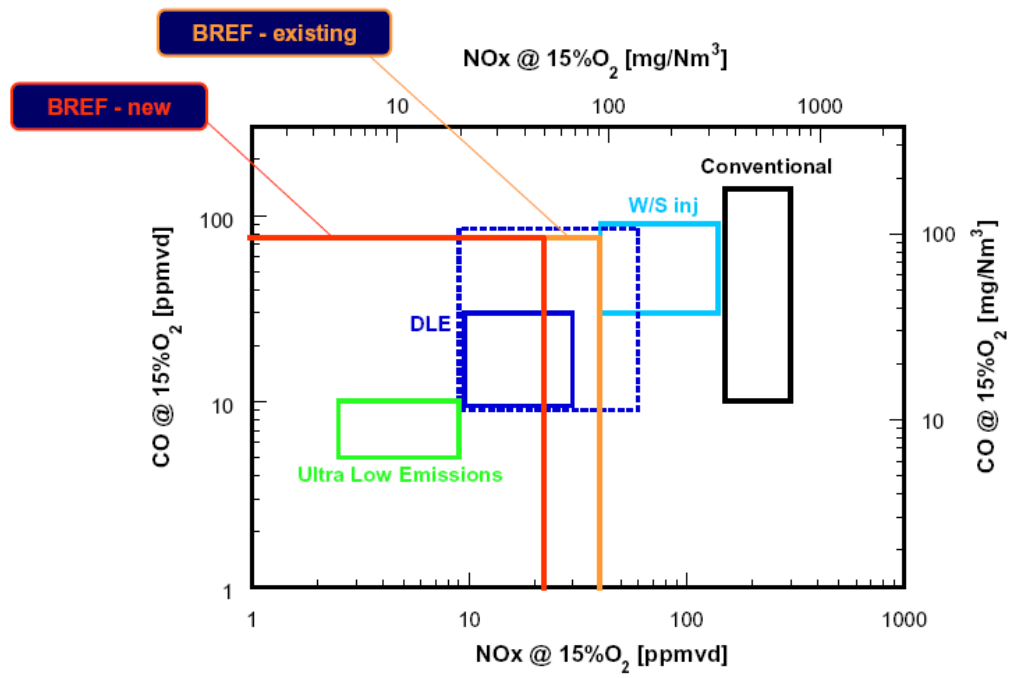
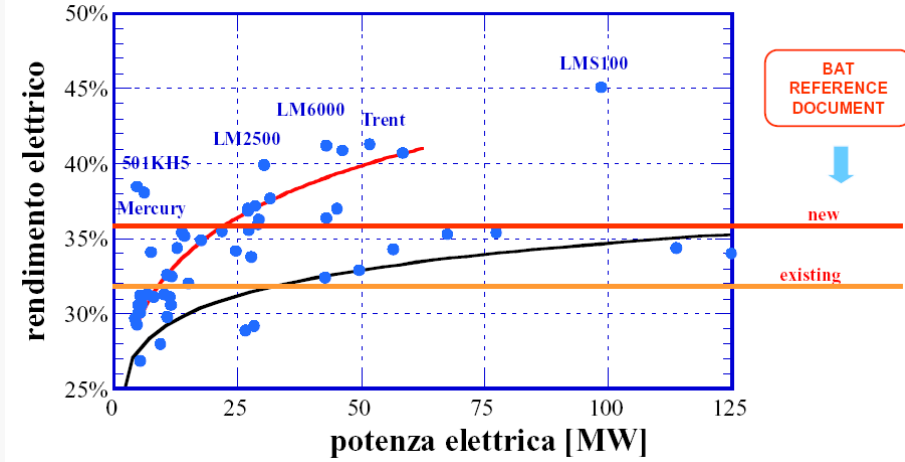
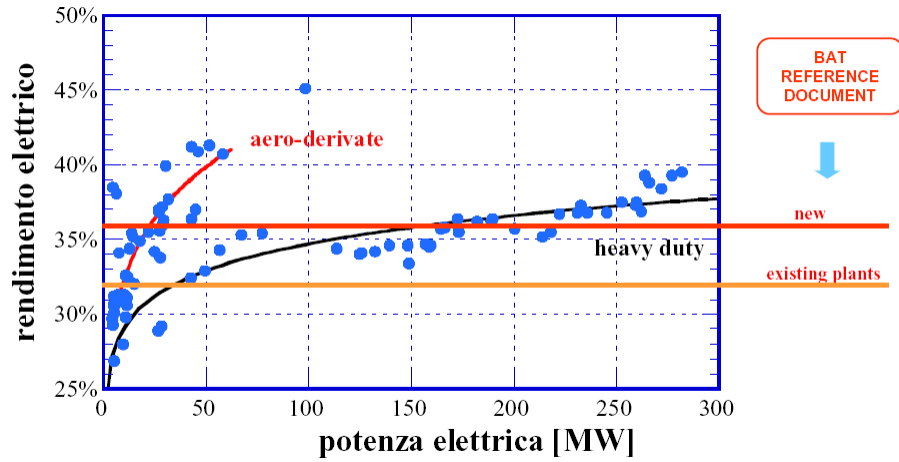


Figura 2.1



Prestazioni di turbine a gas in esercizio



Impianti a ciclo combinato gas-vapore



Ciclo combinato a 1 livello di pressione

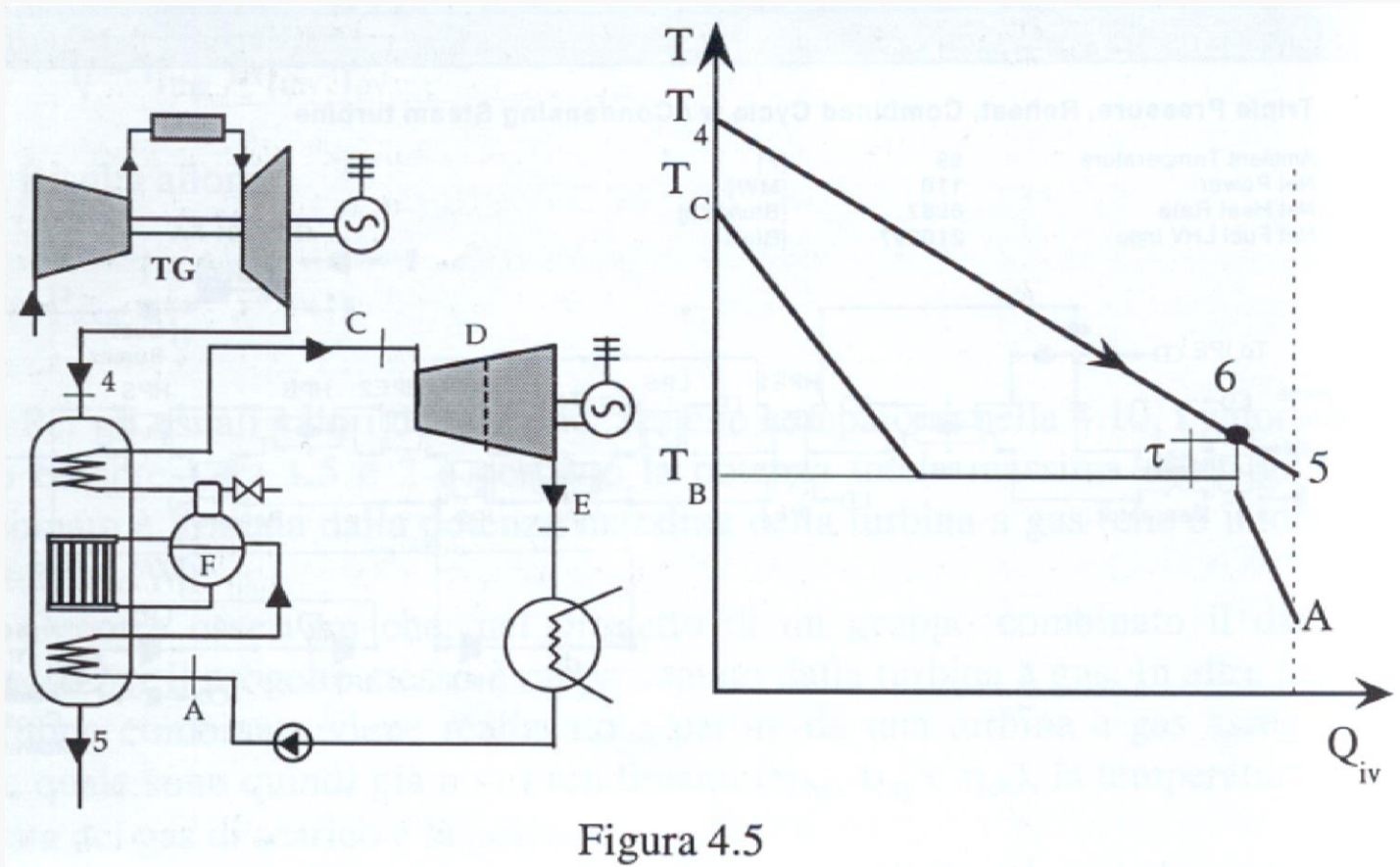
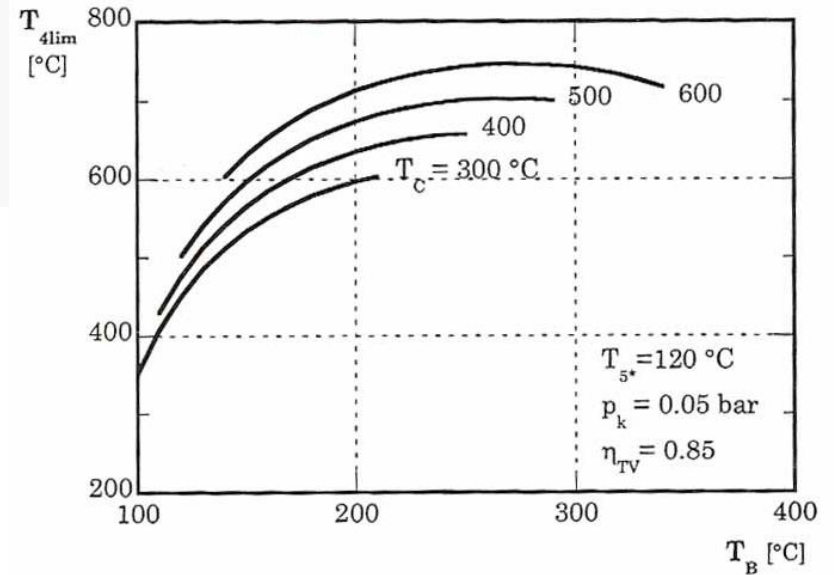
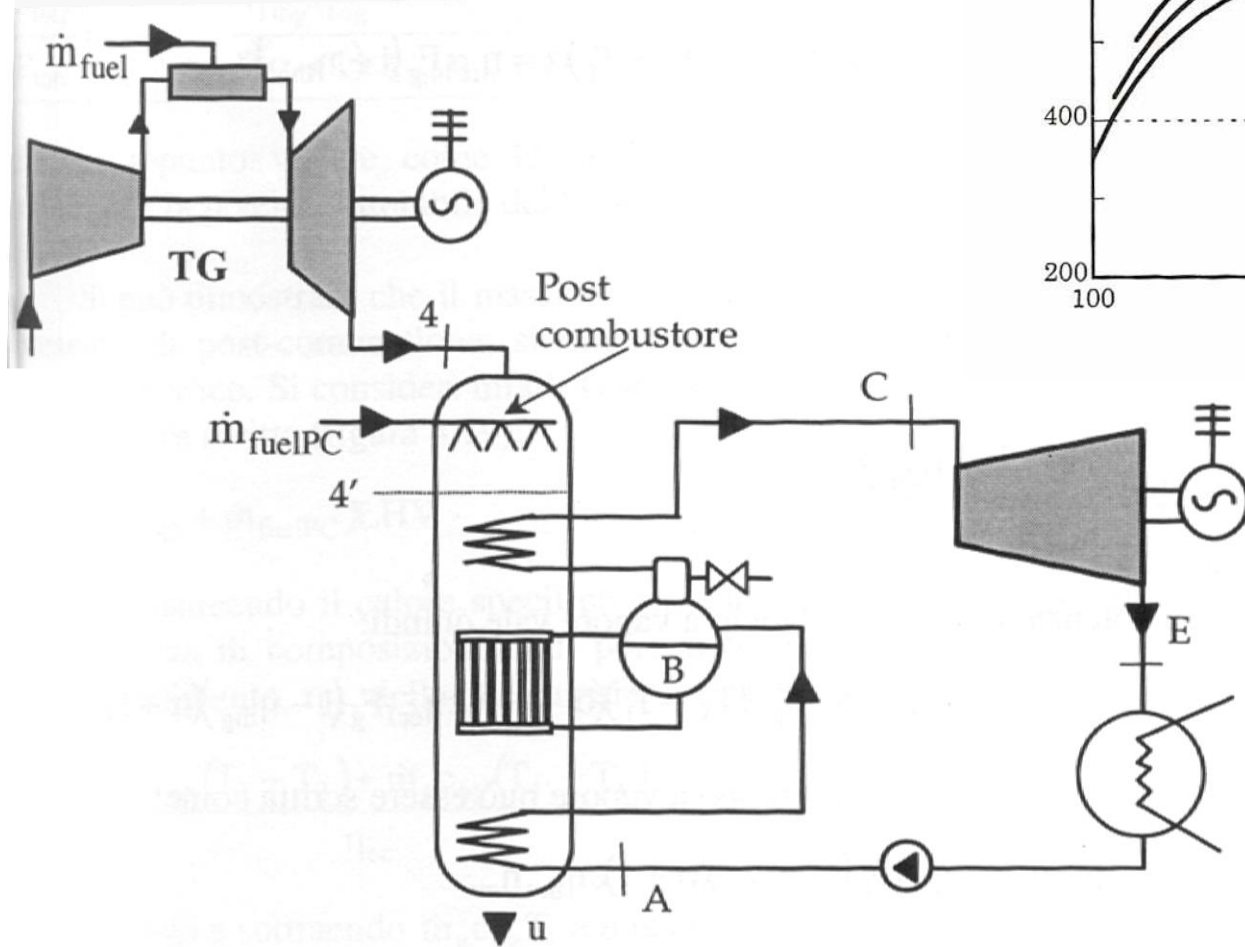


Figura 4.5



Ciclo combinato con post-combustione



Ciclo combinato a 2 livelli di pressione

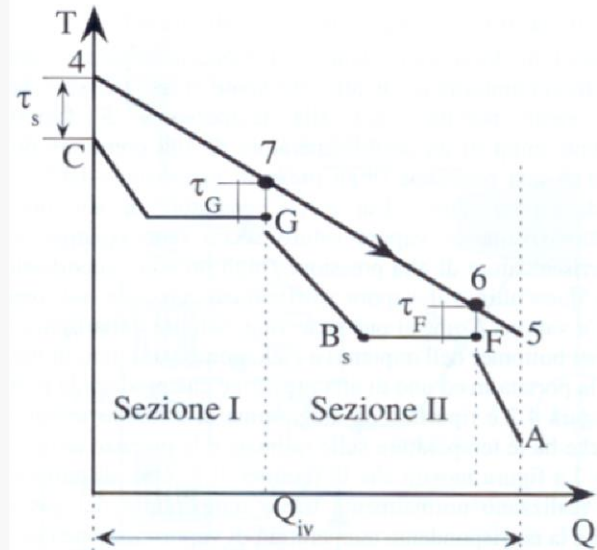
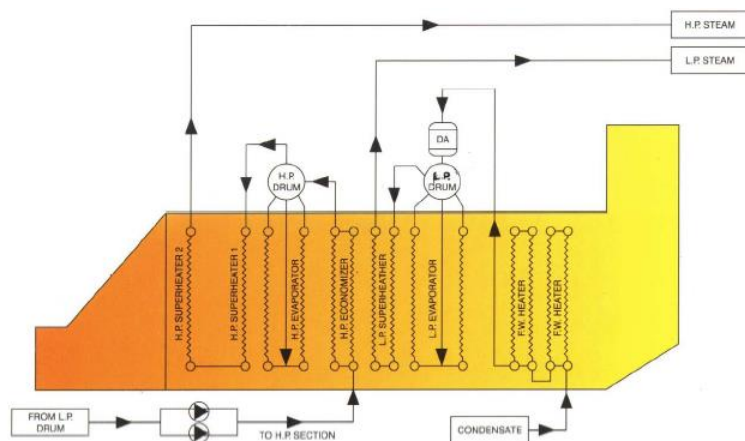
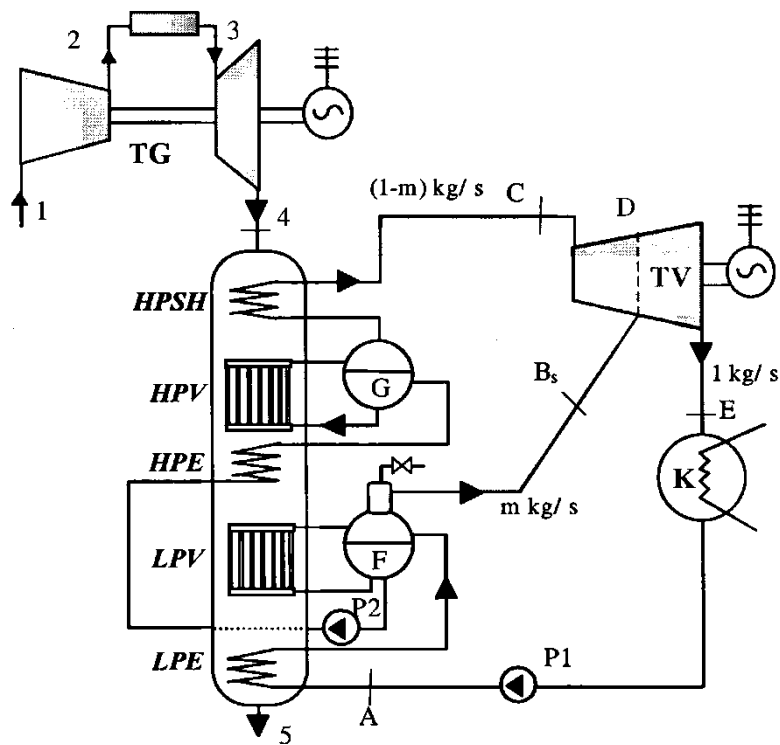


Figura 4.2

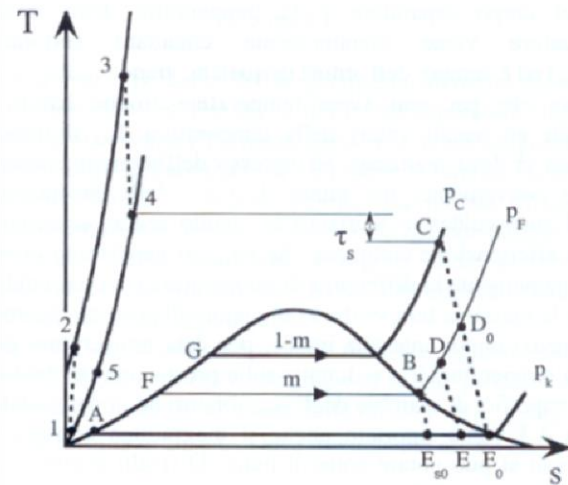
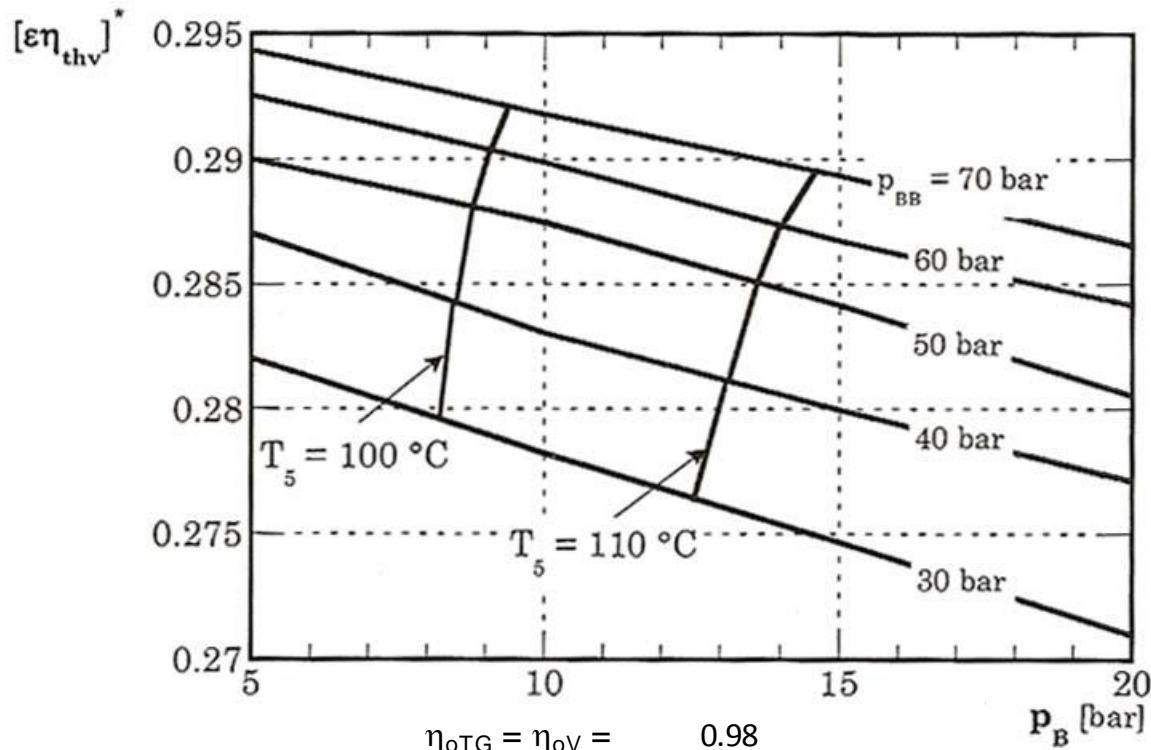


Figura 4.3



Ciclo combinato a 2 livelli di pressione



$\eta_{oTG} = \eta_{oV} = 0.98$

η_{thTG}	0.35	0.40
$\varepsilon \eta_{thV}$	η_{tot}	η_{tot}
0.270	0.515	0.695
0.275	0.518	0.697
0.280	0.521	0.699
0.285	0.525	0.700
0.290	0.528	0.702
0.295	0.531	0.704

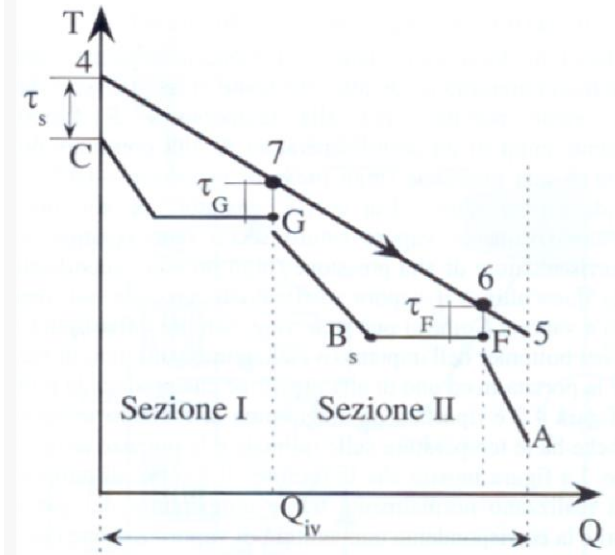


Figura 4.2

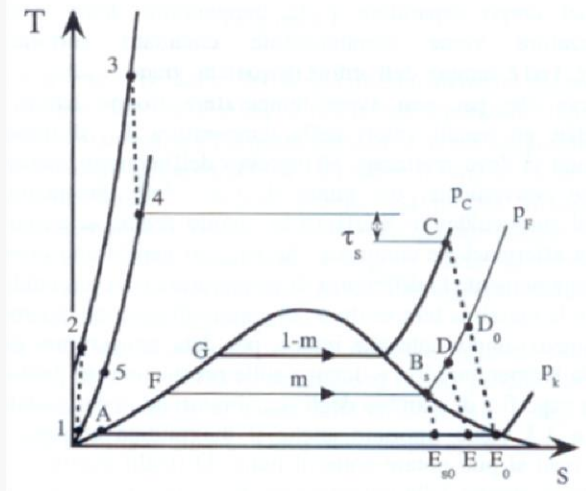
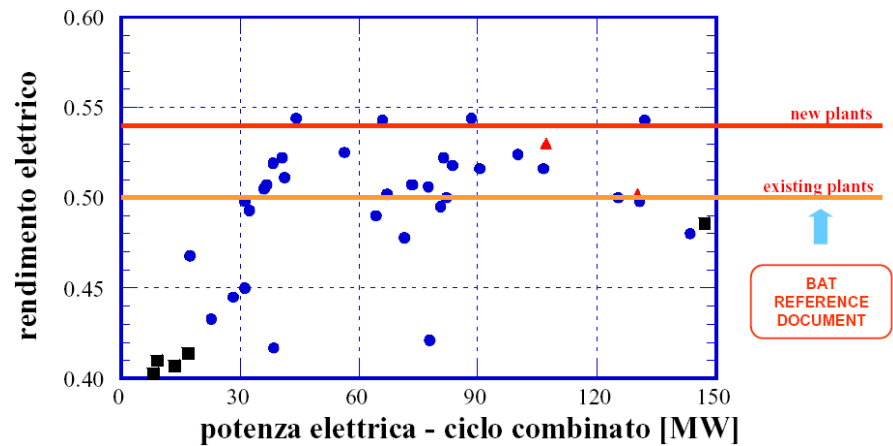
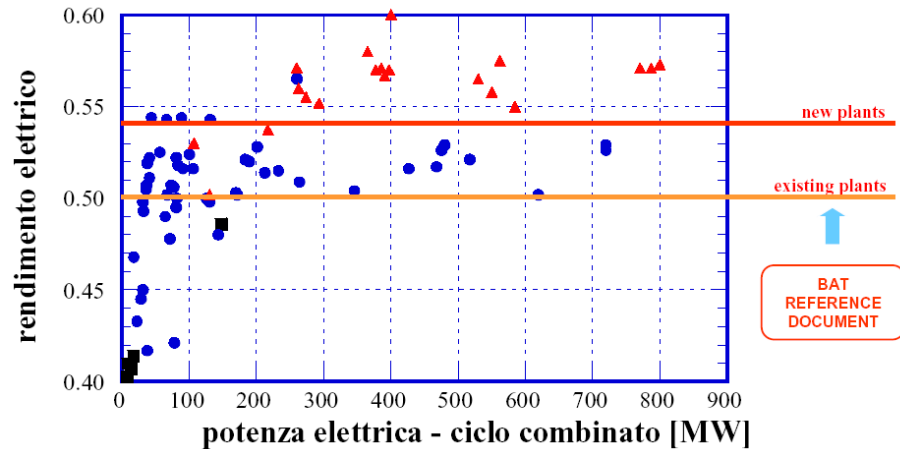


Figura 4.3



Rendimento dei cicli combinati

Il rendimento dei ciclo combinati: dati di progetto < 150 MW elettrici



Modello	Potenza [MW]	Net efficiency %	Heat Rate [kJ/kWh]	Potenza TG	Potenza vapore	N° di TG
3 Livelli+RH						
GE S106FA	118.1	54.6	6593	75.2	44.7	1XMS6001FA
GE S207FB	562.5	57.3	6266	366.3	204	2XMS7001FB
Siemens V94.2A	566.2	55.0	6550	356.0	218.9	2XV94.2A
Siemens V94.3A	794.4	57.5	6261	525.6	281	2XV94.3A
2 Livelli						
Siemens CC10C-2	83.6	51.8	6950	56.8	26.83	2XSGT700
Siemens V94.2	496.9	52.28	6855	319.4	184.5	2XV94.2A
Roll Royce 2 Trent	144.6	50.1	7188	116.4	28.1	2X Trent
Pratt & Whitney FT8-3	74.2	51.3	7022	54.8	20.6	2XFT8-3

Fonte: Gas Turbine World 2004-05 GTW Handbook

