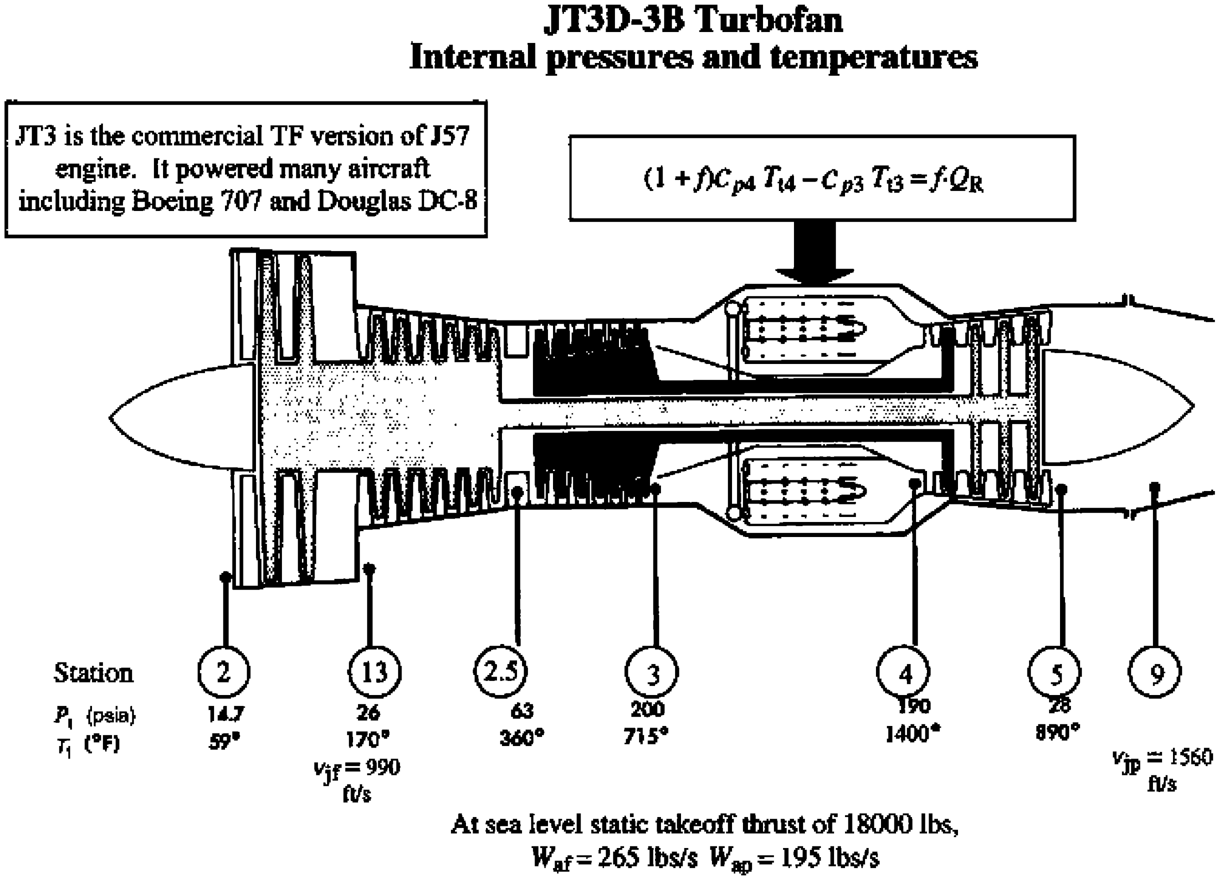
Farokhi problem 3.2

The total pressures and temperatures of the gas are specified for a turbofan engine with separate exhaust streams (JT3D-3B from Pratt & Whitney, 1974). The mass flow rates in the engine core (or primary) and the engine fan are also specified for the sea level static operation. Calculate:



m13(lbm/s)	265	m13(lbm/s	265	m2(kg/s)	120.20	R3(ft2/s2R)	1,717
m3(lbm/s)	195	mf(lbm/s)	195	mf(kg/s)	88.450	R4(ft2/s2R)	1,716
Fn(lbf)	18,000	Fn(lb ft/s2)	579,150	Fn(N)	80,070	gamma3	1.400
V9(ft/s)	1,560			V9(m/s)	475	k	0.286
V13(ft/s)	990			V13(m/s)	302	gamma4	1.358
				SI		k	0.264
Stazioni	pt(psi)	T(F)	T(R)	pt(kN)	T(K)	Si	
2	14.7	59	518.7	101.4	288.1	cp(J/kgK)	1,005
13	26.0	170	629.7	179.3	349.8	cp(J/kgK)	1,089
2.5	63	360	819.7	434.4	455.4	R(J/kgK)	287
3	200	715	1,174.7	1,379.0	652.6	R(J/kgK)	287
4	190.0	1,400	1,859.7	1,310.0	1,033.1		
5	28.0	890	1,349.7	193.1	749.8		
9	14.7	59	518.7	101	288.1		

a) the engine bypass ratio α defined as the ratio of fan-to-core flow rate

$$\alpha = \frac{\dot{m}_{13}}{\dot{m}_3} = \frac{265}{195} = \frac{120}{88.5} = 1.36$$

b) from the total temperature rise across the burner, estimate the fuel-to-air ratio and the fuel flow rate in lbm/h, assuming the fuel heating value is $Q_R \sim 18{,}600 \cdot BTU/lbm$ and the specific heat at constant pressure is 0.24 and 0.26 *BTU/lbm*·R at the entrance and exit of the burner, respectively

$\dot{m}_4 c_{p4} T_{t4} - \dot{m}_3 c_{p3} T_{t3} = \eta_b \dot{m}_f Q_R \qquad (1+f) c_{p4} T_{t4} - c_{p3} T_{t3} = \eta_b f Q_R$

$$f = \frac{c_{p4} T_{t4} - c_{p3} T_{t3}}{\eta_b Q_R - c_{p4} T_{t4}} = \frac{0.26 \cdot 1860 - 0.24 \cdot 1175}{1 \cdot 18.6 \cdot 10^3 - 0.26 \cdot 1860} = 0.0111$$

$$\dot{m}_f = f \dot{m}_3 = 0.0111 \cdot 195 = 2.17 \cdot \frac{lbm}{s}$$

c) the engine static thrust based on the exhaust velocities and the mass flow rates assuming perfectly expanded nozzles and compare your answer to the specified thrust of 18,000 lbf

$$F = \dot{m}_4 V_9 + \dot{m}_{13} V_{13} = (195 + 2.17)1560 + 265 \cdot 990 = 570 \cdot 10^3 lbm \cdot \frac{ft}{s^2} = \frac{570}{32.18} \cdot 10^3 \cdot lbf$$
$$= 17.7 \cdot 10^3 \cdot lbf$$

d) the engine thermal efficiency η_{th}

$$\eta_{\mathrm{th}} = \frac{\dot{m}_4 V_9^2 + \dot{m}_{13} V_{13}^2}{2 \dot{m}_f Q_R} = \frac{(195 + 2.17)1560^2 + 265 \cdot 990^2}{2 \cdot 2.17 \cdot 465.7 \cdot 10^6} = \frac{7.40 \cdot 10^8}{20.21 \cdot 10^8} = 36.6\%$$

e) the thermal efficiency of this engine compared to the afterburning turbojet of Problem 1. Explain the major contributors to the differences in η_{th} in these two engines

$\pi_c = 13.6 \qquad \pi_{c.3.1} = 10.8$

f) the engine thrust specific fuel consumption in lbm/h/lbf

$$TSFC = \frac{\dot{m}_f}{F} = \frac{2.17 \cdot 3600}{17.7 \cdot 10^3} = 0.441 \frac{lbm}{\mathrm{h} \cdot lbf}$$

g) the nondimensional engine specific thrust

$$\frac{F}{\dot{m}_{air} a_0} = \frac{570 \cdot 10^3}{(265 + 195)\sqrt{1.4 \cdot 1717 \cdot 519}} = 1.11$$

h) the Carnot efficiency corresponding to this engine

$$\eta_{Carnot} = 1 - \frac{T_0}{T_{t4}} = 72.1\%$$

i) the engine overall pressure ratio p_{t3}/p_{t2}

$\pi_c = 13.6$

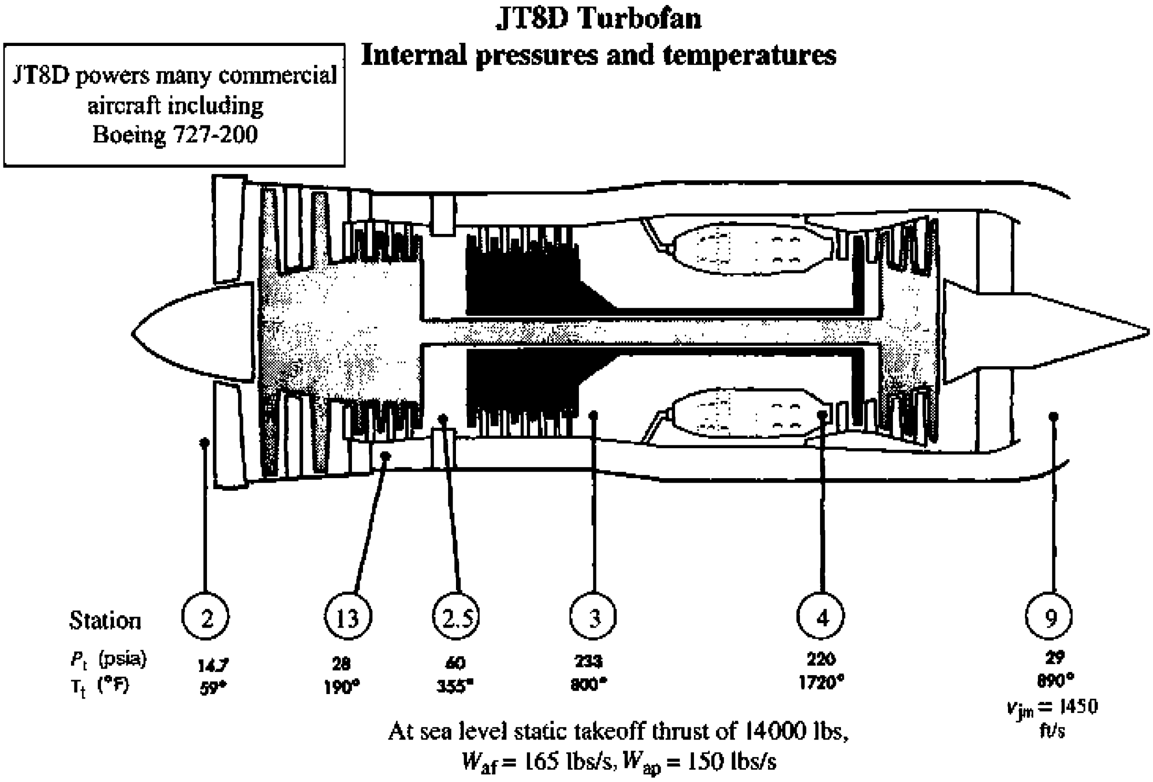
j) fan nozzle exit Mach number (use $T_t = T + V^2/2\mathrm{c_p}$ to calculate local static temperature at the nozzle exit, then local speed of sound.

$$T_t = T + V^2/2 \quad \rightarrow \quad T_{13} = T_{t13} - \frac{V_{13}^2}{2c_p} = 630 - \frac{990^2}{2 \cdot 0.24 \cdot 25 \cdot 10^3} = 548R$$

$$M_{13} = \frac{V_{13}}{a_{13}} = \frac{990}{\sqrt{1.4 \cdot 1717 \cdot 548}} = 0.863$$

				SI				
α	1.359			α	1.359			
f	0.011			f	0.011			
π_{Fan}	1.769			π_{cLP}	1.769			
π_{c}	7.692			π_{cHP}	7.692			
π_{t}	0.147			π_{t}	0.147			
mf	2.170			mf	0.984			
F(lb ft/s2)	569,935	Fn(lbf)	17,714	F(N)	78,796			
η_{th}	0.366			η_{th}	0.366			
TSFC(lbm/h lb	0.441	0.434		TSFC(mg/s N)	12.491			
η_{carnot}	0.721			η_{carnot}	0.721			
ao	1,117			ao	340			
ST/ao	1.110			ST/ao	1.110			
π_{tot}	13.6			π_{tot}	14			
T13(R)	548			T13	305			
a13(m/s)	1,148			a13	350			
M13	0.863			M13	0.863			

Farokhi problem 3.3



A mixed exhaust turbofan engine (JT8D from Pratt and Whitney, 1974) is described by its internal pressures and temperature, as well as air mass flow rates and the mixed jet (exhaust) velocity. Let us examine a few parameters for this engine, for a ballpark approximation.

JT8D	727, dc9 , md80						
Conversioni				Cost K-F	255.37		
g(ft/s2)	32.175	ft->m	0.3048	BTU->J	1,055	BTU/lbm->ft2/s2	25,038
1lb->kg	0.45359	lbft->kgm	0.1383	psi->Pa	6,895	Conv TSFC	115,830
Dati				Si			
QR(BTU/lbm)	18,600	QR(ft2/s2)	465,707,434	QR(kJ/kg)	43266	cp3(BTU/lbmR)	0.24
				SI		cp4(BTU/lbmR)	0.26
m13(lbm/s)	165	m13(lbm/s	165	m2(kg/s)	74.84	R3(ft2/s2R)	1,717
m3(lbm/s)	150	m3(lbm/s)	150	mf(kg/s)	68.039	R4(ft2/s2R)	1,716
Fn(lbf)	14,000	Fn(lb ft/s2)	450,450	Fn(N)	62,277	gamma3	1.400
V9(ft/s)	1,450			V9(m/s)	442	k	0.286
						gamma4	1.358
				SI		k	0.264
Stazioni	pt(psi)	T(F)	T(R)	pt(kN)	T(K)	Si	
2	14.7	59	518.7	101.4	288.1	cp(J/kgK)	1,005
13	28.0	190	649.7	193.1	360.9	cp(J/kgK)	1,089
2.5	60	355	814.7	413.7	452.6	R(J/kgK)	287
3	233	800	1,259.7	1,606.5	699.8	R(J/kgK)	287
4	220.0	1,720	2,179.7	1,516.9	1,210.9		
9	29.0	890	1,349.7	200.0	749.8		

(a) Estimate the fuel flow rate from the total temperature rise across the burner assuming the fuel heating value $Q_R \sim 18{,}600 \cdot BTU/lbm$ and the specific heat at constant pressure is 0.24 and 0.26 *BTU/lbm*·R at the entrance and exit of the burner, respectively

$$f = \frac{c_{p4}T_{t4} - c_{p3}T_{t3}}{\eta_b Q_R - c_{p4}T_{t4}} = \frac{0.26 \cdot 2180 - 0.24 \cdot 1260}{1 \cdot 18.6 \cdot 10^3 - 0.26 \cdot 2180} = 0.0147$$

$$\dot{m}_f = f\dot{m}_3 = 0.0147 \cdot 150 = 2.20 \cdot \frac{lbm}{s}$$

(b) Calculate the momentum thrust at the exhaust nozzle and compare it to the specified thrust of 14,000 lbf

$$F = (\dot{m}_3 + \dot{m}_f + \dot{m}_{13})V_9 = (150 + 2.20 + 165)1450 = 460 \cdot 10^3 lbm \cdot \frac{ft}{s^2} = \frac{460}{32.18} \cdot 10^3 \cdot lbf$$
$$= 14.3 \cdot 10^3 \cdot lbf$$

(c) Estimate the thermal efficiency of this engine and compare it to Problems 3.1 and 3.2 as well as a Carnot cycle operating between the temperature extremes of this engine. Explain the differences

$$\eta_{\text{th}} = \frac{(\dot{m}_3 + \dot{m}_f + \dot{m}_{13})V_9^2}{2\dot{m}_f Q_R} = \frac{(150 + 2.20 + 165)1450^2}{2 \cdot 2.20 \cdot 465.7 \cdot 10^6} = \frac{6.67 \cdot 10^8}{20.5 \cdot 10^8} = 32.6\%$$

$$\eta_{Carnot} = 1 - \frac{T_0}{T_{t4}} = 1 - \frac{519}{2{,}180} = 76.2\%$$

(d) Estimate the specific fuel consumption for this engine in lbm/h/lbf

$$TSFC = \frac{\dot{m}_f}{F} = \frac{2.20 \cdot 3600}{14.3 \cdot 10^3} = 0.554 \frac{lbm}{\text{h} \cdot lbf}$$

(e) The overall pressure ratio (of the fan–compressor section) p_{t3}/p_{t2}

$$\frac{p_{t3}}{p_{t2}} = \frac{233}{14.7} = 15.9$$

(f) What is the bypass ratio α for this engine at takeoff

$$\alpha = \frac{\dot{m}_{13}}{\dot{m}_3} = \frac{165}{150} = 1.10$$

(g) What is the Carnot efficiency corresponding to this engine

$$\eta_{Carnot} = 1 - \frac{T_0}{T_{t4}} = 1 - \frac{519}{1260} = 76.2\%$$

(h) Estimate nozzle exit Mach number [look at part (j in Problem 3.2]

$$T_t = T + V^2/2 \quad \rightarrow \quad T_9 = T_{t9} - \frac{V_9^2}{2c_p} = 1350 - \frac{1450^2}{2 \cdot 0.26 \cdot 25 \cdot 10^3} = 1188 \cdot R$$

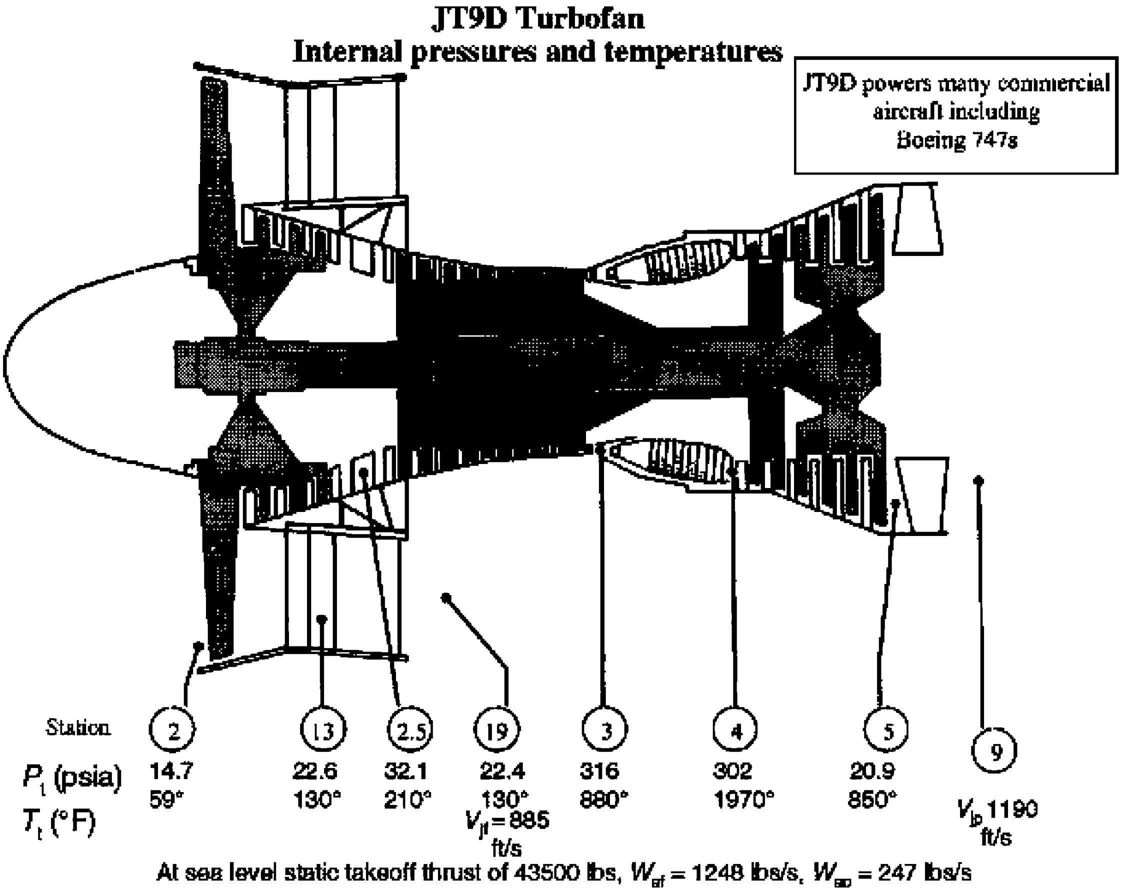
$$M_9 = \frac{V_9}{a_9} = \frac{1450}{\sqrt{1.4 \cdot 1716 \cdot 1188}} = 0.86$$

(i) What is the low-pressure compressor (LPC) pressure ratio p_{t25}/p_{t2}
(j) What is the high-pressure compressor (HPC) pressure ratio p_{t3}/p_{t25}

$$\frac{p_{t25}}{p_{t2}} = \frac{60}{14.7} = 4.08 \qquad \frac{p_{t3}}{p_{t25}} = \frac{233}{60} = 3.88$$

				SI			
α	1.100			α	1.100		
f	0.0147			f	0.0147		
$\pi_{LPC+Fan}$	4.082			π_{cLP}	1.905		
π_{c}	3.883			π_{cHP}	8.321		
π_{t}	0.132			π_{t}	0.132		
mf	2.199			mf	0.998		
F(lb ft/s2)	459,939	Fn(lbf)	14,295	F(N)	63,588		
η_{th}	0.326			η_{th}	0.156		
TSFC(lbm/h lb	0.554			TSFC(mg/s N)	15.687		
η_{carnot}	0.762			η_{carnot}	0.762		
ao	1,117			ao	340		
ST/ao	1.308			ST/ao	1.308		
π_{tot}	16			π_{tot}	16		
T9(R)	1,188			T13	660		
a9(ft/s)	1,664			a13	515		
M9	0.871			M13	0.858		

Farokhi problem 3.4



A large bypass ratio turbofan engine (JT9D engine from Pratt and Whitney, 1974) is described by its fan and core engine gas flow properties.

JT9D	747, A310, 767						
Conversioni				Cost K-F	255.37		
g(ft/s2)	32.175	ft->m	0.3048	BTU->J	1,055	BTU/lbm->ft2/s2	25,038
1lb->kg	0.45359	lbft->kgm	0.1383	psi->Pa	6,895	Conv TSFC	115,830
Dati				Si			
QR(BTU/lbm)	18,600	QR(ft2/s2)	465,707,434	QR(kJ/kg)	43266	cp3(BTU/lbmR)	0.24
				SI		cp4(BTU/lbmR)	0.26
m13(lbm/s)	1,248	m13(lbm/s	1,248	m2(kg/s)	566.08	R3(ft2/s2R)	1,717
m3(lbm/s)	247	mf(lbm/s)	247	m3(kg/s)	112.037	R4(ft2/s2R)	1,716
Fn(lbf)	43,500	Fn(lb ft/s2)	1,399,613	Fn(N)	193,502	gamma3	1.400
V9(ft/s)	1,190			V9(m/s)	363	k	0.286
V19(ft/s)	885			V19(m/s)	270	gamma4	1.358
				SI		k	0.264
Stazioni	pt(psi)	T(F)	T(R)	pt(kN)	T(K)	Si	
2	14.7	59	518.7	101.4	288.1	cp(J/kgK)	1,005
13	22.6	130	589.7	155.8	327.6	cp(J/kgK)	1,089
2.5	32	210	669.7	221.3	372.0	R(J/kgK)	287
3	316	880	1,339.7	2,178.8	744.3	R(J/kgK)	287
4	302.0	1,970	2,429.7	2,082.3	1,349.8		
5	20.9	850	1,309.7	144.1	727.6		
9	14.7	850	1,309.7	101	727.6		
19	22.4	130	589.7	154	327.6		

(a) What is the overall pressure ratio (OPR) of this engine

$\pi_c = \frac{p_{t3}}{p_{t2}} = \frac{316}{14.7} = 21.5$

(b) Estimate the fan gross thrust Fg,fan in lbf

$$F_{Fan} = \dot{m}_{19} V_{19} = 1248 \cdot 885 = 1.10 \cdot 10^6 lbm \cdot \frac{ft}{s^2} = \frac{1.10}{32.18} \cdot 10^6 \cdot lbf = 34.3 \cdot 10^3 \cdot lbf$$

(c) Estimate the fuel-to-air ratio based on the energy balance across the burner, assuming the fuel heating value is $Q_R \sim 18{,}600 \cdot BTU/lbm$ and the specific heat at constant pressure is 0.24 and 0.26 *BTU/lbm*·R at the entrance and exit of the burner, respectively

$$f = \frac{c_{p4} T_{t4} - c_{p3} T_{t3}}{\eta_b Q_R - c_{p4} T_{t4}} = \frac{0.26 \cdot 2430 - 0.24 \cdot 1340}{1 \cdot 18.6 \cdot 10^3 - 0.26 \cdot 2430} = 0.0172$$

$$\dot{m}_f = f \dot{m}_3 = 0.0172 \cdot 247 = 4.25 \cdot \frac{lbm}{s}$$

(d) Calculate the core gross thrust and compare the sum of the fan and the core thrusts to the specified engine thrust of 43,500 lbf

$$F_{Core} = \dot{m}_9 V_9 = (4.25 + 247) \cdot 1190 = 0.299 \cdot 10^6 lbm \cdot \frac{ft}{s^2} = \frac{.299}{32.18} \cdot 10^6 \cdot lbf$$
$$= 9.29 \cdot 10^3 \cdot lbf$$

$$F_{Tot} = F_{Core} + F_{Fan} = (9.29 + 34.3) 10^3 = 43.6 \cdot 10^3 \cdot lbf \qquad \frac{F_{Core}}{F_{Tot}} = \frac{9.29}{43.6} = 21.3\%$$

(e) Calculate the engine thermal efficiency and compare it to Problems 3.1–3.3. Explain the differences

$$\eta_{\mathrm{th}} = \frac{(\dot{m}_3 + \dot{m}_f) V_9^2 + \dot{m}_{19} V_{19}^2}{2 \dot{m}_f Q_R} = \frac{(4.25 + 247) \cdot 1190^2 + 1248 \cdot 885^2}{2 \cdot 4.25 \cdot 465.7 \cdot 10^6} = \frac{13.3 \cdot 10^8}{39.7 \cdot 10^8} = 33.5\%$$

(f) Estimate the thrust-specific fuel consumption (TSFC), in lbm/h/lbf

$$TSFC = \frac{\dot{m}_f}{F} = \frac{4.25 \cdot 3600}{43.6 \cdot 10^3} = 0.352 \frac{lbm}{\mathrm{h} \cdot lbf}$$

(g) What is the bypass ratio of this turbofan engine

$$\alpha = \frac{\dot{m}_{19}}{\dot{m}_3} = \frac{1248}{247} = 5.05$$

(h) What is the Carnot efficiency η Carnot corresponding to this engine

$$\eta_{Carnot} = 1 - \frac{T_0}{T_{t4}} = 1 - \frac{519}{2{,}430} = 78.6\%$$

(i) What is the LPC pressure ratio p_{t25}/p_{t2}
(j) What is the HPC pressure ratio p_{t3}/p_{t25}

$$\pi_{cLP} = \frac{p_{t25}}{p_{t2}} = \frac{32}{14.7} = 2.18 \qquad \pi_{cHP} = \frac{p_{t3}}{p_{t25}} = \frac{316}{32} = 9.88 \qquad \pi_c = 21.5$$

(k) Estimate the fan nozzle exit Mach number [see part (j) in Problem 3.2]

$$T_t = T + V^2/2 \quad \rightarrow \quad T_{19} = T_{t19} - \frac{V_{19}^2}{2c_p} = 590 - \frac{885^2}{2 \cdot 0.24 \cdot 25 \cdot 10^3} = 525 \cdot R$$

$$M_{19} = \frac{V_{19}}{a_{19}} = \frac{885}{\sqrt{1.4 \cdot 1717 \cdot 525}} = 0.788$$

(l) Estimate the primary nozzle exit Mach number

$$T_t = T + V^2/2 \quad \rightarrow \quad T_9 = T_{t9} - \frac{V_9^2}{2c_p} = 1310 - \frac{1190^2}{2 \cdot 0.26 \cdot 25 \cdot 10^3} = 1201 \cdot R$$

$$M_{19} = \frac{V_{19}}{a_{19}} = \frac{1190}{\sqrt{1.4 \cdot 1716 \cdot 1201}} = 0.71$$

Valutare inoltre il lavoro nei vari stadi del compressore, nella turbina e il calore scambiato nella camera di combustione.

$$W_{cLP} = \dot{m}_3 c_p (T_{t25} - T_{t2}) = 247 \cdot 0.24(670 - 519) = 8{,}950 \cdot \frac{BTU}{lbmR} = 9{,}444 \cdot kW$$

$$W_{cHP} = \dot{m}_3 c_p (T_{t3} - T_{t25}) = 247 \cdot 0.24(1340 - 670) = 39.7 \cdot 10^3 \cdot \frac{BTU}{lbmR} = 41.9 \cdot 10^3 \cdot kW$$

$$W_F = \dot{m}_{13} c_p (T_{t19} - T_{t2}) = 1248 \cdot 0.24(590 - 519) = 21{,}230 \cdot \frac{BTU}{lbmR} = 22{,}400 \cdot kW$$

$$W_{tot} = W_c + W_F = 9.444 + 41.9 + 22.4 = 73.8 \cdot MW$$

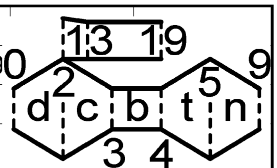
$$W_t = \dot{m}_4 c_{p_4} (T_{t5} - T_{t4}) = (247 + 4.25) \cdot 0.26(1310 - 2430) = 73{,}200 \cdot \frac{BTU}{lbmR} = 77.2 \cdot MW$$

$$\Delta Q_{cc} = \dot{m}_4 c_{p_4} T_{t4} - \dot{m}_3 c_p T_{t3} = (247 + 4.25) \cdot 0.26 \cdot 2430 - 247 \cdot 0.24 \cdot 1340 =$$
$$= 79{,}300 \cdot \frac{BTU}{lbmR} = 83.7 \cdot MW$$

				SI			
α	5.053			α	5.053		
f	0.017			f	0.017		
π_{LPC}	2.184			π_{cLP}	2.184		
π_{cHP}	9.844			π_{cHP}	9.844		
π_t	0.069			π_t	0.069		
mf	4.264			mf	1.934		
F_{Fan}(lb ft/s2)	1,104,480	Fn(lbf)	34,327	F_{Fan}(N)	152,699		
F_{main}(lb ft/s2)	299,004	Fn(lbf)	9,293	F_{main}(N)	41,339		
F(lb ft/s2)	1,403,484	Fn(lbf)	43,620	F(N)	194,038		
η_{th}	0.336			η_{th}	0.336		
TSFC(lbm/h lb	0.352			TSFC(mg/s N)	9.968		
η_{carnot}	0.787			η_{carnot}	0.787		
ao	1,117			ao	340		
ST/ao	0.841			ST/ao	0.841		
π_{tot}	21.5			π_{tot}	21		
T19(R)	525			T19	291		
a19(ft/s)	1,123			a19	342		
M19	0.788			M19	0.788		
T9(R)	1,201			T9	667		
a9(ft/s)	1,673			a9	510		
M9	0.711			M9	0.711		

J79D by Tom

JT9d By Tom									
	2	3	4	5	9	13	19		
	diff	comp	CC	Tur	No	Fan	No FAn		
c_p	1004			1057					
γ	1.4			1.35					
π	1	21.5	0.955		0.98	1.53	0.99		
$\eta, e_{c,t}$		0.92	0.95	0.9		0.96			
Tt				1349.8					
M0	0				QR	42800	kJ/kgK		
T0	288	K	p0	101,300	Pa	η_m	0.98		
alpha	5.053								
k	0.28571			0.25926					
R	286.857			274.037	kJ/kgK				
a0	340.1	m/s	V0	0.0	m/s				



$$k = \frac{\gamma - 1}{\gamma} = \frac{1.4 - 1}{1.4} = 0.2857 \qquad k_t = \frac{\gamma_t - 1}{\gamma_t} = \frac{1.35 - 1}{1.35} = 0.2593$$

$$R = kc_p = 1004 \cdot 0.2857 = 287 \cdot \frac{J}{kg \cdot K}$$

$$R_t = k_t c_{pt} = 1057 \cdot 0.2593 \frac{J}{kg \cdot K} = 274 \cdot \frac{J}{kg \cdot K}$$

Effetto Ram

$$a_0 = \sqrt{\gamma R T_0} = \sqrt{1.4 \cdot 287 \cdot 288} = 340 \cdot \frac{m}{s} \qquad V_0 = M_0 a_0 = 0 \cdot 340 = 0 \, \frac{m}{s}$$

$$\tau_r = \psi_0 = 1 + \frac{\gamma - 1}{2} M_0^2 = 1 \qquad T_{t0} = T_0 \tau_r = 288 \cdot 1 = 288 \cdot K$$

$$p_{t0} = p_0 \tau_r^{\frac{1}{k}} = 1.013 \cdot 10^5 \cdot 1^{\frac{1}{0.2857}} = 1.013 \cdot 10^5 \cdot Pa$$

Diffusore

$$p_{t2} = p_{t0} \pi_d = 1.013 \cdot 10^5 \cdot 1 = 1.013 \cdot 10^5 Pa$$

Compressore

$$\tau_c = \pi_c^{\frac{k}{e_c}} = 21.5^{\frac{0.2857}{0.92}} = 2.59 \qquad p_{t3} = p_{t2} \pi_c = 1.013 \cdot 10^5 \cdot 21.5 = 2.18 \cdot 10^6 \cdot Pa$$

$$T_{t3} = T_{t2} \tau_c = 288 \cdot 2.59 = 746.8 \cdot K$$

Camera di Combustione

$$\tau_\lambda = \frac{c_{pt} T_{t4}}{c_p T_0} = \frac{1057 \cdot 1350}{1004 \cdot 288} = 4.93$$

$$f = \frac{\tau_\lambda - \tau_c \tau_r}{Q_R \eta_b / (c_p T_0) - \tau_\lambda} = \frac{4.93 - 2.59 \cdot 1}{\frac{42.8 \cdot 10^6 \cdot 0.95}{1004 \cdot 288} - 4.93} = 0.01726$$

$$\tau_b = \frac{\tau_\lambda}{\tau_c \tau_r} = \frac{4.93}{2.59 \cdot 1} = 1.903$$

$$p_{t4} = p_{t3}\pi_b = 2.18 \cdot 10^6 \cdot 0.955 = 2.08 \cdot 10^6 \cdot Pa$$

Fan

$$\tau_f = \pi_f^{\frac{k}{e_f}} = 1.53^{\frac{0.2857}{0.96}} = 1.135 \qquad p_{t13} = p_{t2}\pi_f = 1.013 \cdot 10^5 \cdot 1.53 = 1.550 \cdot 10^6 \cdot Pa$$

$$T_{t13} = T_{t2}\tau_f = 288 \cdot 1.135 = 327 \cdot K$$

Turbina

$$\tau_t = 1 - \frac{\tau_r\left[(\tau_c - 1) + \alpha(\tau_f - 1)\right]}{\eta_m(1+f)\tau_\lambda} = 1 - \frac{1[1.59 + 5.05 \cdot 0.135]}{0.98 \cdot 1.017 \cdot 4.93} = 0.538$$

$$\pi_t = \tau_t^{\frac{1}{k_t e_t}} = 0.538^{\frac{1}{0.2593 \cdot 0.90}} = 0.0700$$

$$p_{t5} = p_{t4}\pi_t = 2.08 \cdot 10^6 \cdot 0.0700 = 0.146 \cdot 10^6 \cdot Pa \qquad T_{t5} = T_{t4}\tau_t = 1350 \cdot 0.538 = 726 \cdot K$$

Ugello

$$p_{t9} = p_{t5}\pi_n = 0.146 \cdot 10^6 \cdot 0.98 = 0.143 \cdot 10^6 \cdot Pa \qquad T_{t9} = T_{t5} = 726 \cdot K$$

$$\frac{p_{t9}}{p_9} = \pi_n\pi_t\pi_b\pi_c\pi_d\pi_r\frac{p_0}{p_9} = \frac{p_{t9}}{p_0}\frac{p_0}{p_9} = \frac{1.43}{1.013} \cdot 1 = 1.412$$

$$M_9 = \sqrt{\frac{2}{\gamma_t - 1}\left[\left(\frac{p_{t9}}{p_9}\right)^{k_t} - 1\right]} = \sqrt{\frac{2}{0.35}(1.412^{0.2593} - 1)} = 0.731$$

$$\frac{T_{t9}}{T_9} = \psi_9 = 1 + \frac{\gamma_t - 1}{2}M_9^2 = \left(\frac{p_{t9}}{p_9}\right)^{k_t} = 1.412^{0.2593} = 1.094 \qquad T_9 = \frac{T_9}{T_{t9}}T_{t9} = \frac{726}{1.094} = 664 \cdot K$$

$$a_9 = \sqrt{\gamma_t R_9 T_9} = \sqrt{1.35 \cdot 274 \cdot 664} = 496 \cdot \frac{m}{s} \qquad V_9 = M_9 a_9 = 0.731 \cdot 496 = 363 \cdot \frac{m}{s}$$

$$V_{9.e} = V_9\left(1 + \frac{1 - \frac{p_0}{p_9}}{\gamma_9 M_9^2}\right) = V_9 \qquad \frac{V_9}{a_0} = \frac{363}{340} = 1.061$$

Ugello Fan

$$p_{t19} = p_{t13}\pi_{nf} = 1.550 \cdot 10^5 \cdot 0.99 = 1.534 \cdot 10^5 \cdot Pa \qquad T_{t19} = T_{t13} = 327 \cdot K$$

$$\frac{p_{t19}}{p_{19}} = \frac{p_{t19}}{p_0}\frac{p_0}{p_{19}} = \frac{1.534}{1.013} \cdot 1 = 1.515$$

$$M_{19} = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{p_{t19}}{p_{19}}\right)^{k} - 1\right]} = \sqrt{\frac{2}{0.40}(1.515^{0.2856} - 1)} = 0.794$$

$$\frac{T_{t19}}{T_{19}} = \psi_{19} = 1 + \frac{\gamma - 1}{2}M_{19}^2 = \left(\frac{p_{t19}}{p_{19}}\right)^{k} = 1.515^{0.2856} = 1.126$$

$$T_{19} = \frac{T_{19}}{T_{t19}}T_{t19} = \frac{327}{1.126} = 290 \cdot K \qquad a_{19} = \sqrt{\gamma R T_{19}} = \sqrt{1.40 \cdot 287 \cdot 290} = 341.6\frac{m}{s}$$

$$V_{19} = M_{19} a_{19} = 0.794 \cdot 341.6 = 271 \cdot \frac{m}{s}$$

$$V_{19.e} = V_{19}\left(1 + \frac{1 - \frac{p_0}{p_{19}}}{\gamma M_{19}^2}\right) = V_{19} \qquad \frac{V_{19}}{a_0} = \frac{271}{340} = 0.797$$

Spinta e rendimenti

$$\frac{F_u}{\dot{m}_{air} a_0} = \frac{(1+f)}{1+\alpha}\frac{V_{9.\mathrm{e}}}{a_0} + \frac{\alpha}{1+\alpha}\frac{V_{19.\mathrm{e}}}{a_0} - M_0 = 0.1782 + 0.665 - 0 = 0.843$$

$$\frac{F_{u.core}}{\dot{m}_{air} a_0} = \frac{(1+f)}{1+\alpha}\frac{V_{9.\mathrm{e}}}{a_0} - \frac{M_0}{1+\alpha} = \frac{1.017}{6.05} 1.061 - 0 = 0.1782$$

$$\frac{F_{u.Fan}}{\dot{m}_{air} a_0} = \frac{\alpha}{1+\alpha}\frac{V_{19.\mathrm{e}}}{a_0} - \frac{\alpha M_0}{1+\alpha} = \frac{5.05}{6.05} 0.797 - 0 = 0.665$$

$$\frac{F_{u.core}}{F_u} = \frac{0.1782}{0.843} = 21\% \qquad \frac{F_{u.Fan}}{F_u} = \frac{0.165}{0.843} = 79\%$$

$$TSFC = \frac{f}{F_u/\dot{m}_0} = \frac{f}{(1+f)V_{9.\mathrm{e}} + \alpha V_{19.\mathrm{e}} - V_0} = \frac{0.01726}{1.017 \cdot 363 + 5.05 \cdot 271} = 9.93 \cdot 10^{-6}$$

$$N = (1+f)V_{9.e}^2 + \alpha V_{19.e}^2 - (1+\alpha)V_0^2 = 1.017 \cdot 363^2 + 5.05 \cdot 271^2 = 5.03 \cdot 10^5$$

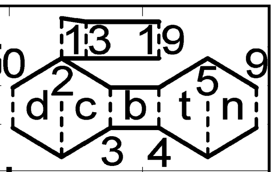
$$\eta_{\mathrm{th}} = \frac{\Delta \dot{KE}}{\mathcal{P}_t} = \frac{(1+f)V_{9.e}^2 + \alpha V_{19.e}^2 - (1+\alpha)V_0^2}{2fQ_R} = \frac{N}{2fQ_R} = \frac{5.03 \cdot 10^5}{2 \cdot 0.1726 \cdot 42.8 \cdot 10^6} = 34\%$$

$$\eta_p = \frac{2V_0\{[(1+f)V_{9.e}] + \alpha V_{19.e} - (1+\alpha)V_0\}}{(1+f)V_{9.e}^2 + \alpha V_{19.e}^2 - (1+\alpha)V_0^2} = 0$$

Section	c	f	t	λ		t			
τ	2.59299	1.13493	0.53755	4.93422	π	0.06993			
Section	0	2	3	4	5	9	13	19	
Tt	288.0	288	746.8	1349.8	725.586	725.586	326.859	326.859	
pt	101,300	101,300	2.18E+06	2.08E+06	145,448	142,539	154,989	153,439	
Core		f	0.01726						
Pt9/p9	M9	M9 Eff	Tt9/T9	P9	po/p9				
1.4071	0.72735	0.72735	1.09258	101300	1				
T9	a9	V9	V9/a0	V9/a0 eff	F/ma0	F/maira0		Fc/Ft	
664.102	495.666	360.524	1.06009	1.06009	1.07838	0.17816		0.21127	
Fan									
Pt19/p19	M19	M19 Eff	Tt19/T19	P19	po/p19				
1.5147	0.79359	0.79359	1.12596	101300	1				
T19	a19	V19	V19/a0	V19/a0 ef	F/ma0	F/maira0		FF/Ft	
290.294	341.441	270.965	0.79675	0.79675	4.02595	0.66512		0.78873	
Num	Section	t	th	p	0	TSFC*1e3	F/ma0	F/maira0	
5.03E+05	η	0.9281	0.3407	0	0	0.0099	5.10433	0.84327	

J79D by Tom M0=0.85

JT9d By Tom							
	2	3	4	5	9	13	19
	diff	comp	CC	Tur	No	Fan	No FAn
c_p	1004			1057			
γ	1.4			1.35			
π	1	21.5	0.955		0.98	1.53	0.99
$\eta, e_{c,t}$		0.92	0.95	0.9		0.96	
Tt				1349.8			
M0	0.85				QR	42800	kJ/kgK
T0	288	K	p0	101,300	Pa	η_m	0.98
alpha	5.053						



$$k = \frac{\gamma - 1}{\gamma} = \frac{0.4}{1.4} = 0.2867 \quad k_5 = \frac{\gamma_5 - 1}{\gamma_5} = \frac{0.35}{1.35} = 0.2593$$

$$R = kc_p = 0.2867 \cdot 1004 = 286.9 J/kgK \quad R_5 = 0.2593 \cdot 1057 = 274.0 J/kgK$$

$$a_0 = \sqrt{\gamma R T_0} = 1.4 \cdot 286.9 \cdot 288 = 340.1 m/s$$

$$V_0 = M_0 \cdot a_0 = 0.85 \cdot 340.1 = 289.1 m/s$$

Presa d'aria

$$\tau_r = \psi_0 = 1 + \frac{\gamma - 1}{2} M_0^2 = 1 + 0.2 \cdot 0.85^2 = 1.145$$

$$T_{t0} = T_{t2} = T_0 \tau_r = 288 \cdot 1.145 = 329.6K \quad p_{t0} = \tau_r^{\frac{1}{k}} p_0 = 1.145^{\frac{1}{0.2867}} 1.013 \cdot 10^5 = 162.5 kPa$$

$$p_{t2} = p_{t0} \pi_d = 162.5 \cdot 1 = 162.5 kPa$$

Compressore

$$\tau_c = \pi_c^{\frac{k}{e_c}} = 21.5^{\frac{0.2867}{0.92}} = 2.593$$

$$p_{t3} = p_{t2} \pi_c = 162.5 \cdot 21.5 \cdot 10^3 = 3493 kPa \qquad T_{t3} = T_{t2} \tau_c = 329.6 \cdot 2.593 = 854.7K$$

Camera di combustione

$$p_{t4} = p_{t3} \pi_b = 3.493 \cdot 0.955 \cdot 10^3 = 3336 kPa \qquad \tau_\lambda = \frac{c_{p5} T_{t4}}{c_p T_0} = \frac{1057 \cdot 1350}{288 \cdot 1004} = 4.934$$

$$f = \frac{\tau_\lambda - \tau_c \tau_r}{Q_R \eta_b / (c_p T_0) - \tau_\lambda} = \frac{4.934 - 2.593 \cdot 1.145}{42.8 \cdot 10^6 \cdot 0.95 / (288 \cdot 1004) - 4.934} = 0.01449$$

Fan

$$\tau_f = \pi_f^{\frac{k}{e_f}} = 1.53^{\frac{0.2867}{0.96}} = 1.135$$

$$p_{t13} = p_{t2} \pi_f = 162.5 \cdot 1.53 \cdot 10^3 = 248.6 kPa \quad T_{t13} = T_{t2} \tau_f = 329.6 \cdot 1.135 = 374.1K$$

Turbina

$$\tau_t = 1 - \frac{\tau_r\left[(\tau_c - 1) + \alpha\left(\tau_f - 1\right)\right]}{\eta_m(1+f)\tau_\lambda} = 1 - \frac{1.145[1.593 + 5.053 \cdot 0.135]}{0.98 \cdot 1.014 \cdot 4.934} = 0.4693$$

$$\pi_t = \tau_t^{\frac{1}{k_5 e_t}} = 0.4693^{\frac{1}{0.2593 \cdot 0.900}} = 0.03907$$

$$p_{t5} = p_{t4}\pi_t = 333.6 \cdot 0.03907 \cdot 10^3 = 130.3kPa$$

$$T_{t5} = T_{t4}\tau_t = 1350 \cdot 0.4693 = 633.4K$$

Ugello

$$p_{t9} = p_{t5}\pi_n = 130.3 \cdot 0.98 \cdot 10^3 = 127.7kPa$$

$$\frac{p_{t9}}{p_9} = \frac{127.7}{101.3} = 1.261 \qquad \psi_9 = \left(\frac{p_{t9}}{p_9}\right)^{k_5} = 1.261^{0.2593} = 1.062$$

$$M_9 = \sqrt{\frac{2}{\gamma_5 - 1}[\psi_9 - 1]} = \sqrt{\frac{2}{.35}[1.062 - 1]} = 0.5950$$

$$M_9 < 1 \to p_9 = p_0 \text{ (OK)}$$

$$T_9 = T_{t9}/\psi_9 = T_{t5}/\psi_9 = 633.4/1.062 = 596.5K$$

$$a_9 = \sqrt{\gamma_5 R_5 T_9} = \sqrt{1.35 \cdot 274.0 \cdot 596.5} = 469.8m/s$$

$$V_9 = M_9 \cdot a_9 = 0.5950 \cdot 469.8 = 279.5m/s$$

$$\frac{V_9}{\mathrm{a}_0} = \frac{279.5}{340.1} = 0.8219 \quad < M_0 \quad (??)$$

Ugello Fan

$$p_{t19} = p_{t13}\pi_{nf} = 248.6 \cdot 0.99 \cdot 10^3 = 246.1kPa$$

$$T_{t19} = T_{t13} = 374 \cdot K \qquad \frac{p_{t19}}{p_{19}} = \frac{p_{t19}}{p_0}\frac{p_0}{p_{19}} = \frac{2.46}{1.013} \cdot 1 = 2.43$$

$$M_{19} = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{p_{t19}}{p_{19}}\right)^k - 1\right]} = \sqrt{\frac{2}{0.40}(2.43^{0.2856} - 1)} = 1.201$$

Se l'ugello non è convergente divergente allora $\frac{p_0}{p_{19}} \neq 1$. Si impone quindi $M_{19} = 1$

$$\frac{T_{t19}}{T_{19}} = \psi_{19} = 1 + \frac{\gamma - 1}{2}M_{19}^2 = 1.200 \qquad T_{19} = \frac{T_{19}}{T_{t19}}T_{t19} = \frac{374}{1.200} = 312 \cdot K$$

$$p_{19} = \frac{p_{19}}{p_{t19}}p_{t19} = p_{t19}\psi_{19}^{-\frac{1}{k}} = 246(1.2)^{\frac{-1}{0.2856}} = 130 \cdot kPa$$

$$a_{19} = \sqrt{\gamma R T_{19}} = \sqrt{1.40 \cdot 287 \cdot 312} = 354\frac{m}{s}$$

$$V_{19} = M_{19}a_{19} = 1 \cdot 354 = 354 \cdot \frac{m}{s} \qquad \frac{p_0}{p_{19}} = \frac{1.013}{1.300} = 0.779$$

$$V_{19.e} = V_{19}\left(1 + \frac{1 - \frac{p_0}{p_{19}}}{\gamma M_{19}^2}\right) = 354\left(1 + \frac{1 - 0.779}{1.4 \cdot 1}\right) = 410 \cdot \frac{m}{s} \qquad \frac{V_{19.e}}{a_0} = \frac{410}{340} = 1.206$$

Spinta

$$\frac{F_u}{\dot{m}_{air} a_0} = \frac{(1+f)}{1+\alpha}\frac{V_{9.\mathrm{e}}}{a_0} + \frac{\alpha}{1+\alpha}\frac{V_{19.\mathrm{e}}}{a_0} - M_0 = -.00268 + .296 = .293$$

$$\frac{F_{u.core}}{\dot{m}_{air} a_0} = \frac{(1+f)}{1+\alpha}\frac{V_{9.\mathrm{e}}}{a_0} - \frac{M_0}{1+\alpha} = \frac{1.017}{6.05}0.822 - \frac{0.85}{6.05} = -.00268$$

$$\frac{F_{u.Fan}}{\dot{m}_{air} a_0} = \frac{\alpha}{1+\alpha}\frac{V_{19.\mathrm{e}}}{a_0} - \frac{\alpha M_0}{1+\alpha} = \frac{5.05}{6.05}.1.206 - \frac{5.05}{6.05}0.85 = 0.296$$

$$\frac{F_{u.core}}{F_u} = \frac{0.1782}{0.843} = 21\% \qquad \frac{F_{u.Fan}}{F_u} = \frac{0.165}{0.843} = 79\%$$

$$TSFC = \frac{f}{F_u/\dot{m}_0} = \frac{f}{(1+f)V_{9.\mathrm{e}} + \alpha V_{19.\mathrm{e}} - V_0} = \frac{0.01449}{1.014 \cdot 280 + 5.05 \cdot 410 - 289} = 24.3 \cdot 10^{-6}$$

$$N = (1+f)V_{9.e}^2 + \alpha V_{19.e}^2 - (1+\alpha)V_0^2 = 1.017 \cdot 280^2 + 5.05 \cdot 410^2 - 6.05 \cdot 289^2 = 4.21 \cdot 10^5$$

$$\eta_{\mathrm{th}} = \frac{\Delta K\dot{E}}{\mathcal{P}_t} = \frac{(1+f)V_{9.e}^2 + \alpha V_{19.e}^2 - (1+\alpha)V_0^2}{2 f Q_R} = \frac{N}{2 f Q_R} = \frac{4.21 \cdot 10^5}{2 \cdot 0.1449 \cdot 42.8 \cdot 10^6} = 34\%$$

$$\eta_p = \frac{2V_0\{[(1+f)V_{9.e}] + \alpha V_{19.e} - (1+\alpha)V_0\}}{(1+f)V_{9.e}^2 + \alpha V_{19.e}^2 - (1+\alpha)V_0^2} = \frac{2 \cdot 289(1.017 \cdot 280 + 5.05 \cdot 410 - 6.05 \cdot 289)}{4.21 \cdot 10^5} = 83\%$$

k	0.28571			0.25926					
R	286.857			274.037	kJ/kgK				
a0	340.1	m/s	V0	289.1	m/s				
$\tau_r = T_{t0} = 0$ /	1.1445								
Section	c	f	t	λ		t			
τ	2.59299	1.13493	0.46929	4.93422	π	0.03907			
Section	0	2	3	4	5	9	13	19	
Tt	329.6	329.616	854.7	1349.8	633.443	633.443	374.09	374.0899	
pt	162,467	162,467	3.49E+06	3.34E+06	130,342	127,735	248,574	246,089	
Core		f	0.01449						
Pt9/p9	M9	M9 Eff	Tt9/T9	P9	po/p9				
1.26096	0.59502	0.59502	1.06196	101300	1				
T9	a9	V9	V9/a0	V9/a0 eff	F/ma0	F/maira0		Fc/Ft	
596.486	469.755	279.513	0.82188	0.82188	-0.01621	-0.00268		-0.00913	
Fan									
Pt19/p19	M19	M19 Eff	Tt19/T19	P19	po/p19				
2.4293	1.20137	1	1.2	130004	0.77921				
T19	a19	V19	V19/a0	V19/a0 ef	F/ma0	F/maira0		FF/Ft	
311.742	353.83	353.83	1.0404	1.20448	1.7912	0.29592		1.00913	
Num	Section	t	th	p	0	TSFC*1e3	F/ma0	F/maira0	
4.21E+05	η	0.93345	0.3396	0.82835	0.28131	0.0240	1.775	0.293243	

Farokhi Example 4.16

	2	3	4	5	13	15	6	7	9
	diff	comp	CC	Tur	Fan		Mixer		No
c_p	1004			1152				1241	
γ	1.4			1.33				1.3	
π	0.9	13	0.95		1.9	0.99	0.9709	0.92	0.95
η, $e_{c,t}$		0.9	0.98	0.8	0.9			0.98	
Tt			1600					2000	
M0	2.0000				QR	42000	kJ/kgK		
T0	223.0	K	p0	10000.0	Pa	η_m	0.95	p9/p0	3.8
k	0.2857			0.2481				0.2308	
R	286.9			285.8	kJ/kgK			286.4	kJ/kgK
a0	299.3	m/s	V0	598.5	m/s	τ_r =(ψ)	1.8		

$$k = \frac{\gamma - 1}{\gamma} = \frac{1.4 - 1}{1.4} = 0.2857 \qquad k_t = \frac{\gamma_t - 1}{\gamma_t} = \frac{1.33 - 1}{1.33} = 0.2481$$

$$k_9 = \frac{\gamma_9 - 1}{\gamma_9} = \frac{1.3 - 1}{1.3} = 0.2308 \qquad R = kc_p = 1004 \cdot 0.2857 = 287 \cdot \frac{J}{kg \cdot K}$$

$$R_t = k_t c_{pt} = 1057 \cdot 0.2593 \frac{J}{kg \cdot K} = 286 \cdot \frac{J}{kg \cdot K}$$

$$R_9 = k_9 c_{p9} = 286 \cdot \frac{J}{kg \cdot K} \qquad p_0 = 10 \cdot kPa$$

Effetto Ram

$$a_0 = \sqrt{\gamma R T_0} = \sqrt{1.4 \cdot 287 \cdot 223} = 299 \cdot \frac{m}{s}$$

$$V_0 = M_0 a_0 = 2.0 \cdot 299 = 598 \ \frac{m}{s} \qquad \tau_r = \psi_0 = 1 + \frac{\gamma - 1}{2} M_0^2 = 1.8$$

$$T_{t0} = T_0 \tau_r = 223 \cdot 1.8 = 401 \cdot K$$

$$p_{t0} = p_0 \tau_r^{\frac{1}{k}} = 10 \cdot 1.8^{\frac{1}{0.2857}} = 78.2 \cdot kPa$$

Diffusore

$$p_{t2} = p_{t0} \pi_d = 78.2 \cdot 0.9 = 70.4 \cdot kPa$$

Compressore

$$\tau_c = \pi_c^{\frac{k}{e_c}} = 13^{\frac{0.2857}{0.90}} = 2.26 \qquad p_{t3} = p_{t2} \pi_c = 70.4 \cdot 13 = 915 \cdot kPa$$

$$T_{t3} = T_{t2} \tau_c = 401 \cdot 2.26 = 906 \cdot K$$

Camera di Combustione

$$\tau_\lambda = \frac{c_{pt} T_{t4}}{c_p T_0} = \frac{1152 \cdot 1600}{1004 \cdot 223} = 8.23$$

$$f=\frac{\tau_\lambda-\tau_c\tau_r}{Q_R\eta_b/(c_pT_0)-\tau_\lambda}=\frac{8.23-2.26\cdot 1.8}{\frac{42.0\cdot 10^6\cdot 0.98}{1004\cdot 223}-8.23}=0.0237$$

$$\tau_b=\frac{\tau_\lambda}{\tau_c\tau_r}=\frac{8.23}{2.26\cdot 1.8}=2.03$$

$$p_{t4}=p_{t3}\pi_b=915\cdot 0.95=870\cdot kPa$$

Fan

$$\tau_f=\pi_f^{\frac{k}{e_f}}=1.90^{\frac{0.2857}{0.90}}=1.226 \qquad p_{t13}=p_{t2}\pi_f=70.4\cdot 1.90=134\cdot kPa$$

$$T_{t13}=T_{t2}\tau_f=401\cdot 1.226=492\cdot K$$

Turbina

$$\pi_t=\frac{\pi_{fd}\pi_f}{\pi_b\pi_c}=\frac{0.99\cdot 1.90}{0.95\cdot 13}=0.1523 \qquad \tau_t=\pi_t^{k_te_t}=0.1523^{0.2481\cdot 0.8}=0.688$$

$$p_{t5}=p_{t4}\pi_t=870\cdot 0.1523=132\cdot kPa \qquad T_{t5}=T_{t4}\tau_t=1600\cdot 0.688=1101\cdot K$$

Mixer

$$\alpha=\frac{\eta_m(1+f)(1-\tau_t)\tau_\lambda-\tau_r(\tau_c-1)}{\tau_r(\tau_f-1)}=\frac{0.95\cdot 1.024(1-0.688)8.23-1.8(2.26-1)}{1.8(1.226-1)}=0.571$$

$$\tau_M=\frac{\frac{\alpha\tau_f\tau_r}{\tau_t\tau_\lambda}+(1+f)}{1+\alpha+f}=\frac{0.571\frac{1.226\cdot 1.8}{0.688\cdot 8.23}+1.024}{1.024+0.571}=0.782$$

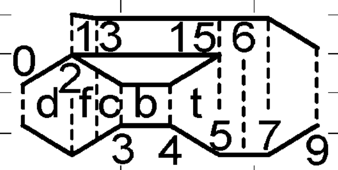
$$p_{t6}=p_{t5}\pi_M=132\cdot 0.9709=128.6\cdot kPa \qquad T_{t6}\sim T_{t5}\tau_M=1101\cdot 0.782=861\cdot K$$

Post Bruciatore

$$\tau_{\lambda AB}\frac{c_{p9}T_{t7}}{c_pT_0}=\frac{1241\cdot 2000}{1004\cdot 223}=11.09$$

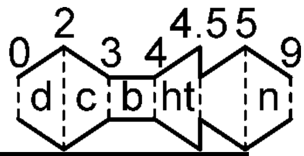
$$f_{AB}=\left(1+\frac{f}{1+\alpha}\right)\frac{\tau_{\lambda AB}-\tau_M\tau_t\tau_\lambda}{\frac{Q_{R.AB}\eta_{AB}}{c_pT_0}-\tau_{\lambda.AB}}=\left(1+\frac{0.0237}{1.571}\right)\frac{11.09-0.782\cdot 0.688\cdot 8.23}{\frac{42\cdot 10^6 0.98}{1004\cdot 223}-11.09}=0.0391$$

Section	c	f	t	λ	M	λ_{AB}			
τ	2.258	1.2260	0.6883	8.233	0.78147	11.0857			
Section	0	2	3	4	5	6	7	9	13
Tt	401.4	401.4	906.2	1600	1101.27	860.61	2000	2000	492.12
pt	78,244	70,420	915,461	869,688	132,460	128,606	118,317	112,401	133,798
π_t	0.15231	f	0.02374	α	0.5707	f_{AB}	0.03912	f_{tot}	0.05424
Pt9/p9	M9	M9 Eff	Tt9/T9	P9	po/p9				
2.958	1.377	1.377	1.28437	38000	0.26316				
T9	a9	V9	V9/a0	V9/a0 eff	F/ma0	F/maira0			
1557.19	761.407	1048.36	3.50318	4.551	4.39376	2.79736			
Num	Section	t	th	p	0	TSFC*e3			
1.6E+06	η	0.83551	0.3505	0.6275	0.21996	0.06479		64.787	



Farokhi Example 4.386

	2	3	4	4.5	5	9	
	diff	comp	CC	Tur	Tur	No	Prop
cp	1004			1152	J/kgs		
g	1.4			1.33			
p	0.99	35	0.96				
h, ec,t		0.92	0.99	0.8	0.859	0.95	0.85
Tt				1650			
M0	0.82				QR	42000	kJ/kgK
T0	258	K	p0	30,000	Pa		
alpha	0.75	m0	50	kg/s			



η_mH	0.99
η_mL	0.99
η_{gb}	0.995

$$k = \frac{\gamma - 1}{\gamma} = \frac{0.4}{1.4} = 0.2867 \qquad k_5 = \frac{\gamma_5 - 1}{\gamma_5} = \frac{0.33}{1.33} = 0.2481$$

$$R = kc_p = 0.2867 \cdot 1004 = 286.9 J/kgK \qquad R_5 = 0.2481 \cdot 1152 = 285.8 J/kgK$$

$$a_0 = \sqrt{\gamma R T_0} = 1.4 \cdot 286.9 \cdot 258 = 321.9 m/s$$

$$V_0 = M_0 \cdot a_0 = 0.82 \cdot 321.9 = 263.9 m/s$$

Effetto Ram

$$\tau_r = \psi_0 = 1 + \frac{\gamma - 1}{2} M_0^2 = 1 + 0.2 \cdot 0.81 = 1.134$$

$$T_{t0} = T_0 \tau_r = 288 \cdot 1.134 = 292.7K \qquad p_{t0} = \tau_r^{\frac{1}{k}} p_0 = 1.135^{\frac{1}{0.2867}} 30.00 \cdot 10^3 = 46.66 kPa$$

Diffusore

$$p_{t2} = p_{t0} \pi_d = 46.66 \cdot 0.99 \cdot 10^3 = 46.19 kPa \qquad T_{t0} = T_{t2}$$

Compressore

$$\tau_c = \pi_c^{\frac{k}{e_c}} = 35^{\frac{0.2867}{0.92}} = 3.017$$

$$p_{t3} = p_{t2} \pi_c = 46.19 \cdot 35 \cdot 10^3 = 1617 kPa \qquad T_{t3} = T_{t2} \tau_c = 292.7 \cdot 3.017 = 883.0K$$

Camera di combustione

$$p_{t4} = p_{t3} \pi_b = 1.617 \cdot 0.99 \cdot 10^3 = 1552 kPa \qquad \tau_\lambda = \frac{c_{p5} T_{t4}}{c_p T_0} = \frac{1152 \cdot 1650}{258 \cdot 1004} = 7.338$$

$$f = \frac{\tau_\lambda - \tau_c \tau_r}{Q_R \eta_b / (c_p T_0) - \tau_\lambda} = \frac{7.338 - 3.017 \cdot 1.134}{42.0 \cdot 10^6 \cdot 0.99 / (258 \cdot 1004) - 7.338} = 0.02556$$

Turbina HP

$$\tau_{tH} = 1 - \frac{\tau_r (\tau_c - 1)}{\eta_{mH} (1 + f) \tau_\lambda} = 1 - \frac{1.134(2.017)}{0.99 \cdot 1.026 \cdot 7.338} = 0.6929$$

$$\pi_{tH} = \tau_{tH}^{\frac{1}{k_5 e_{tH}}} = 0.6929^{\frac{1}{0.2481\cdot 0.800}} = 0.1575$$

$$p_{t45} = p_{t4}\pi_{tH} = 155.2 \cdot 0.1575 \cdot 10^3 = 244.5kPa \qquad T_{t45} = T_{t4}\tau_{tH} = 1650 \cdot 0.6929 = 1143K$$

Turbina LP

Supponendo funzionamento corretto nell'ugello: $\frac{p_9}{p_0}$=1

$$\tau_{tL} = 1 - \eta_{tL}\alpha_p\left[1 - \left(\frac{p_0}{p_{t45}}\right)^{k_5}\right] = 1 - \eta_{tL}0.75\left[1 - \left(\frac{30}{244.5}\right)^{0.2481}\right]$$

$$\tau_{tL} = 1 - \eta_{tL}0.75[1 - 0.5942] = 1 - \eta_{tL}0.3044$$

Supponendo $\eta_{tL} = 1 \rightarrow \tau_{tL} = 0.6956$ $\qquad \eta_{tL} = \frac{1-\tau_{tL}}{1-\tau_{\tau L}^{\frac{1}{e_{tL}}}} = \frac{1-0.6956}{1-0.6956^{\frac{1}{0.859}}} = 0.8833$

Iterando si ha in sequenza: $\tau_{tL} = 0.7312$, $\eta_{tL} = 0.88010$, $\tau_{tL} = 0.7321$, $\eta_{tL} = 0.8800$, $\tau_{tL} = 0.7322$

$$\pi_{tL} = \tau_{tL}^{\frac{1}{k_5 e_{tL}}} = 0.7322^{\frac{1}{0.2481\cdot 0.859}} = 0.2316$$

$$p_{t5} = p_{t45}\pi_{tL} = 244.5 \cdot 0.2316 \cdot 10^3 = 56.63kPa \qquad T_{t5} = T_{t45}\tau_{tL} = 1143 \cdot 0.7322 = 837.1K$$

Ugello

$$\eta_n = \frac{\left(\frac{p_{t5}}{p_9}\right)^{k_5} - \pi_n^{-k_5}}{\left(\frac{p_{t5}}{p_9}\right)^{k_5} - 1} \rightarrow \pi_n = \left\{\left(\frac{p_{t5}}{p_9}\right)^{k_9} - \eta_n\left[\left(\frac{p_{t5}}{p_9}\right)^{k_9} - 1\right]\right\}^{-\frac{1}{k_5}}$$

$$\left(\frac{p_{t5}}{p_9}\right)^{k_5} = \left(\frac{p_{t5}}{p_0}\right)^{k_5} = \left(\frac{56.63}{30}\right)^{0.2481} = 1.171$$

$$\pi_n = \{1.171 - 0.95[1.171 - 1]\}^{-\frac{1}{0.2481}} = 0.9663$$

$$p_{t9} = p_{t5}\pi_n = 56.63 \cdot 0.9663 \cdot 10^3 = 54.72kPa \qquad \frac{p_{t9}}{p_9} = \frac{54.72}{30} = 1.824$$

$$\psi_9 = \left(\frac{p_{t9}}{p_9}\right)^{k_5} = 1.824^{0.2481} = 1.161 \quad M_9 = \sqrt{\frac{2}{\gamma_5 - 1}[\psi_9 - 1]} = \sqrt{\frac{2}{.33}[1.161 - 1]} = 0.9873$$

$M_9 < 1 \rightarrow p_9 = p_0$ (OK)

$T_9 = T_{t9}/\psi_9 = T_{t5}/\psi_9 = 837.1/1.161 = 721.1K$

$a_9 = \sqrt{\gamma_5 R_5 T_9} = 1.33 \cdot 285.8 \cdot 721.1 = 523.6m/s$

$$V_9 = M_9 \cdot a_9 = 0.9873 \cdot 523.6 = 516.9m/s \qquad \frac{V_9}{\mathrm{a}_0} = \frac{516.9}{321.9} = 1.606 > M_0 \quad (OK)$$

Propeller

$$\frac{\mathcal{P}_s}{\dot{m}_0} = (1 + f)\eta_{gb}\eta_{m_{tL}}(1 - \tau_{tL})c_{p5}T_{t45} =$$

$$\frac{\mathcal{P}_s}{\dot{m}_0} = 1.026 \cdot 0.995 \cdot 0.99 \cdot (1 - 0.7322) \cdot 1152 \cdot 1143 = 356.4\frac{kJ}{kg}$$

Spinta

$$\frac{F_{u.c}}{\dot{m}_0 a_0} = (1+f)\frac{V_{9.e}}{a_0} - M_0 = 1.026 \cdot 1.606 - 0.82 = 0.8270$$

$$\frac{F_{u.p}}{\dot{m}_0 a_0} = \frac{\eta_{prop}\mathcal{P}_S}{\dot{m}_0 V_0 a_0} = \frac{0.85 \cdot 356.4}{263.9 \cdot 321.9}10^3 = 3.565$$

$$\frac{F_u}{\dot{m}_0 a_0} = \left(\frac{F_{u.c}}{\dot{m}_0 a_0} + \frac{F_{u.o}}{\dot{m}_0 a_0}\right) = 0.8279 + 3.565 = 4.392$$

$$TSFC = \frac{f}{F_u/\dot{m}_0} = \frac{0.02556 \cdot 10^3}{4.392 \cdot 321.9} = 0.01808\frac{g}{s}\frac{1}{N}$$

$$\eta_{th} = \frac{\mathrm{a}_0^2[(1+f)V_{9.e}^2/\mathrm{a}_0^2 - M_0^2] + 2\mathcal{P}_S/\dot{m}_0}{2fQ_R} =$$

$$\eta_{th} = \frac{321.9^2[1.026 \cdot 0.8279^2 - 0.82^2] + 2 \cdot 356.4}{2 \cdot 0.02556 \cdot 42.0 \cdot 10^6} = \frac{9.171 \cdot 10^5}{2.147 \cdot 10^6} = 0.4271$$

$$\eta_p = \frac{2\frac{F_u}{\dot{m}_0 a_0}a_0 V_0}{\mathrm{a}_0^2[(1+f)V_{9.e}^2/\mathrm{a}_0^2 - M_0^2] + 2\mathcal{P}_S/\dot{m}_0} = \frac{2 \cdot 4.392 \cdot 263.9 \cdot 321.9}{9.171 \cdot 10^5} = 0.8138$$

$$\eta_0 = \eta_{th}\eta_p = 0.4271 \cdot 0.8138 = 0.3476$$

k	0.28571			0.24812				
R	286.857			285.835	kJ/kgK			
a0	321.9	m/s	V0	263.9	m/s			
$\tau_r = T_{t0} = 0$,	1.13448							
Section	c	tH	tL	λ		tH	tL	
τ	3.01665	0.69292	0.73216	7.33809	π	0.15754	0.23161	
Section	0	2	3	4	4.5	5	9	
Tt	292.7	292.696	883.0	1650	1143.32	837.102	837.102	
pt	46,656	46,190	1.62E+06	1.55E+06	244,499	56,629	54,722	
Core		f	0.02556					
Pt9/p9	M9	M9 Eff	Tt9/T9	P9	po/p9			
1.82407	0.98729	0.98729	1.16083	30000	1			
T9	a9	V9	V9/a0	V9/a0 eff	F/ma0	Fc/Ft		
721.122	523.585	516.931	1.60593	1.60593	0.82698	0.18828		
Prop								
PS/mo					F/ma0	FP/Ft		
356,378	J/kg				3.56535	0.81172		
Num	Section	t	th	p	0	TSFC*1e3	F/ma0	
9.17E+05	η	0.83491	0.42712	0.8138	0.34759	0.0181	4.39233	
Calcolo iterativo rendimento TL partendo da eTL								
p9/pt45	η_{TL}	τ	η_{TL}	τ	η_{TL}	τ	η_{TL}	τ
0.1227	1	0.69564	0.88325	0.73117	0.88008	0.73214	0.88	0.73216
	0.88	0.73216	0.88	0.73216	0.88	0.73216	0.88	0.73216
Calcolo π_n partendo da η_n								