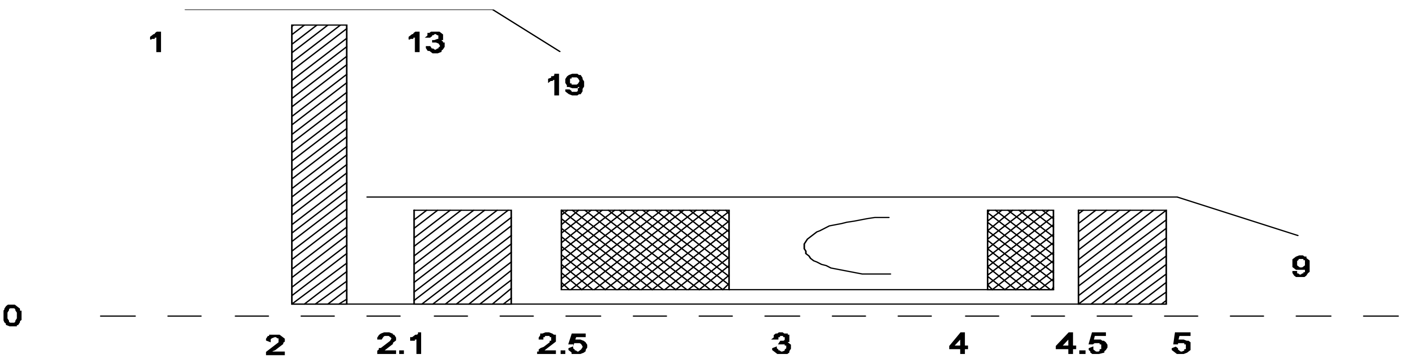
Turbofan de Correntes Separadas com Dois Eixos (“Twin-Spool”)

Diagrama Esquemático



Análise de Ciclo Não-Ideal

Dados de Entrada

Dados de voo

$$M_o[Mach],\ (P_0\ [Pa],\ \ T_0\ [K])\ ou\ H_0[m]$$

Dados do combustível e limite tecnológico da turbina

$$h_{PR}[J/kg],\ T_{t4}[K]$$

Dados dos fluidos de trabalho

$$\gamma,\ R\ [J/(kg.K)], c_p[J/(kg.K)]$$

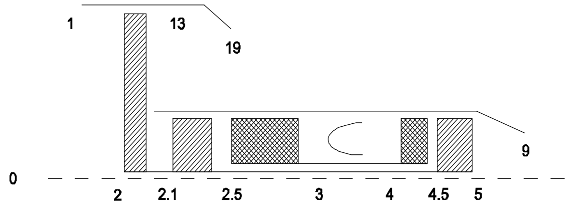
ar (subscrito *c*)

$\gamma_c = 1{,}4$ $\quad R_c = 287\, J/(kg.K)$ $\quad c_{pc} = 1004\, J/(kg.K)$

gás queimado (subscrito *t*)

$\gamma_t = 1{,}3$ $\quad R_t = 291\, J/(kg.K)$ $\quad c_{pt} = 1100\, J/(kg.K)$

Dados de componentes do motor



$$\pi_{dmax},\ \pi_f, \pi_{cL}, \pi_{cH}, \pi_b,\ \eta_b,\ \pi_n$$

Escoamento livre (0), não perturbado (T_0, P_0, M_0)

Entrada de Ar (0-1)

$$\tau_r = 1 + \frac{\gamma - 1}{2} {M_0}^2 \qquad \pi_r = \tau_r^{\frac{\gamma}{\gamma-1}}$$

Entrada de Ar (1-2), com eficiência de recuperação (η_r)

$$\eta_r = [1 - 0{,}075(M_0 - 1)^{1{,}35}]$$
$$para\ M_0 > 1$$
$$e \quad \eta_r = 1\ para\ M_0 \leq 1$$

$$\pi_d = \eta_r \pi_{dmax} \qquad \tau_d = \pi_d^{\frac{\gamma_c - 1}{\gamma_c}}$$

Fan (2-2.1) e (2-13)

$$\tau_f = \pi_f^{\frac{\gamma_c - 1}{\gamma_c e_f}}$$

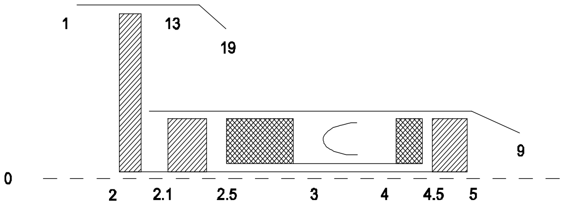
Compressor de baixa pressão (2.1-2.5)

$$\tau_{cL} = \pi_{cL}^{\frac{\gamma_c - 1}{\gamma_c e_{cL}}} \qquad \eta_{cL} = \frac{\pi_{cL}^{(\gamma_c - 1)/\gamma_c} - 1}{\tau_{cL} - 1}$$

Compressor de alta pressão (2.5-3)

$$\tau_{cH} = \pi_{cH}^{\frac{\gamma_c - 1}{\gamma_c e_{cH}}} \qquad \eta_{cH} = \frac{\pi_{cH}^{(\gamma_c - 1)/\gamma_c} - 1}{\tau_{cL} - 1}$$

Combustor (3-4)



$$\tau_\lambda = \frac{c_{pt}T_{t4}}{c_{pc}T_0}$$

$$\eta_b \dot{m}_f h_{PR} = \left(\dot{m}_f + \dot{m}_C\right) c_{pt}T_{t4} - \dot{m}_C c_{pt} T_{t3}$$

$$f = \frac{\dot{m}_f}{\dot{m}_C} = \frac{\tau_\lambda - \tau_r\tau_d\tau_f\tau_{cL}\tau_{cH}}{\eta_b h_{PR}/(c_{pc}T_0) \ - \tau_\lambda}$$

Turbina de alta pressão (4-4.5)

$$\dot{m}_C c_{pc}(T_{t3} - T_{t2.5}) = -\eta_{mH}\left(\dot{m}_C + \dot{m}_f\right) c_{pt}(T_{t4.5} - T_{t4})$$

$$\tau_{tH} = 1 - \ \eta_{mH} \frac{(\tau_{cH} - 1)}{(1 + f)} \frac{\tau_r\tau_d\tau_f\tau_{cL}}{\tau_\lambda}$$

$$\pi_{tH} = {\tau_{tH}}^{\gamma_t/(\gamma_t - 1)e_{tH}}$$

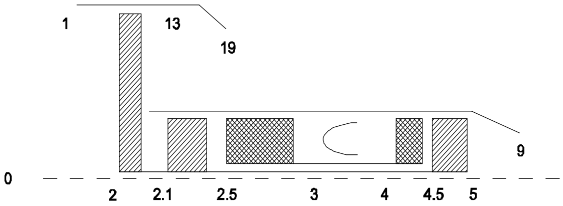
$$\eta_{tH} = \frac{\tau_{tH} - 1}{{\pi_{tH}}^{(\gamma_t - 1)/\gamma_t} - 1}$$

Turbina de baixa pressão (4.5-5)

$$[\dot{m}_F c_{pc}(T_{t13} - T_{t2}) - \dot{m}_C c_{pc}(T_{t2.5} - T_{t2})] = -\eta_{mL}\left(\dot{m}_C + \dot{m}_f\right) c_{pt}(T_{t5} - T_{t4.5})$$

$$\tau_{tL} = 1 - \ \eta_{mL} \frac{\left[\alpha\left(\tau_f - 1\right) + (\tau_{cL} - 1)\right]}{(1 + f)} \frac{\tau_r\tau_d}{\tau_\lambda\tau_{tH}}$$

$$\alpha = \frac{\dot{m}_F}{\dot{m}_C}$$



$$\dot{m}_0 = \dot{m}_C + \dot{m}_F$$

$$\pi_{tL} = \tau_{tL}{}^{\gamma_t/(\gamma_t-1)e_{tL}}$$

$$\eta_{tL} = \frac{\tau_{tL} - 1}{\pi_{tL}{}^{(\gamma_t-1)/\gamma_t} - 1}$$

Tubeira do motor central (5-9)

Condição prescrita $\frac{P_0}{P_9}$

$$\frac{P_{t9}}{P_9} = \frac{P_0}{P_9}\pi_r\pi_d\pi_f\pi_{cL}\pi_{cH}\pi_b\pi_{tH}\pi_{tL}\pi_n$$

Condição subsônica $\frac{P_{t9}}{P_9} < \left(\frac{\gamma_t+1}{2}\right)^{\gamma_t/(\gamma_t-1)}$ $\frac{P_0}{P_9} = 1$

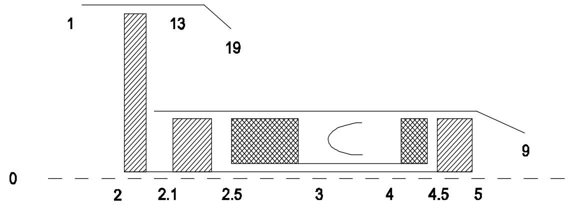
$$M_9 = \sqrt{\frac{2}{\gamma_t - 1}\left[\left(\frac{P_{t9}}{P_9}\right)^{(\gamma_t-1)/\gamma_t} - 1\right]}$$

$$\frac{T_{t9}}{T_0} = \frac{c_{pc}}{c_{pt}}\tau_\lambda\tau_{tH}\tau_{tL}\tau_n$$

$$\frac{T_9}{T_0} = \frac{T_{t9}/T_0}{(P_{t9}/P_9)^{(\gamma_t-1)/\gamma_t}}$$

$$\frac{V_9}{a_0} = M_9\sqrt{\frac{\gamma_t R_t}{\gamma_c R_c}\frac{T_9}{T_0}}$$

Tubeira do fan (13-19)



Condição subsônica $\frac{P_{t19}}{P_{19}} < \left(\frac{\gamma_c+1}{2}\right)^{\gamma_c/(\gamma_c-1)}$ $\frac{P_0}{P_{19}} = 1$

$$\frac{P_{t19}}{P_{19}} = \frac{P_0}{P_{19}} \pi_r \pi_d \pi_f \pi_{fn}$$

$$M_{19} = \sqrt{\frac{2}{\gamma_c - 1}\left[\left(\frac{P_{t19}}{P_{19}}\right)^{(\gamma_c-1)/\gamma_c} - 1\right]}$$

$$\frac{T_{t19}}{T_0} = \tau_r \tau_f \tau_{fn}$$

$$\frac{T_{19}}{T_0} = \frac{T_{t19}/T_0}{(P_{t19}/P_{19})^{(\gamma_c-1)/\gamma_c}}$$

$$\frac{V_{19}}{a_0} = M_{19}\sqrt{\frac{T_{19}}{T_0}}$$

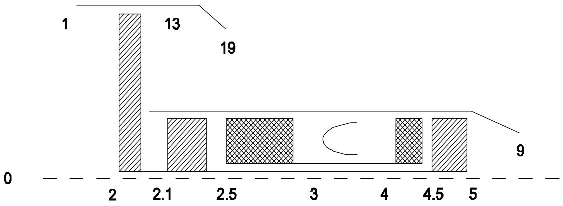
Empuxo específico

$$\frac{F_C}{\dot{m}_0} = \frac{a_0}{(1+\alpha)}\left[(1+f)\frac{V_9}{a_0} - M_0 + (1+f)\frac{R_t\, T_9/T_0}{R_c\, V_9/a_0}\frac{(1 - P_0/P_9)}{\gamma_c}\right]$$

$$\frac{F_F}{\dot{m}_0} = \frac{\alpha a_0}{(1+\alpha)}\left[\frac{V_{19}}{a_0} - M_0 + \frac{T_{19}/T_0}{V_{19}/a_0}\frac{(1 - P_0/P_{19})}{\gamma_c}\right]$$

$$\frac{F}{\dot{m}_0} = \frac{F_C}{\dot{m}_0} + \frac{F_F}{\dot{m}_0}$$

Razão de Empuxo $$FR = \frac{F_F}{\dot{m}_0} \Big/ \frac{F_C}{\dot{m}_0}$$



Consumo específico

$$S = \frac{f}{(1+\alpha)\, F/\dot{m}_0}$$

Eficiências (*conferir*)

$$\eta_t = \frac{{a_0}^2\left[(1+f)\left(\frac{V_9}{a_0}\right)^2 + \alpha\left(\frac{V_{19}}{a_0}\right)^2 - (1+\alpha){M_0}^2\right]}{2fh_{PR}}$$

$$\eta_p = \frac{2M_0\left[(1+f)\frac{V_9}{a_0} + \alpha\frac{V_9}{a_0} - (1+\alpha)M_0\right]}{\left[(1+f)\left(\frac{V_9}{a_0}\right)^2 + \alpha\left(\frac{V_{19}}{a_0}\right)^2 - (1+\alpha){M_0}^2\right]}$$

$$\eta_o = \eta_p\eta_t$$