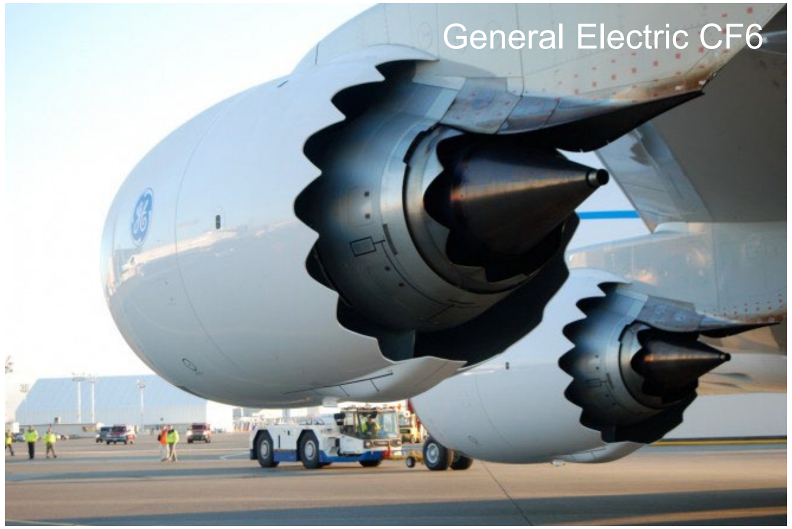
Universidade de São Paulo
Escola de Engenharia de São Carlos

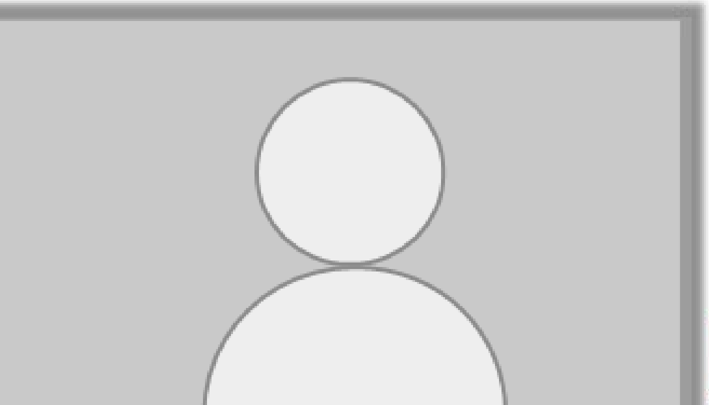
SEM0551 Fenômenos de Transporte

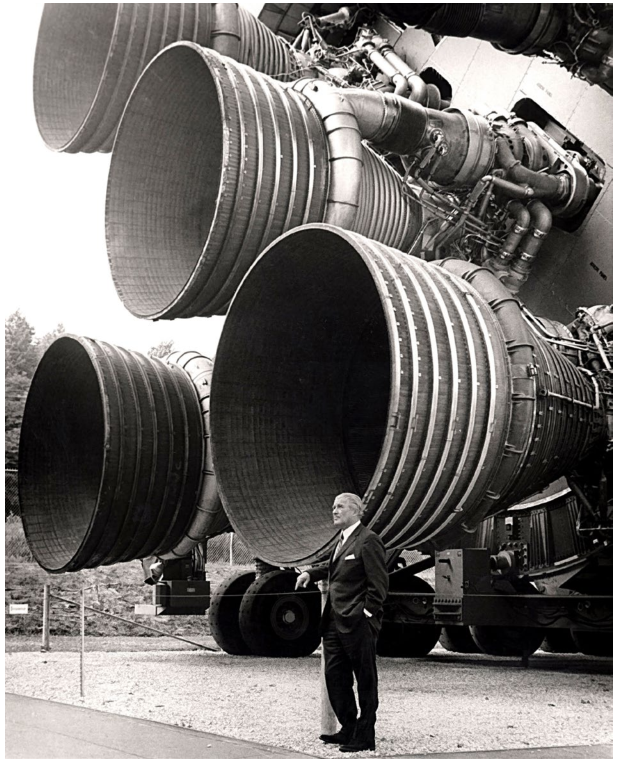
EQUAÇÕES DE BALANÇO DE ENERGIA PARA SISTEMAS ABERTOS

Paulo Seleghim Jr.
Universidade de São Paulo

Aplicação: análise termodinâmica do Boeing 747







150 GW !!!

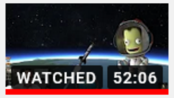
15 ton/sec !!!

Como um foguete pode acelerar no espaço - a terceira lei de Newton
Prof. P. Seleghim

Minha Equação Malvada Favorita (Tsiolkovsky) - análise do lançamento da missão MARS2020 Perseverance
Prof. P. Seleghim

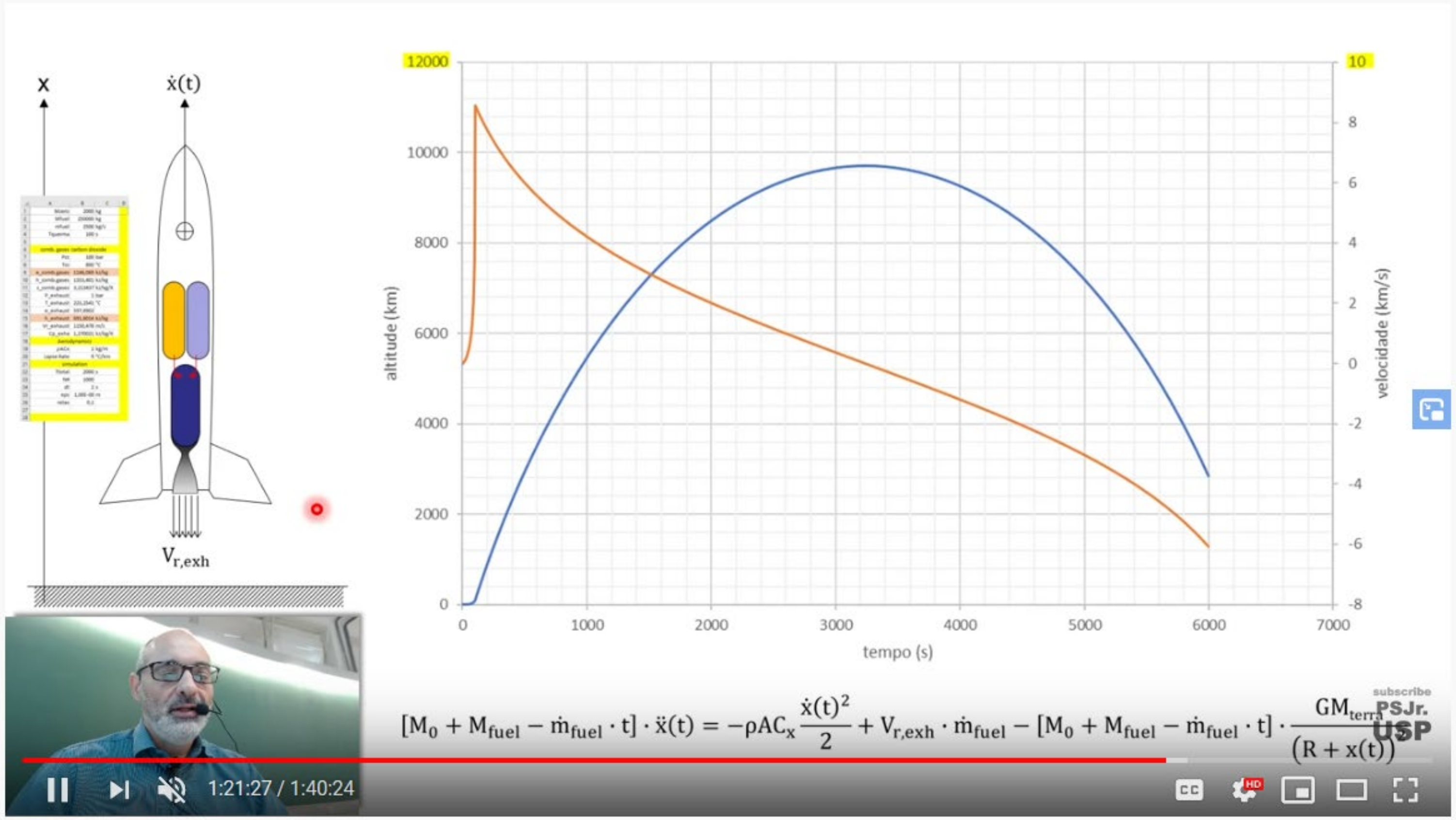
Entendendo o Estagiamento de um Foguete
Prof. P. Seleghim

Entendendo a pilotagem de um foguete - análise da telemetria do lançame SpaceX
Prof. P. Seleghim



Entendendo o Lançamento de um Foguete / Simulador de Voo
Prof. P. Seleghim

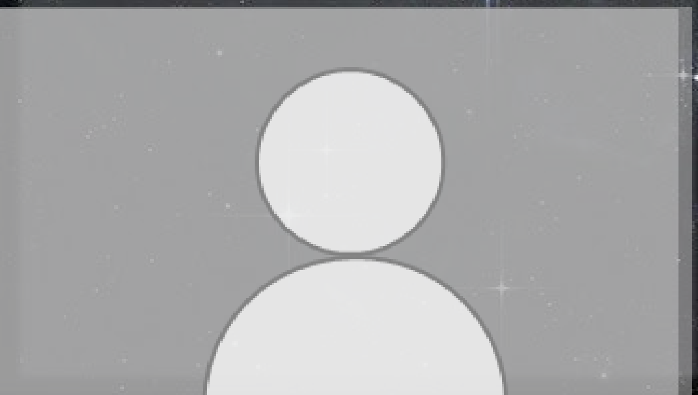
Entendendo os Motores de Foguete 1/2 Configurações
Prof. P. Seleghim



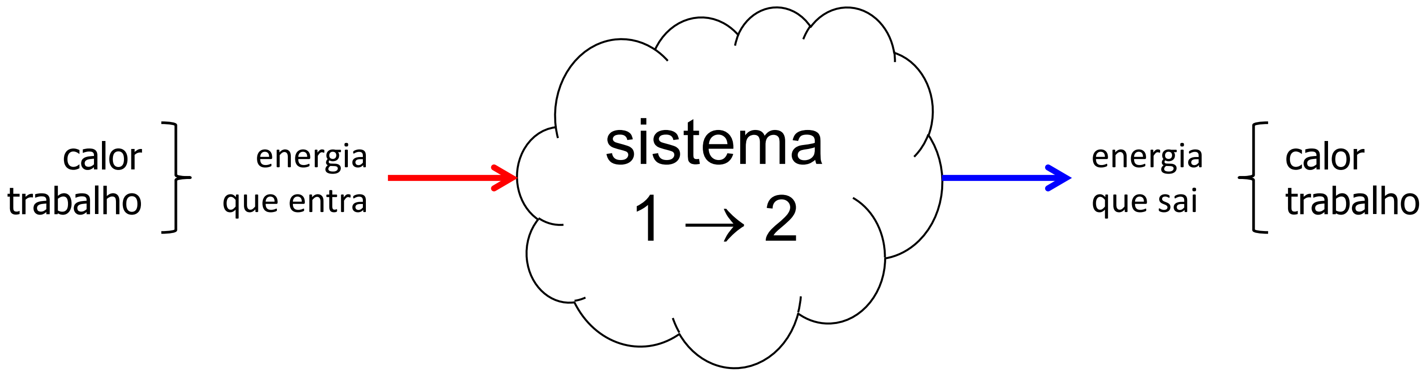
Termodinâmica: T5bis Rocket Simulation/ Equação de balanço para volumes de controle 2/2

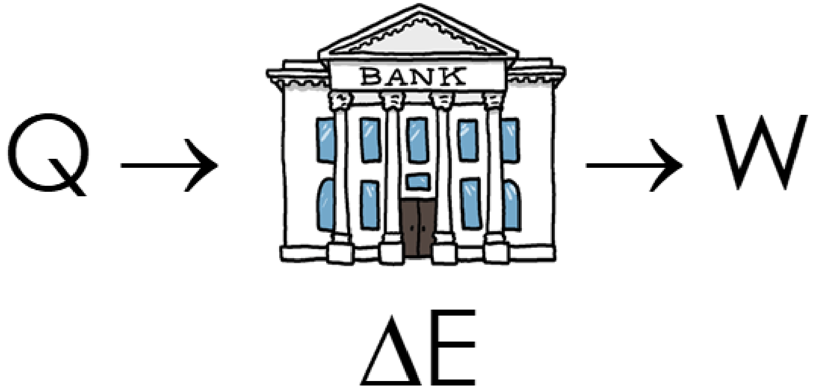
As questões postadas no Chat do YouTube serão respondidas ao final da aula.

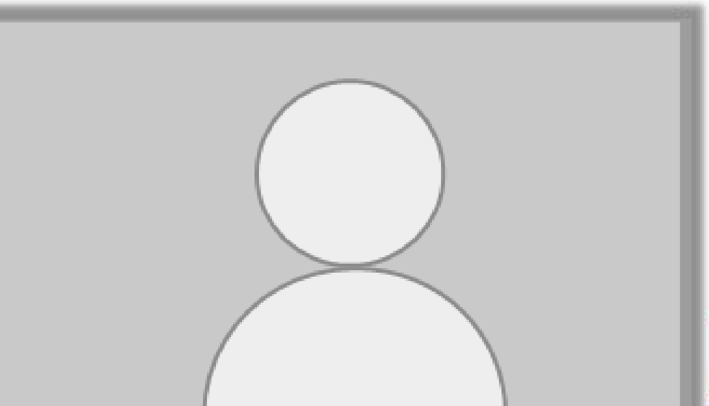
Adequando o inventário energético para os sistemas abertos...



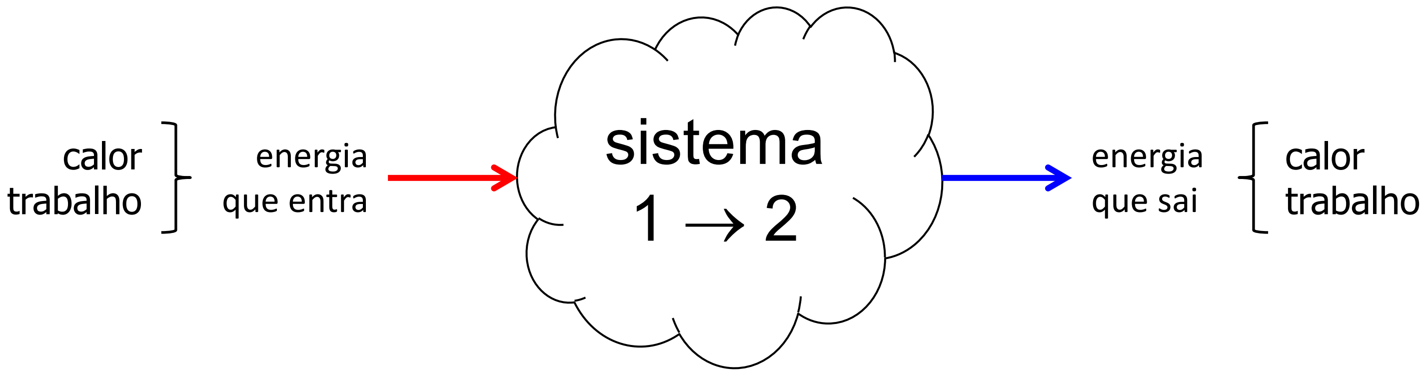
Princípio da conservação da energia: sistema fechado







Princípio da conservação da energia: sistema fechado

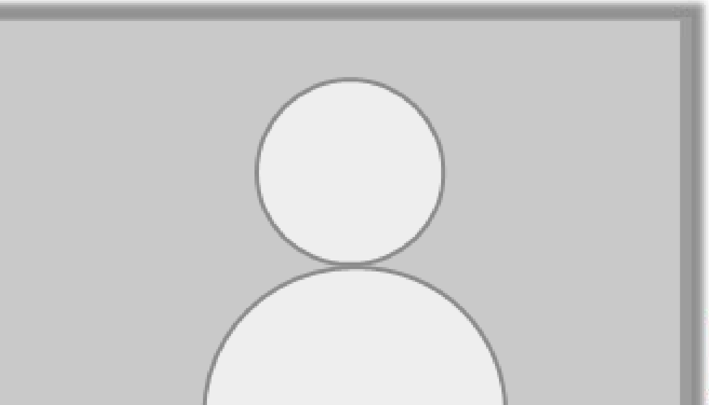


$$\Delta E = \Delta U + \Delta EC + \Delta EP$$

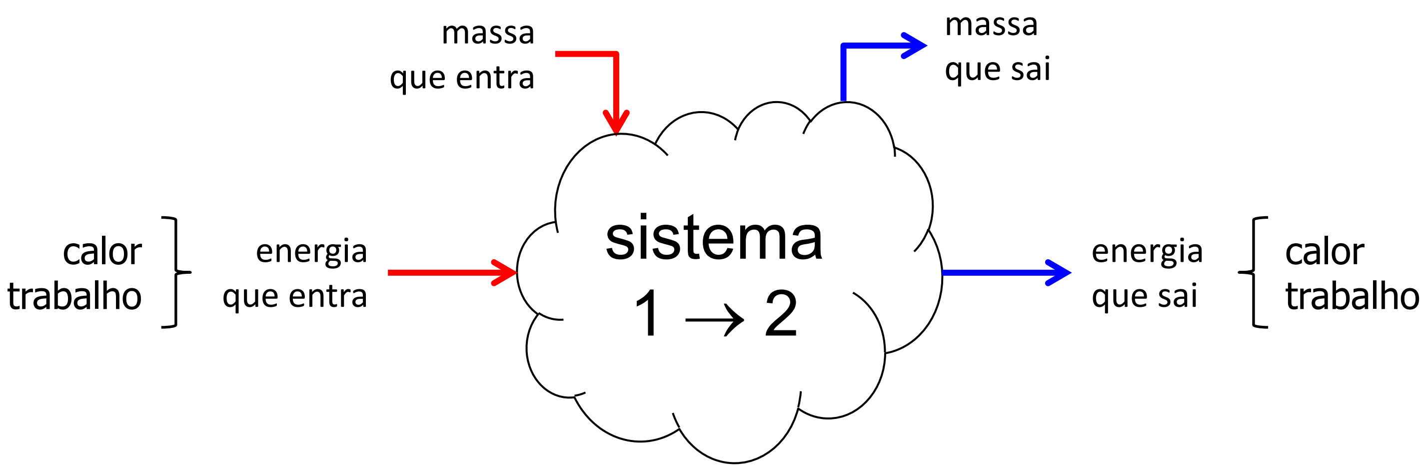
ΔU → energia interna (agitação molecular)

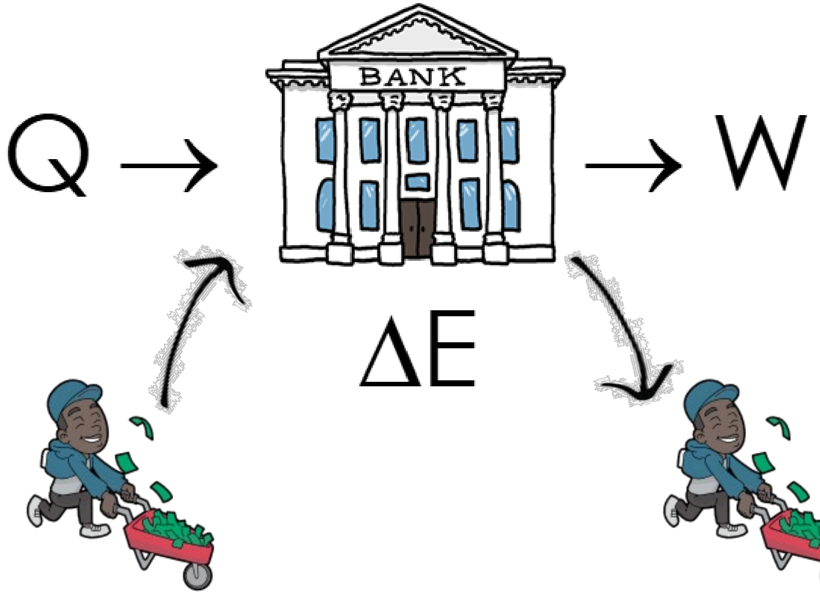
ΔEC → energia cinética macroscópica

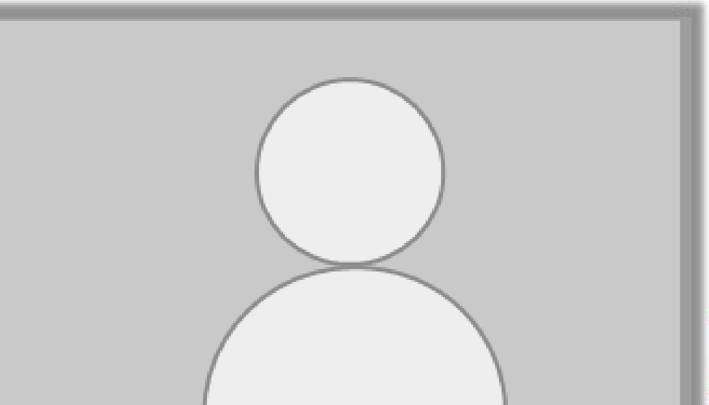
ΔEP → energia potencial macroscópica



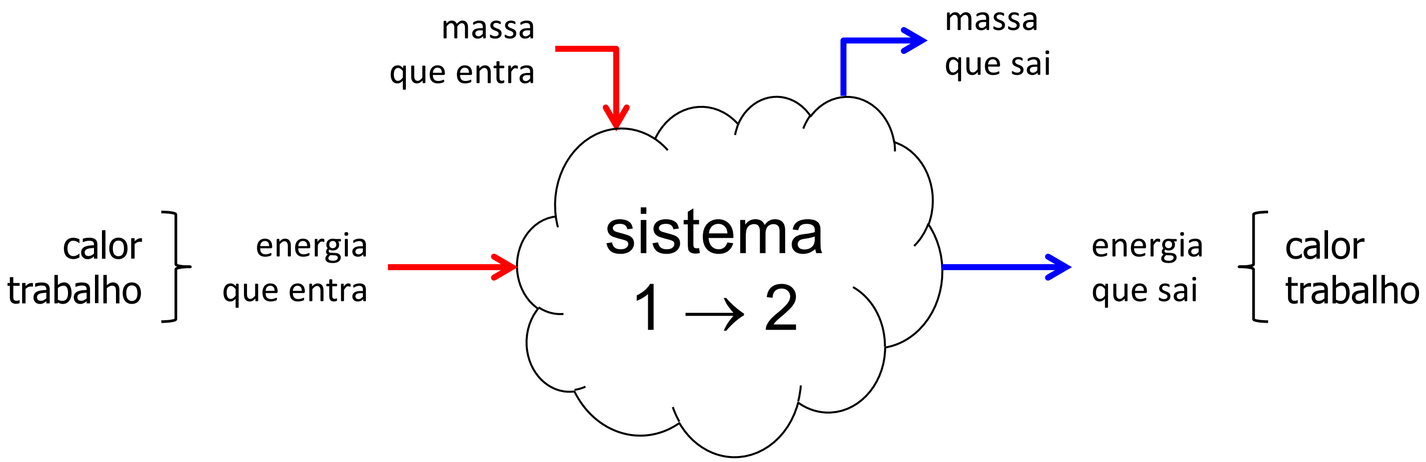
Princípio da conservação da energia: sistema aberto







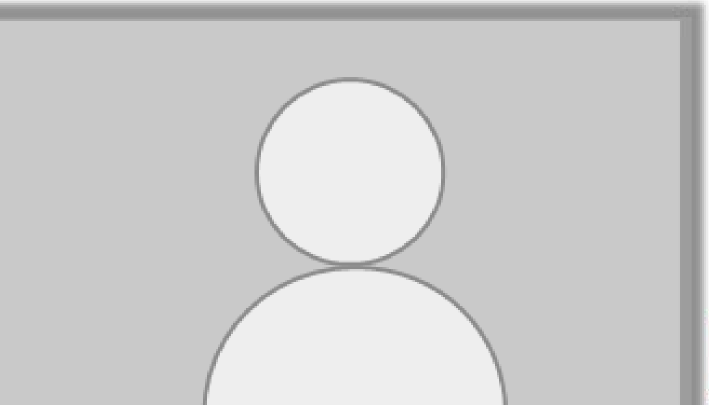
Princípio da conservação da energia: sistema aberto



$$\Delta E = \left(E_{entra} - E_{sai}\right)_{Q,W} + \left(E_{entra} - E_{sai}\right)_{massa}$$

$$\Downarrow$$

$$\frac{dE}{dt} = \left(\frac{dE_{entra}}{dt} - \frac{dE_{sai}}{dt}\right)_{Q,W} + \left(\frac{dE_{entra}}{dt} - \frac{dE_{sai}}{dt}\right)_{massa}$$



Equação generalizada para o balanço de massa de um sistema aberto...

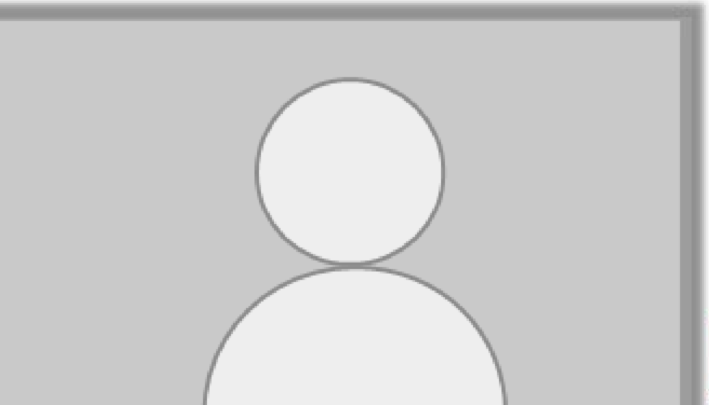
Depois vamos adaptar para energia...

Equação de balanço de massa: forma generalizada

$$\begin{pmatrix}\text{taxa de variação} \\ \text{da massa do sistema}\end{pmatrix} - \begin{pmatrix}\text{fluxo total de} \\ \text{massa entrando}\end{pmatrix} = 0$$

$$\frac{d}{dt}M + \int_{SC} \rho(\vec{V} \cdot \vec{n})\,dA = 0$$

$$\frac{d}{dt}\int_{VC} \rho \, d\forall + \int_{SC} \rho(\vec{V} \cdot \vec{n})\,dA = 0$$

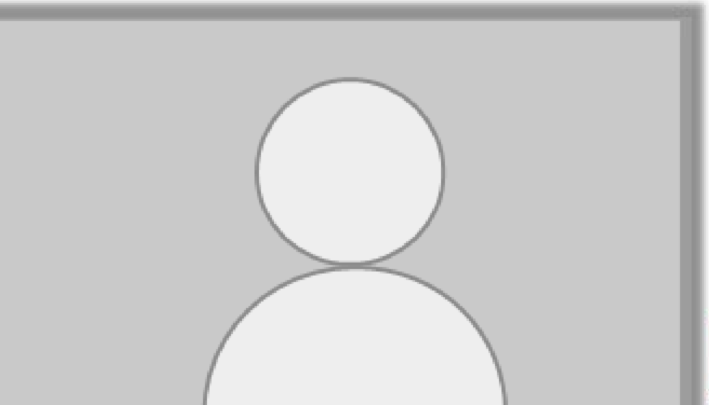


Equação de balanço de massa: forma discreta

$$\left(\begin{array}{c}\text{taxa de variação}\\ \text{da massa do sistema}\end{array}\right) - \left(\begin{array}{c}\text{fluxo total de}\\ \text{massa entrando}\end{array}\right) = 0$$

$$\frac{d}{dt}M + \left(\sum_{\text{saídas}} m_{sai,k} - \sum_{\text{entradas}} m_{ent,k} \right) = 0$$

$$\frac{d}{dt}M + \left(\sum_{\text{saídas}} \rho_k V_{n,k} A_k - \sum_{\text{entradas}} \rho_k V_{n,k} A_k \right) = 0$$



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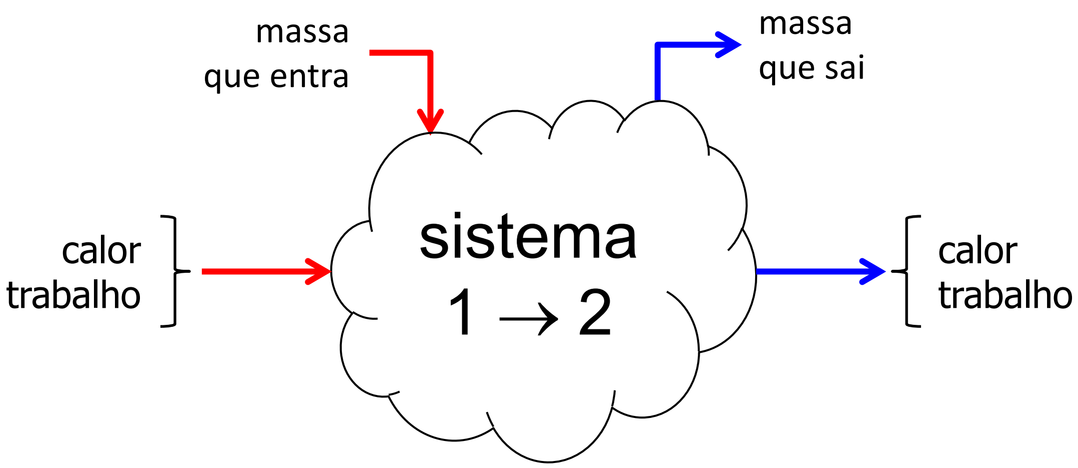
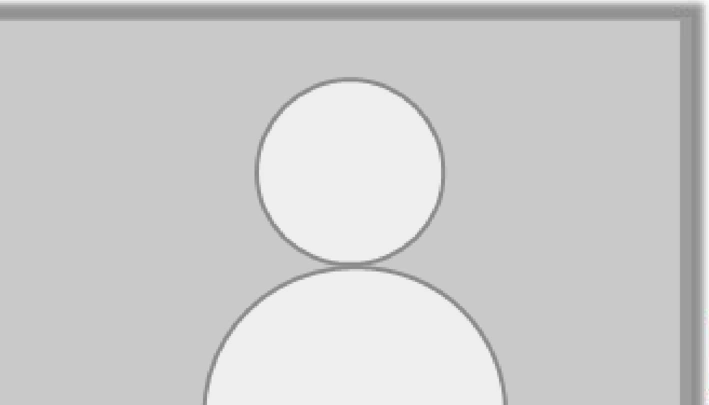
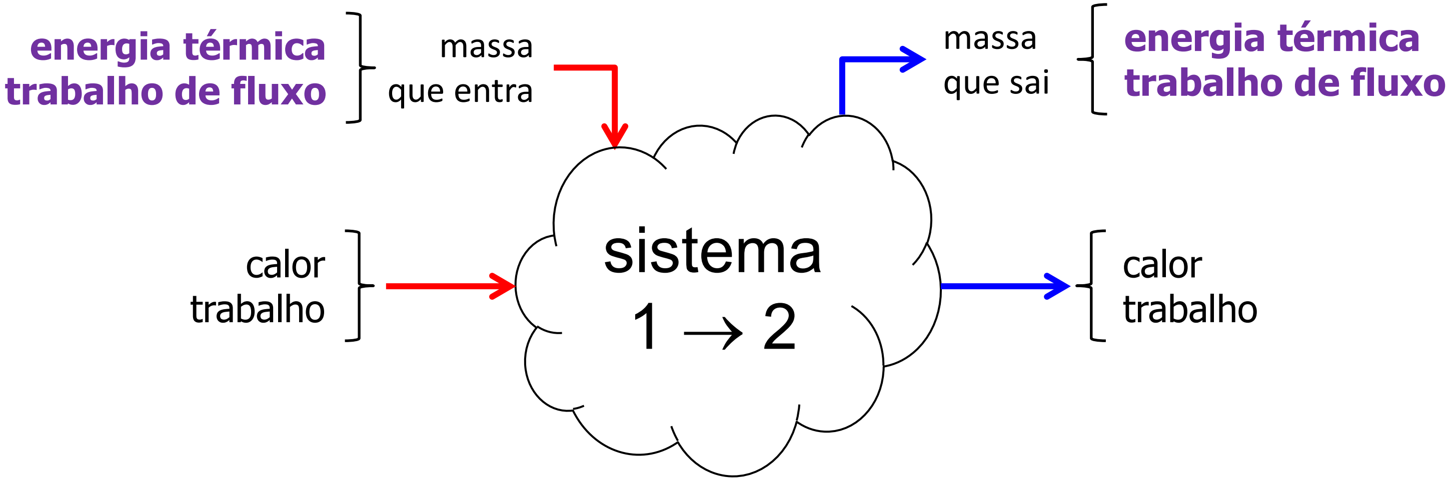
Calculando a energia associada aos fluxos de massa...

Princípio da conservação da energia: sistema aberto



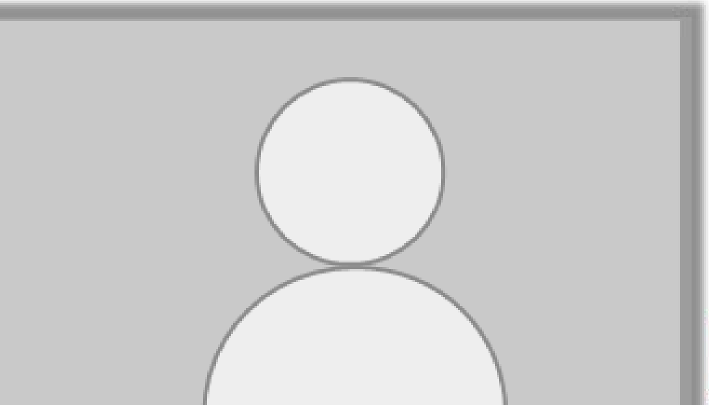


Princípio da conservação da energia: sistema aberto

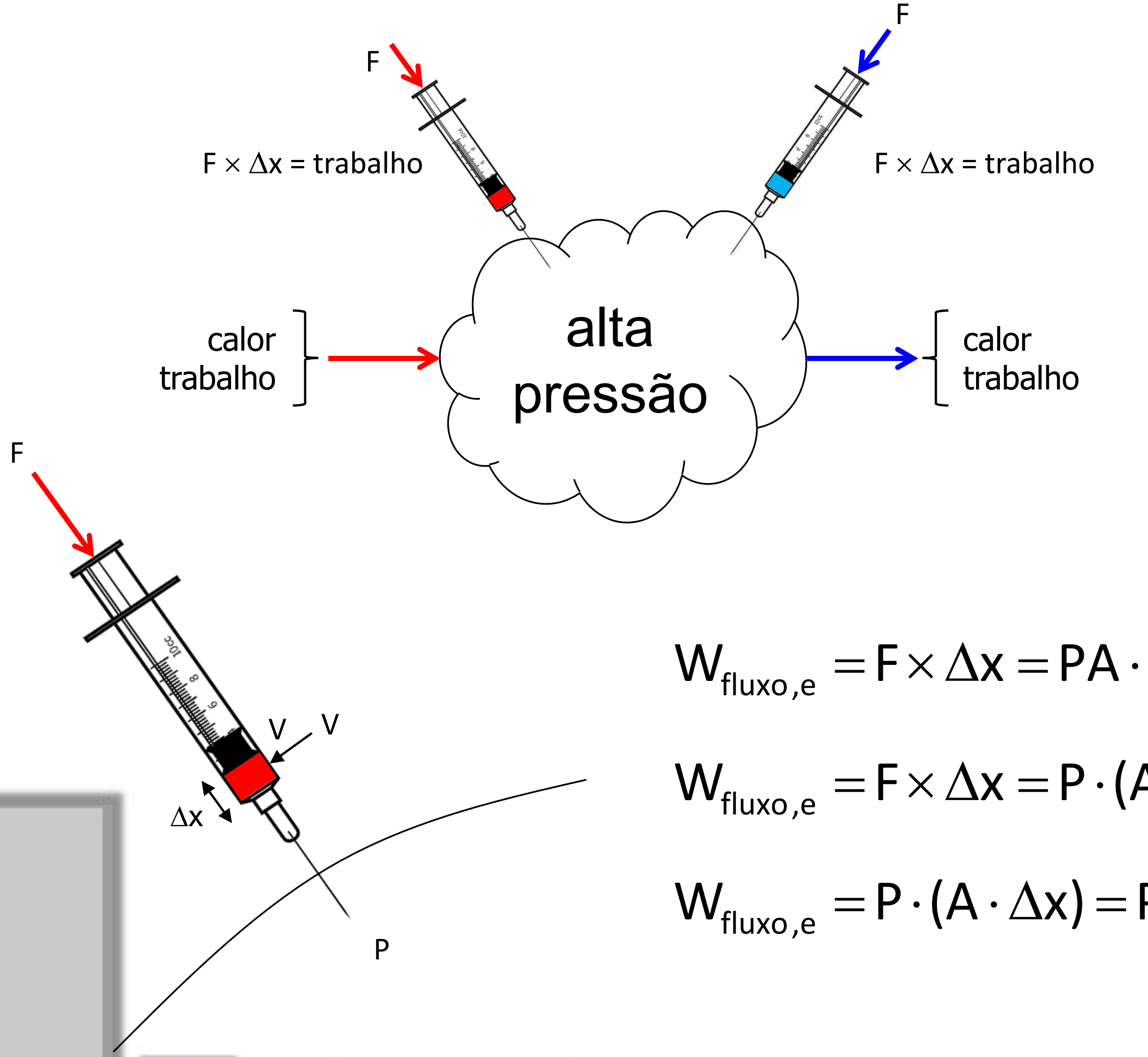


transporte de energia térmica ⇨ Energia térmica, ou interna (u + ep + ec), associada ao fluxo de massa entrando/saindo do VC e que deve ser contabilizado

trabalho de fluxo ⇨ Trabalho mecânico (força × deslocamento) necessário para que um elemento de massa entre/saia do VC...



Trabalho necessário para entrar no sistema: trabalho de fluxo...

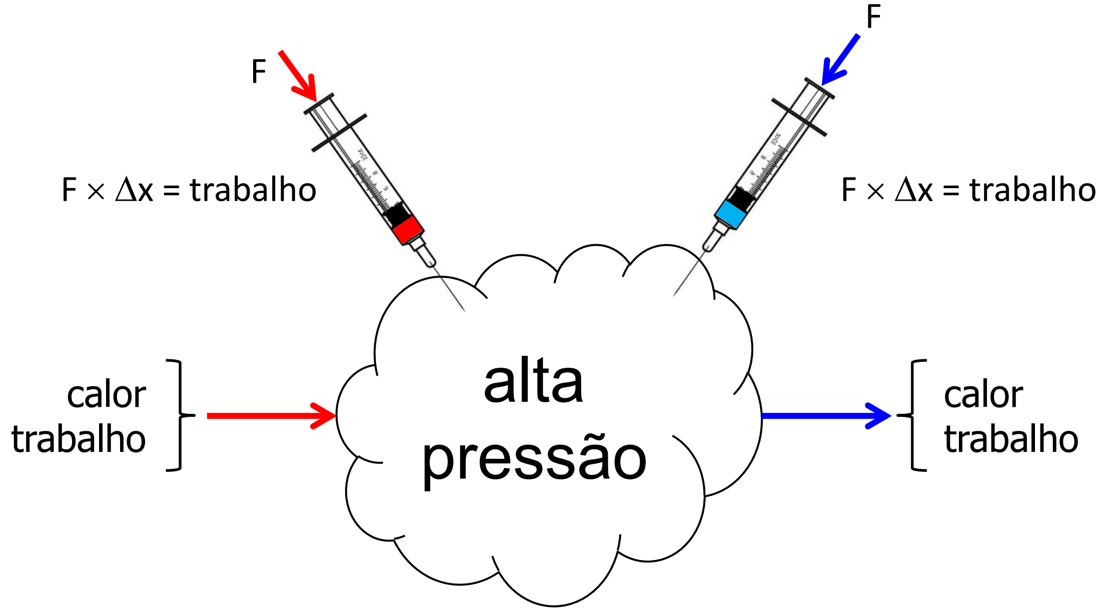


$$W_{fluxo,e} = F \times \Delta x = PA \cdot \Delta x$$

$$W_{fluxo,e} = F \times \Delta x = P \cdot (A \cdot \Delta x)$$

$$W_{fluxo,e} = P \cdot (A \cdot \Delta x) = P \cdot V$$

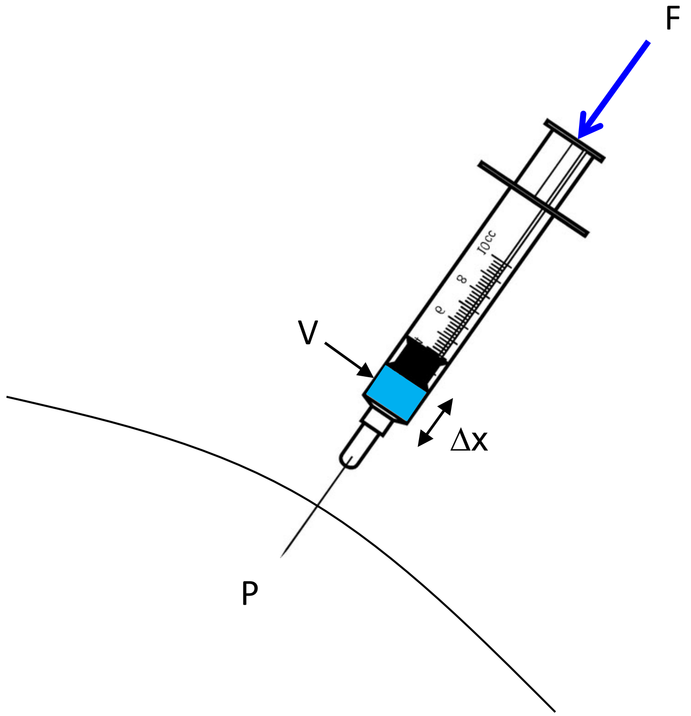
Trabalho necessário para sair no sistema: trabalho de fluxo...



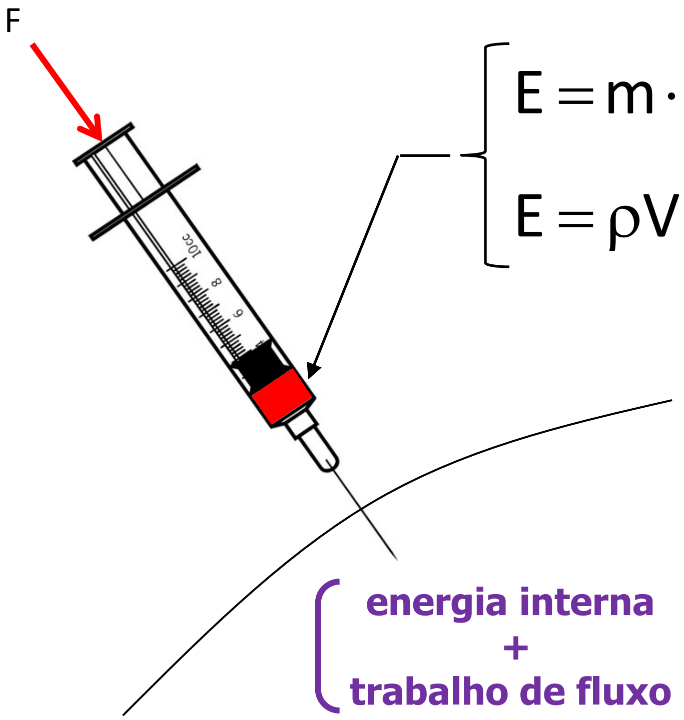
$$W_{fluxo,s} = F \times \Delta x = PA \cdot \Delta x$$

$$W_{fluxo,s} = F \times \Delta x = P \cdot (A \cdot \Delta x)$$

$$W_{fluxo,s} = P \cdot (A \cdot \Delta x) = P \cdot V$$



Energia total associada ao fluxo de massa entrando/saindo...

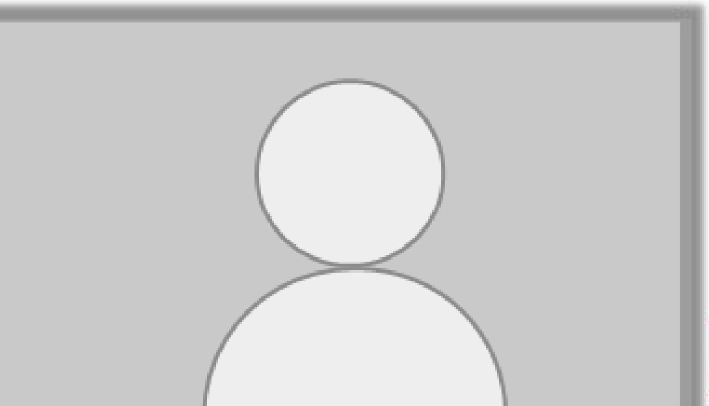


$$\begin{cases} E = m \cdot \left(u + gz + \forall^2/2\right) \\ E = \rho V \cdot \left(u + gz + \forall^2/2\right) \end{cases}$$

(energia interna + trabalho de fluxo)

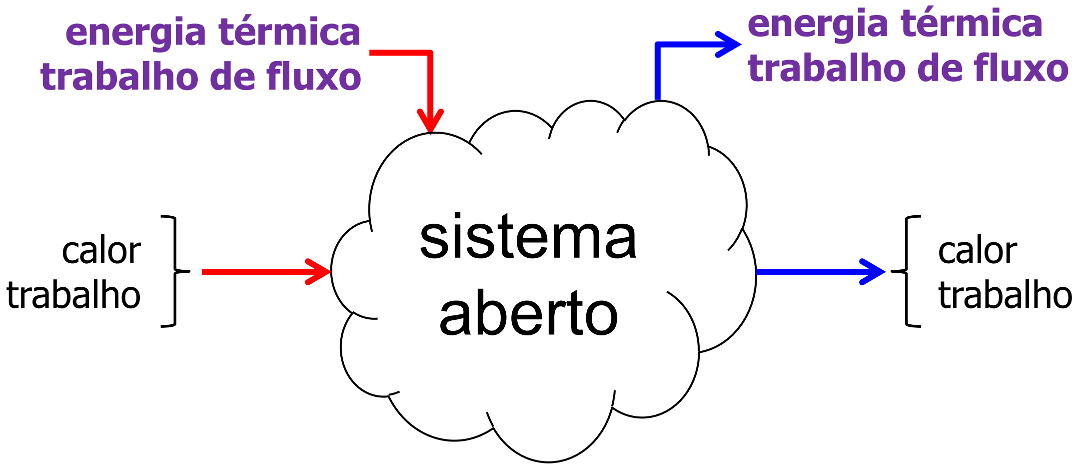
$$\begin{cases} \theta = E + W_{fluxo} \\ \theta = m \cdot \left(u + gz + \forall^2/2\right) + (F \cdot \Delta x) \\ \theta = m \cdot \left(u + gz + \forall^2/2\right) + m \cdot (Pv) \end{cases}$$

$$\theta = m \cdot \left(h + gz + \forall^2/2\right)$$



Formulando o inventário de energia para um sistema aberto...

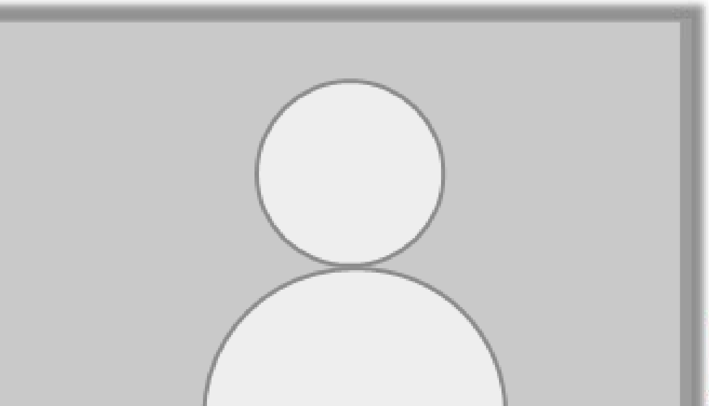
Inventário de energia no VC... (regime permanente)



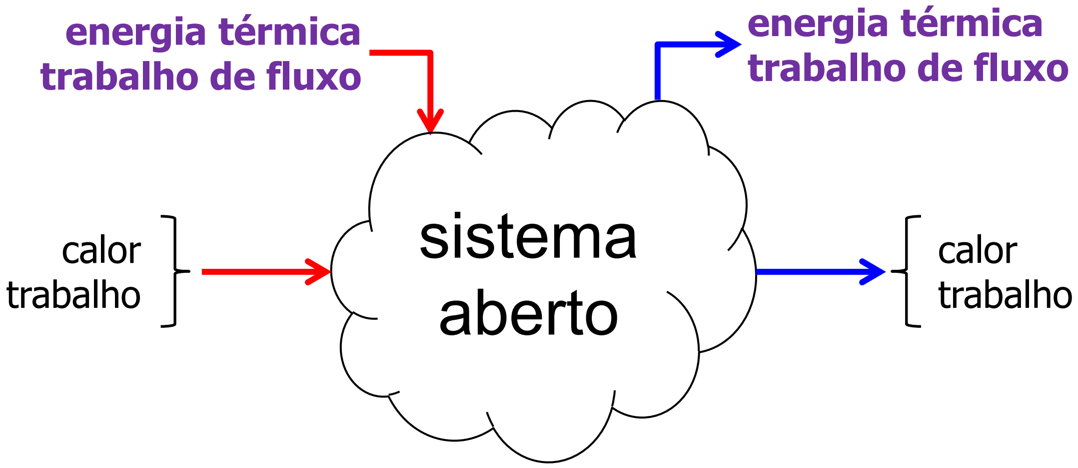
(energia total (líquida) entrando no VC) = (taxa de variação da energia interna do VC)

⇓ regime permanente

(energia total (líquida) entrando no VC) = (0)



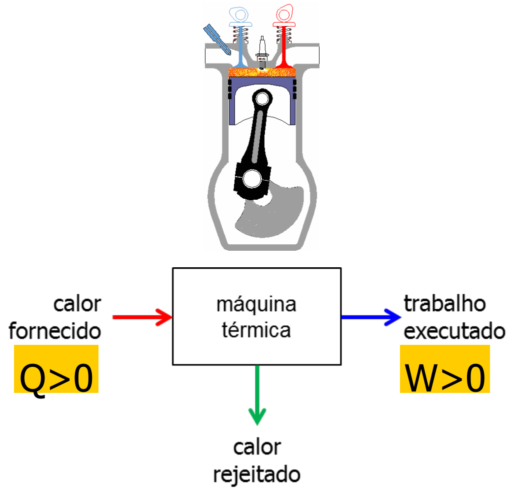
Inventário de energia no VC... (regime permanente)

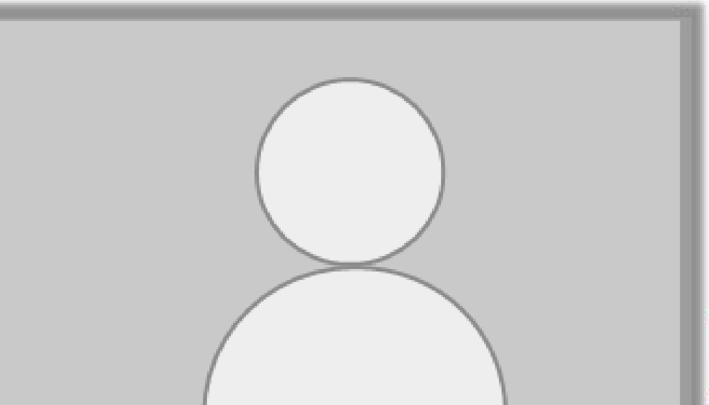


$$\dot{Q}_e + \dot{W}_e + \sum_{\text{entra}} \dot{m}_k \theta_k = \dot{Q}_s + \dot{W}_s + \sum_{\text{sai}} \dot{m}_k \theta_k$$

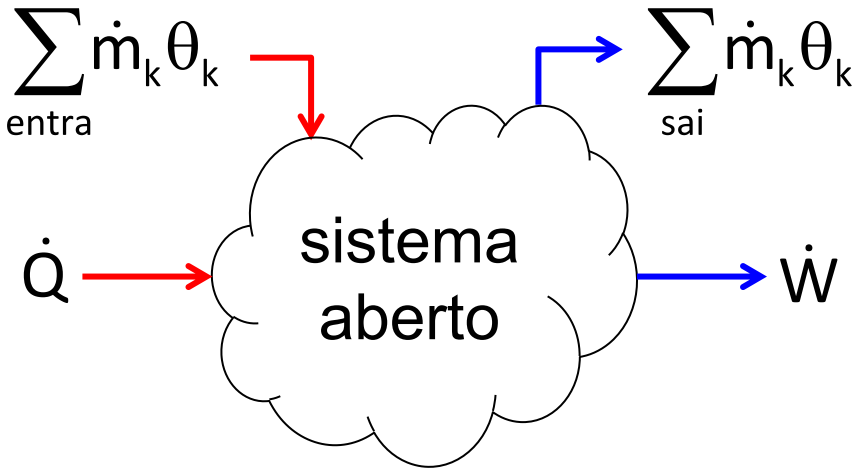
$$(\dot{Q}_e - \dot{Q}_s) - (\dot{W}_s - \dot{W}_e) = \sum_{\text{sai}} \dot{m}_k \theta_k - \sum_{\text{entra}} \dot{m}_k \theta_k$$

$$\dot{Q} - \dot{W} = \sum_{\text{sai}} \dot{m}_k \theta_k - \sum_{\text{entra}} \dot{m}_k \theta_k$$



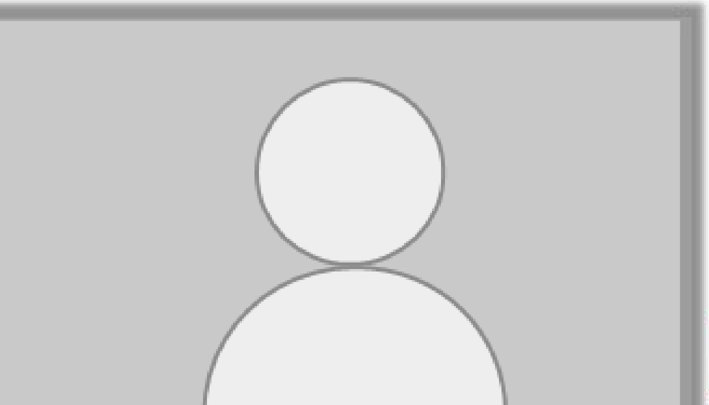


Inventário de energia no VC... (regime permanente)

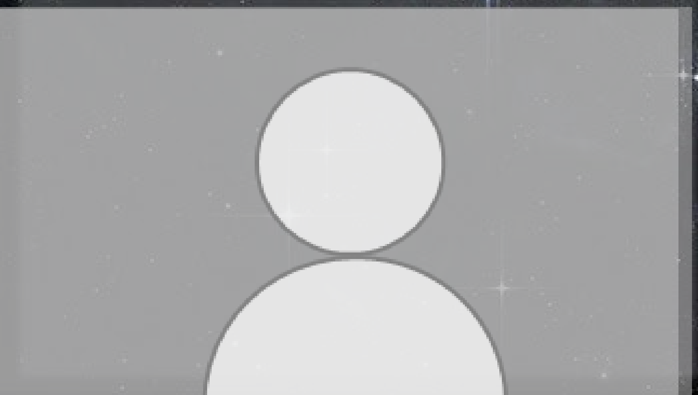


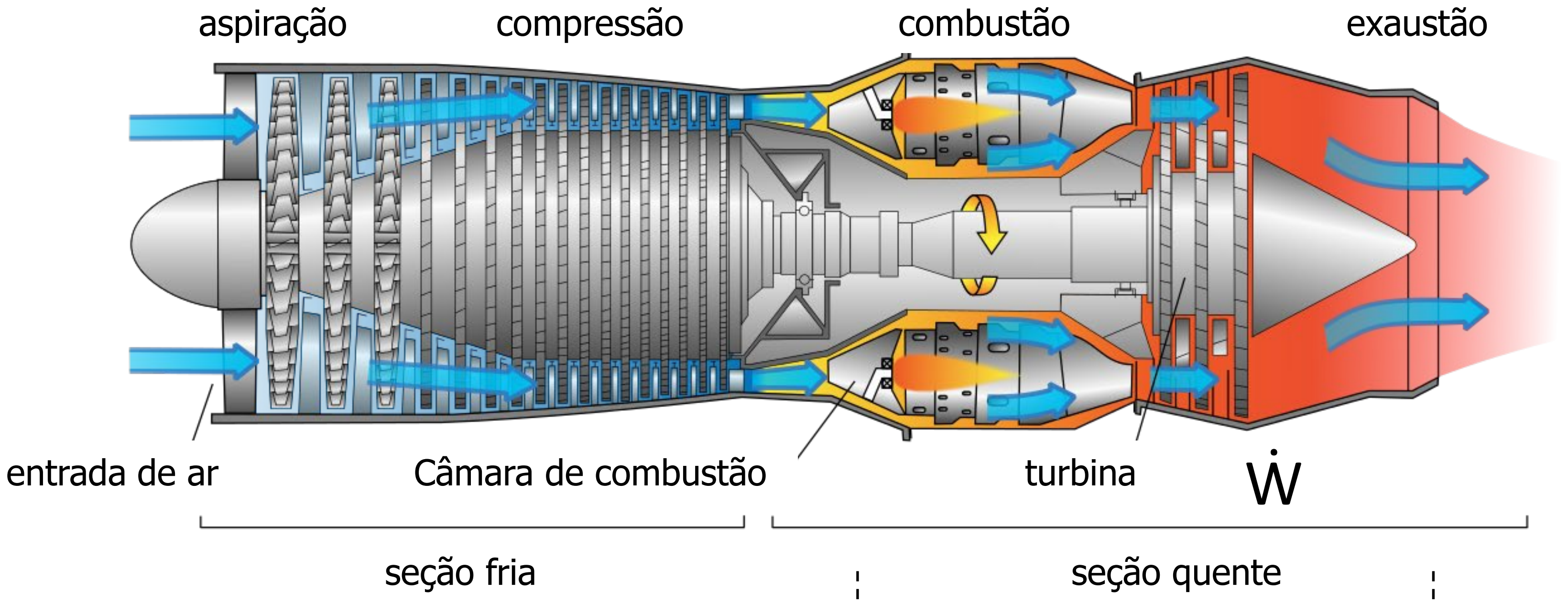
$$\dot{Q} - \dot{W} = \sum_{sai} \dot{m}_k \theta_k - \sum_{entra} \dot{m}_k \theta_k$$

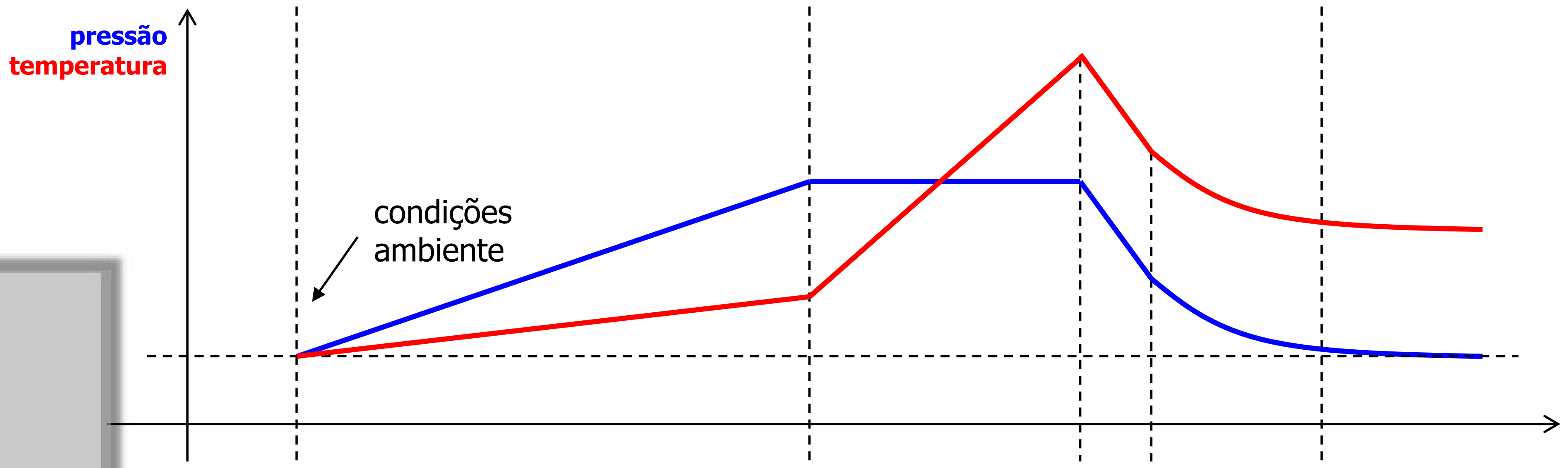
$$\dot{Q} - \dot{W} = \sum_{sai} \dot{m}_k \cdot \left(h_k + g z_k + V_k^2/2\right) - \sum_{entra} \dot{m}_k \cdot \left(h_k + g z_k + V_k^2/2\right)$$

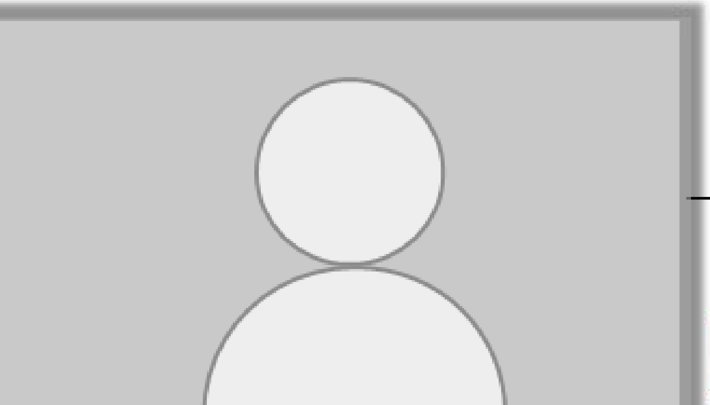


Aplicação: análise de motores de propulsão a jato e turboélice

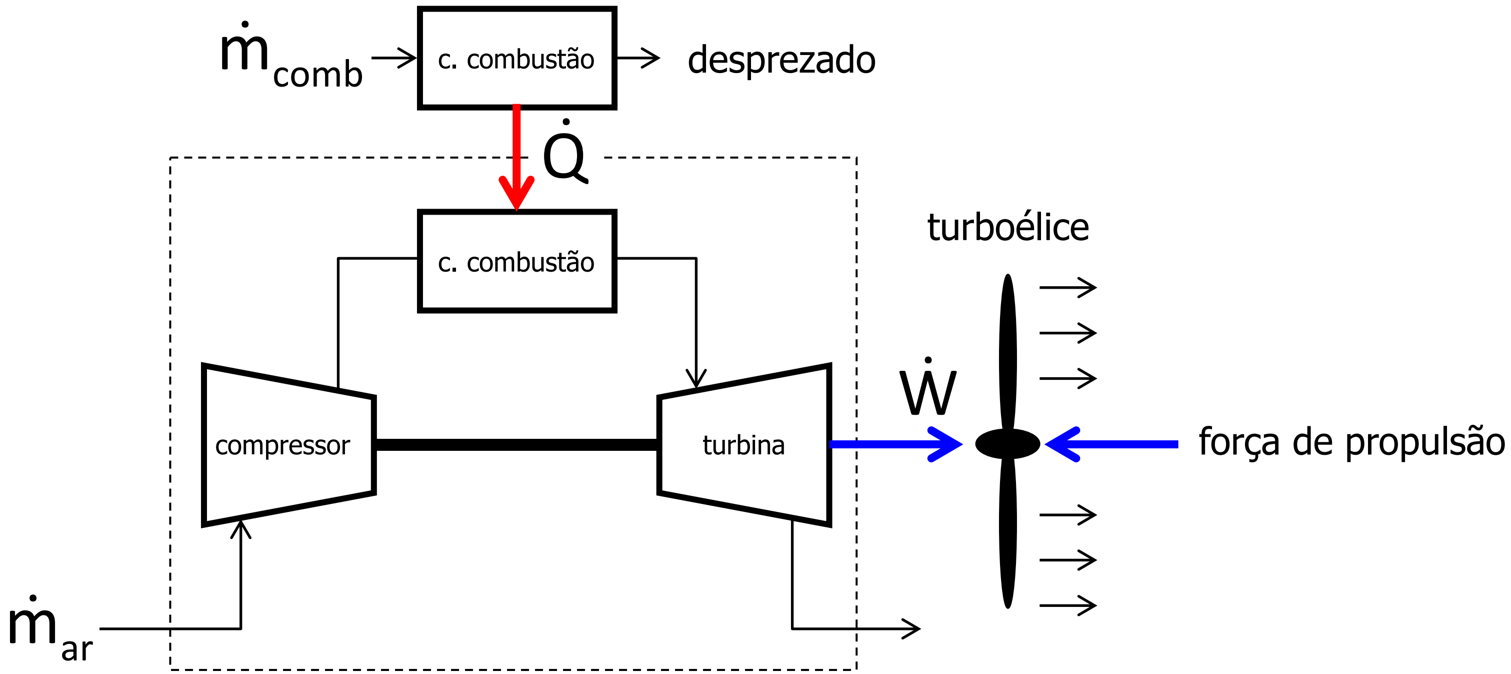



aspiração
compressão
combustão
exaustão
entrada de ar
Câmara de combustão
turbina
$\dot{W}$
seção fria
seção quente

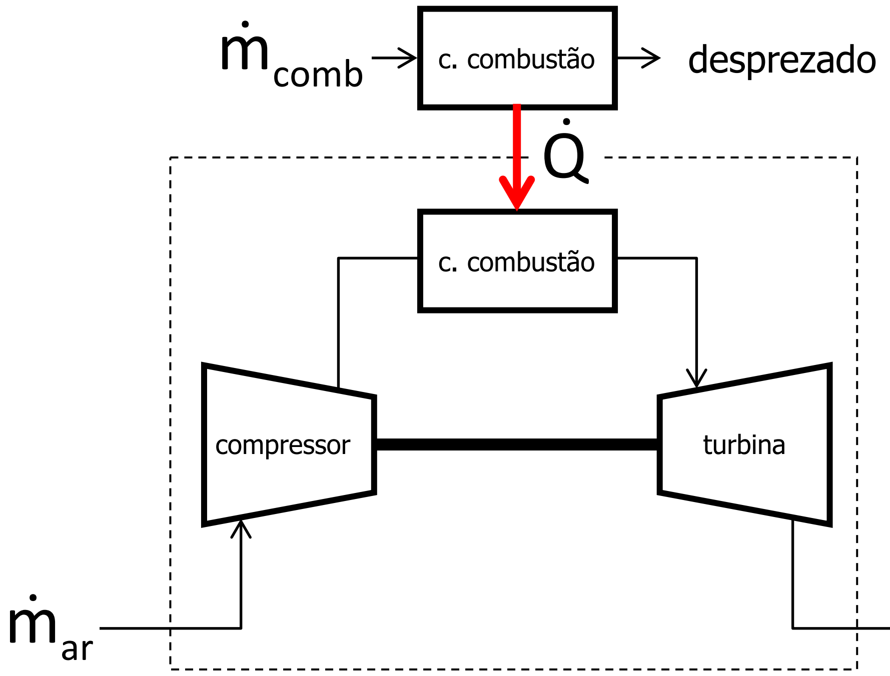

pressão
temperatura
condições
ambiente

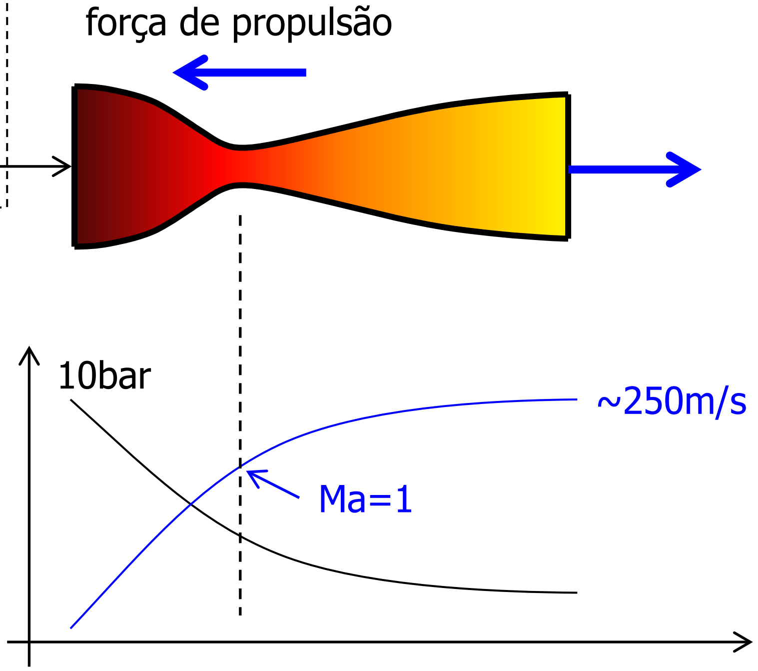


Modelo simplificado: turboélice

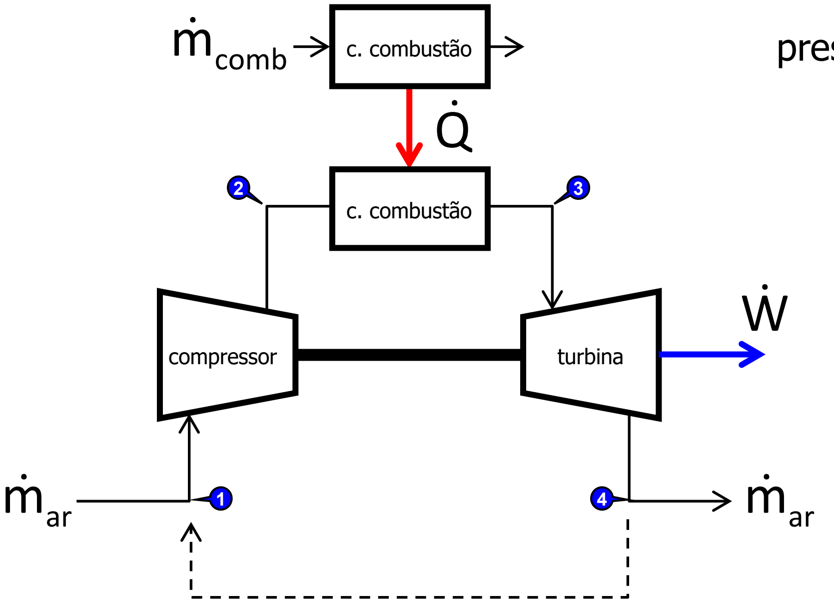


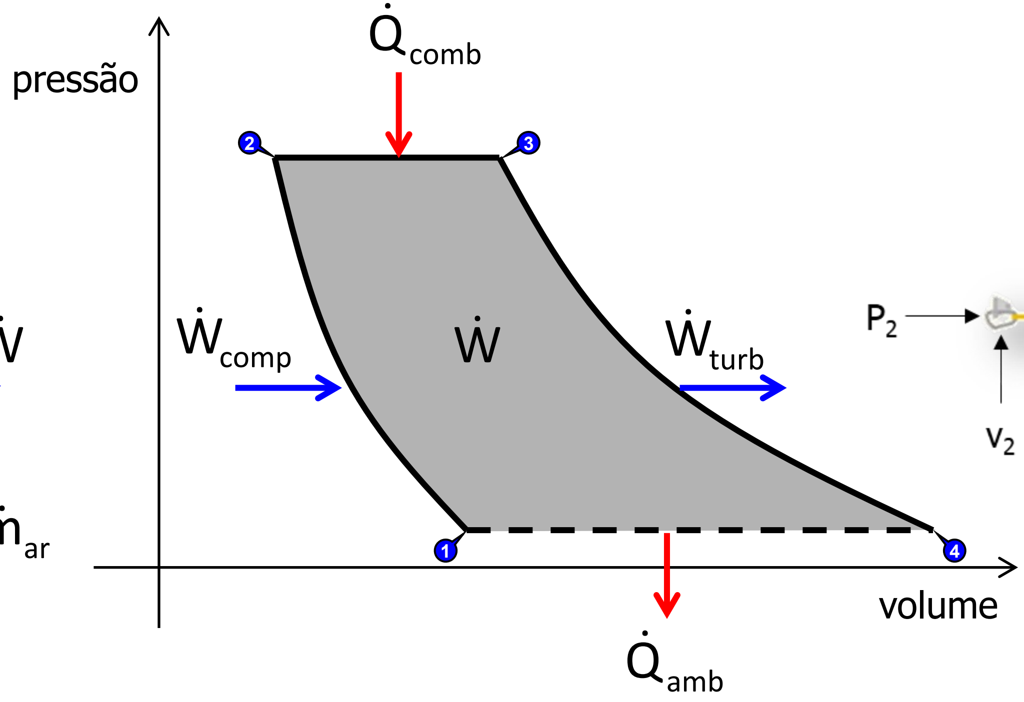
Modelo simplificado: motor a jato

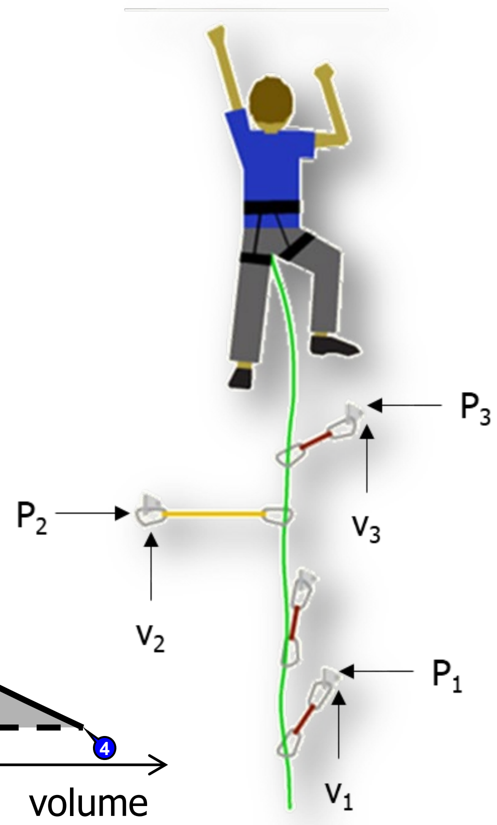




Análise termodinâmica – ciclo de Brayton

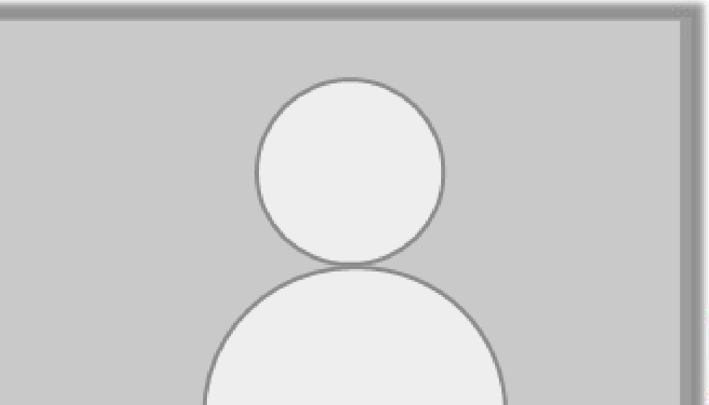






Análise termodinâmica

"PASSO ZERO": Determinação das propriedades de estado



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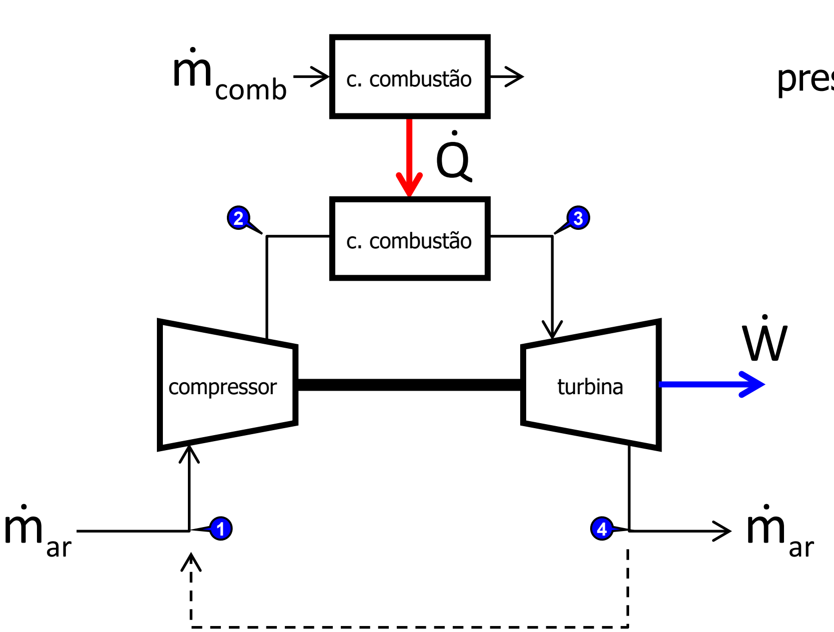
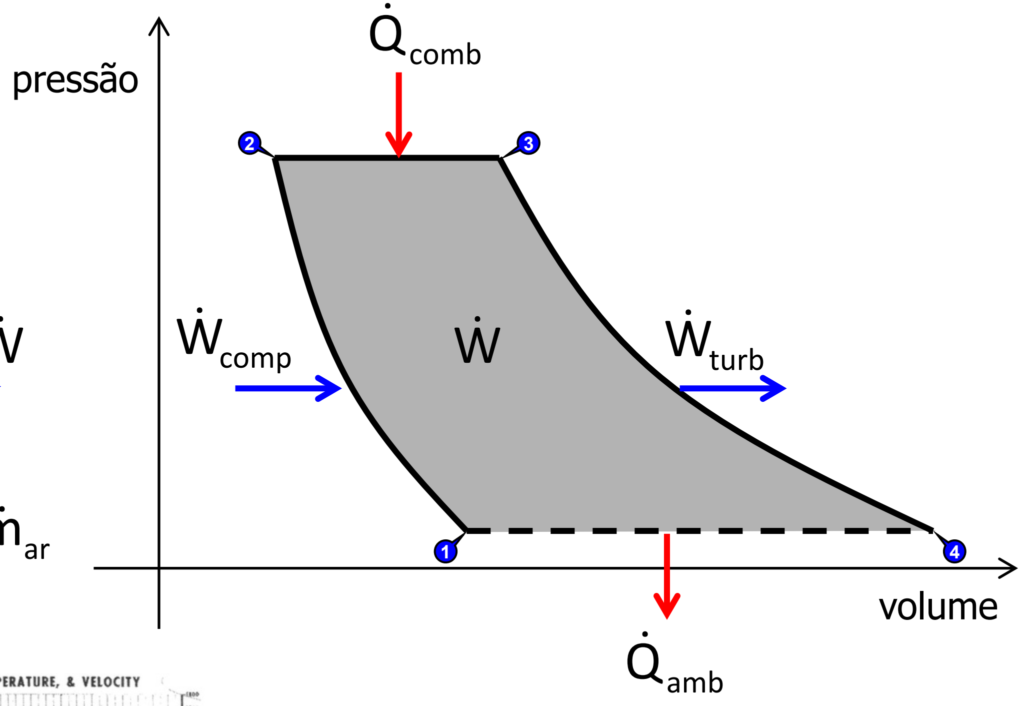
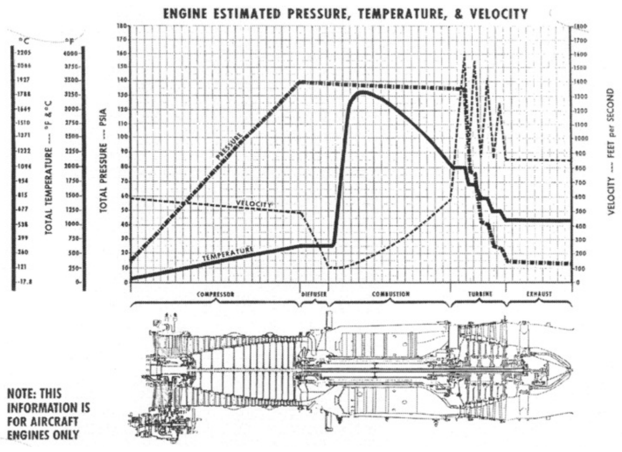
Análise termodinâmica – ciclo de Brayton







estimativas práticas

P2=10bar

T2=?????

P3=10bar

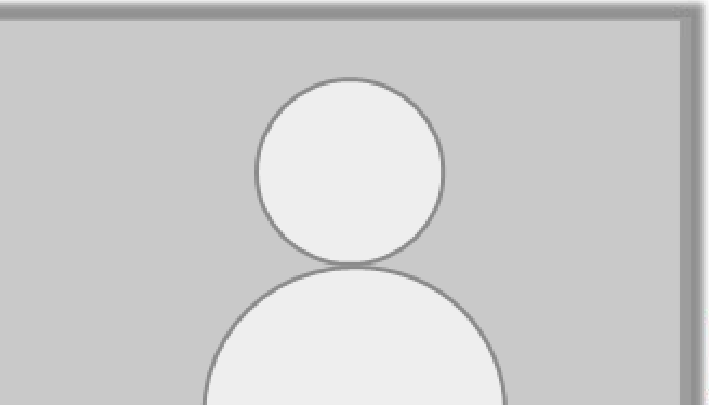
T3=?????

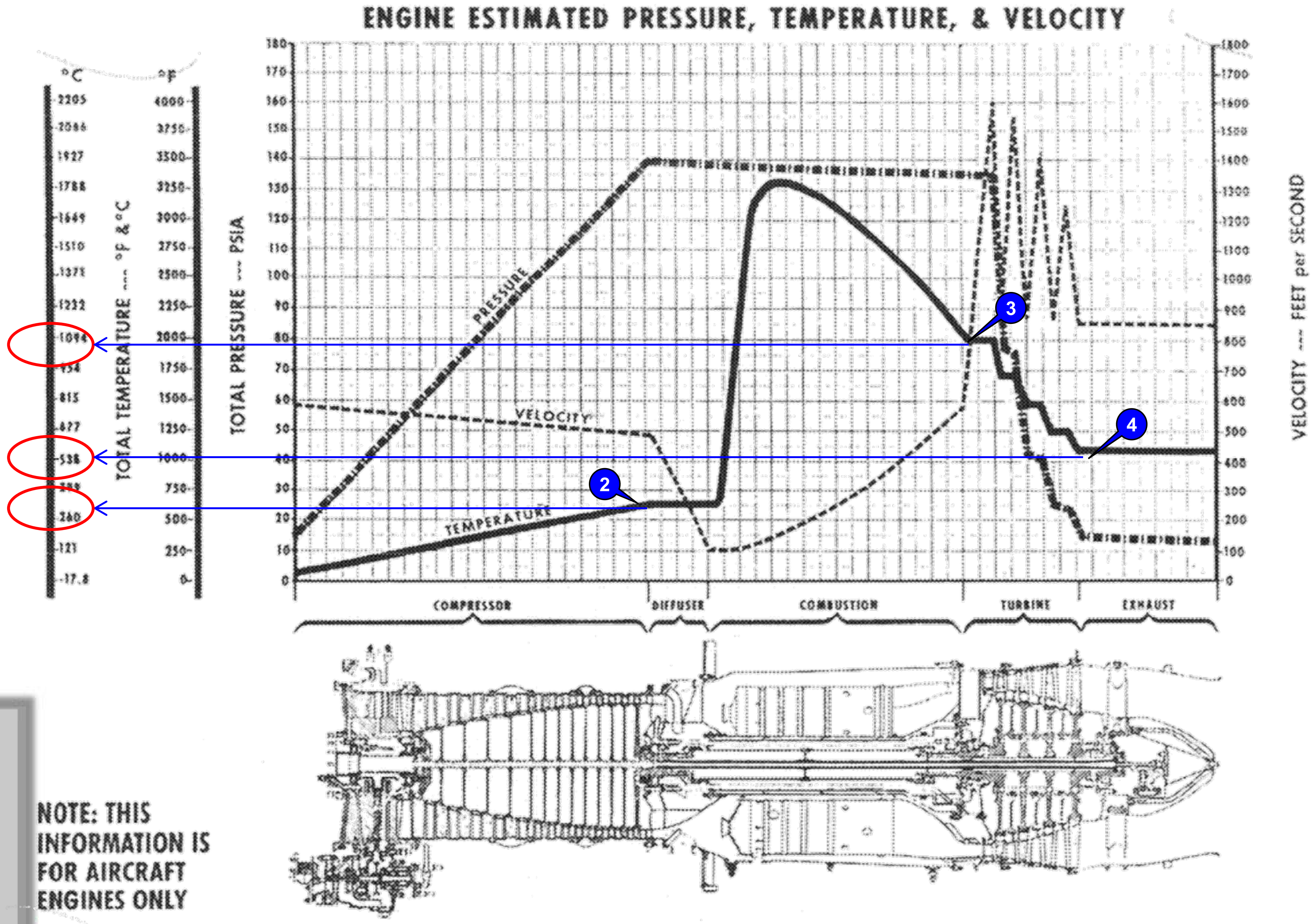
P1=1bar

T1=25ºC

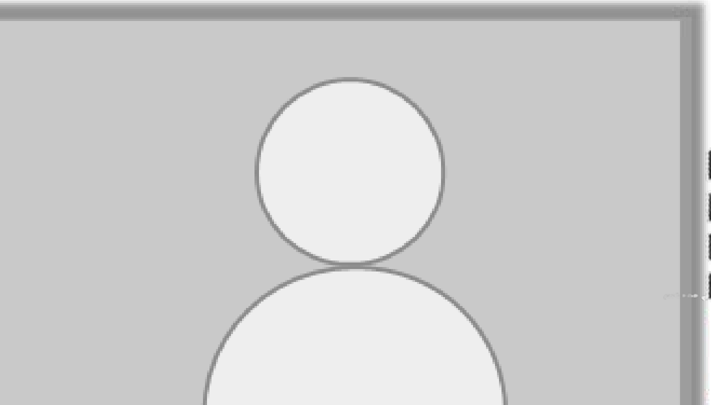
P4=1bar

T4=?????



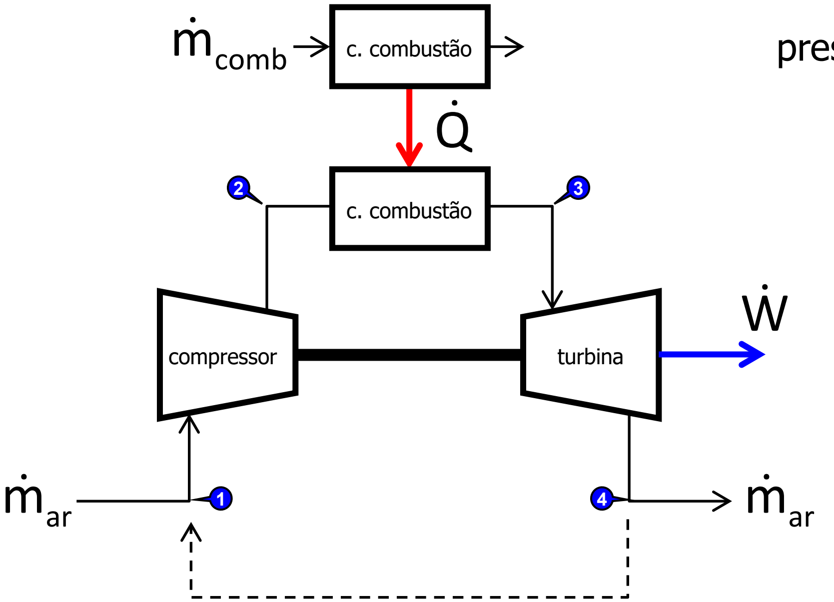


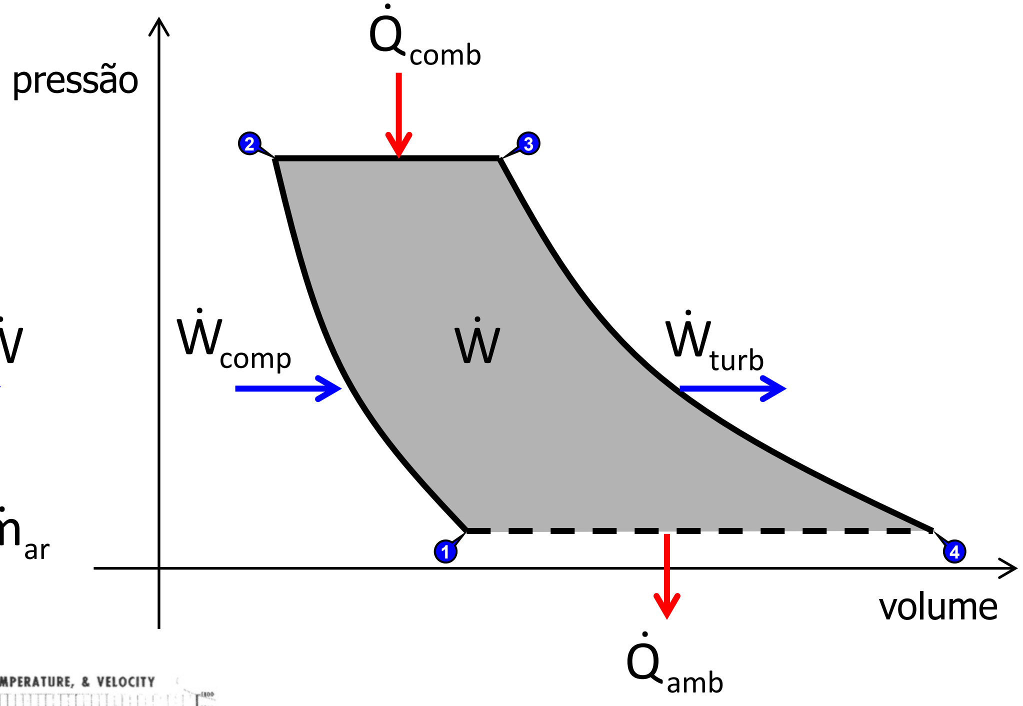
NOTE: THIS INFORMATION IS FOR AIRCRAFT ENGINES ONLY

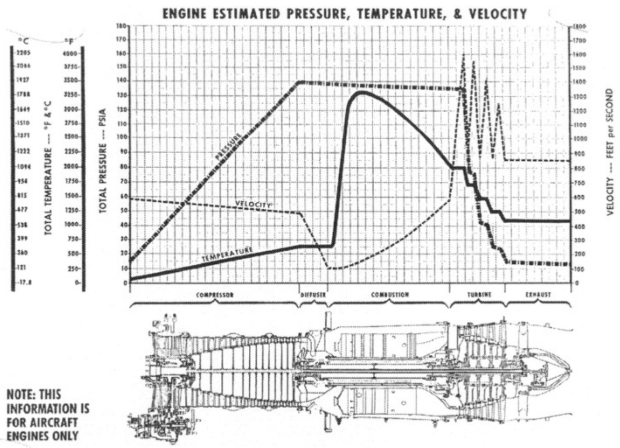


Estimativa das variáveis termodinâmicas...

Análise termodinâmica – ciclo de Brayton







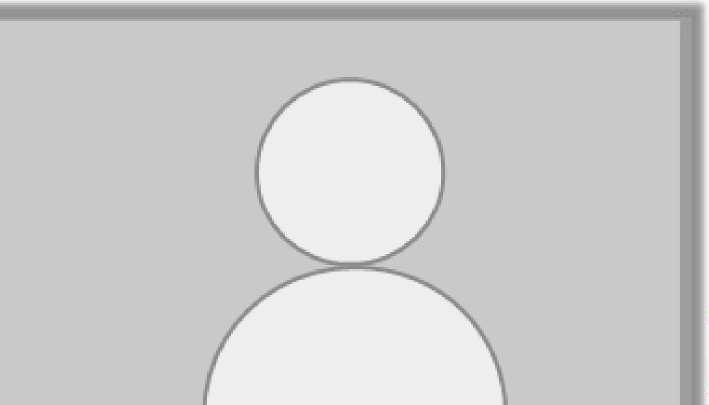
estimativas práticas

P2=10bar
T2≈290ºC

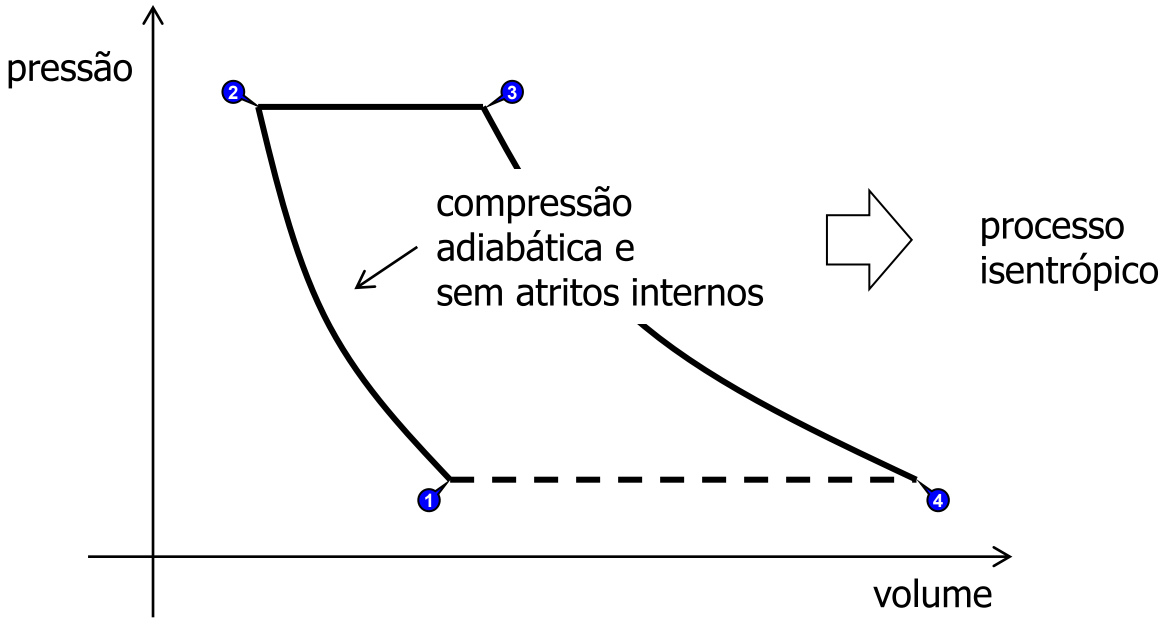
P1=1bar
T1=25ºC

P3=10bar
T3≈1094ºC

P4=1bar
T4≈570ºC



Determinação das propriedades em (2)



P1=1bar

T1=25ºC

⇩

s1=3,88kJ/kg/K

→

P2=10bar

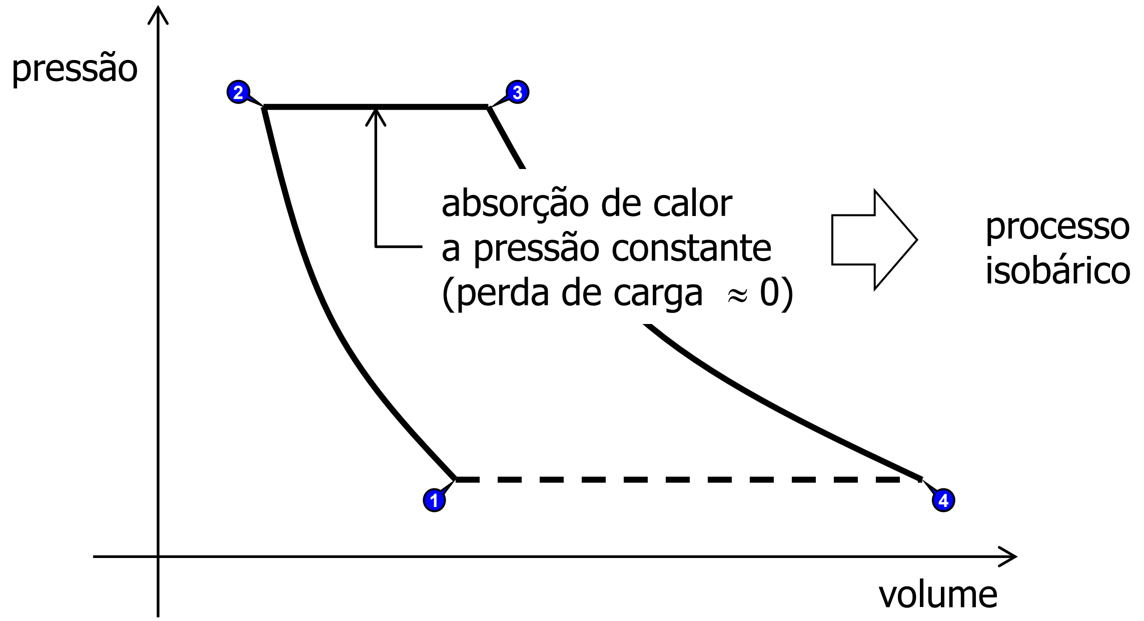
s2=s1=3,88kJ/kg/K

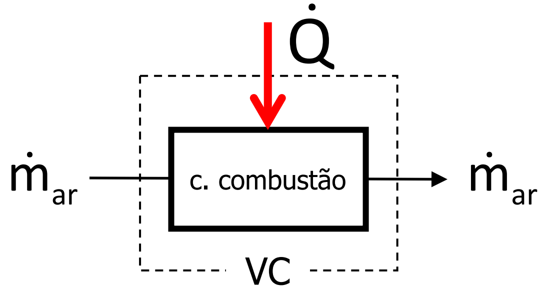
⇩

T2=297,8ºC
h2=703,05kJ/kg

→ **estimado: T2≈290ºC**

Determinação das propriedades em (3)





$$\dot{Q} - \dot{W} = \sum_{sai} \dot{m}_k \theta_k - \sum_{entra} \dot{m}_k \theta_k$$

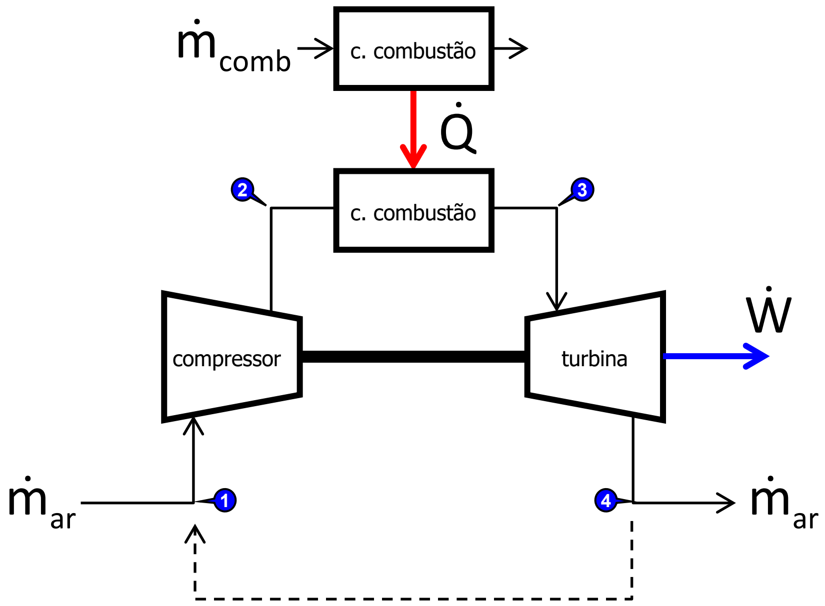
$$\dot{Q} = \dot{m}_{ar} \cdot \left[\left(h + \cancel{gz} + \cancel{\frac{V^2}{2}} \right)_3 - \left(h + \cancel{gz} + \cancel{\frac{V^2}{2}} \right)_2 \right]$$

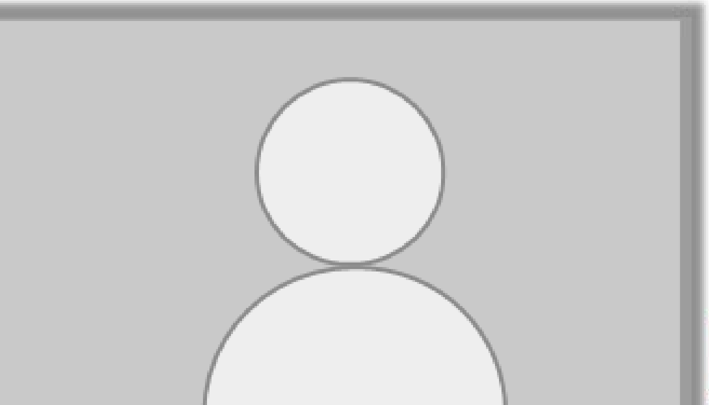
$$\dot{Q} = \dot{m}_{ar} \cdot (h_3 - h_2) \quad \Rightarrow \quad \dot{Q} / \dot{m}_{ar} = h_3 - h_2$$

Determinação das propriedades em (3)

$$\dot{Q} = \dot{m}_{comb} \cdot (\eta_{comb} PCI_{comb}) = \dot{m}_{ar} \cdot (h_3 - h_2)$$

$$h_3 = h_2 + \dot{m}_{comb} / \dot{m}_{ar} \cdot \eta_{comb} \cdot PCI_{comb}$$





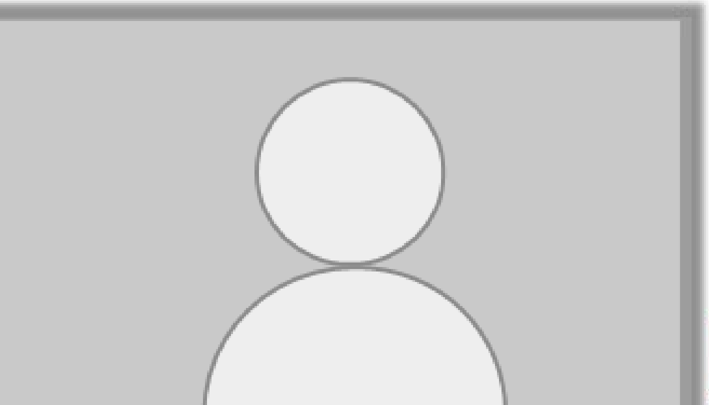
Determinação das propriedades em (3)

$$\dot{Q} = \dot{m}_{comb} \cdot (\eta_{comb} PCI_{comb}) = \dot{m}_{ar} \cdot (h_3 - h_2)$$

$$h_3 = h_2 + \dot{m}_{comb} / \dot{m}_{ar} \cdot \eta_{comb} \cdot PCI_{comb}$$

Equação estequiométrica de combustão

$$C_{12}H_{26}(\ell) + \quad O_2(g) \rightarrow \quad CO_2(g) + \quad H_2O(g) - \eta_{comb} \cdot PCI_{C_{12}H_{26}}$$



Determinação das propriedades em (3)

$$\dot{Q} = \dot{m}_{comb} \cdot (\eta_{comb} PCI_{comb}) = \dot{m}_{ar} \cdot (h_3 - h_2)$$

$$h_3 = h_2 + \dot{m}_{comb} / \dot{m}_{ar} \cdot \eta_{comb} \cdot PCI_{comb}$$

Equação estequiométrica de combustão

$$2C_{12}H_{26}(\ell) + 37O_2(g) \rightarrow 24CO_2(g) + 26H_2O(g) - \eta_{comb} \cdot PCI_{C_{12}H_{26}}$$

Determinação das propriedades em (3)

$$\dot{Q} = \dot{m}_{comb} \cdot (\eta_{comb} PCI_{comb}) = \dot{m}_{ar} \cdot (h_3 - h_2)$$

$$h_3 = h_2 + \dot{m}_{comb} / \dot{m}_{ar} \cdot \eta_{comb} \cdot PCI_{comb}$$

Equação estequiométrica de combustão

$$2C_{12}H_{26}(\ell) + 37O_2(g) \rightarrow 24CO_2(g) + 26H_2O(g) - \eta_{comb} \cdot PCI_{C_{12}H_{26}}$$

2 mols de querosene
37 mols de oxigênio

$\eta_{comb} = 1$ ⇨ PCI=15,026MJ

$$M_{C_{12}H_{26}} = 170{,}3 g/mol \quad \Rightarrow \quad PCI = \frac{15{,}026 MJ}{2 \cdot 170{,}3 \cdot 10^{-3} kg} = 44{,}19 MJ/kg$$

Determinação das propriedades em (3)

$$2C_{12}H_{26}(\ell) + 37O_2(g) \rightarrow 24CO_2(g) + 26H_2O(g) - \eta_{comb} \cdot PCI_{C12}H_{26}$$

$37O_2(g)$ → 32,0g/mol → 1,184kg de oxigênio

$2C_{12}H_{26}(\ell)$ → 170,3g/mol → 0,341kg de querosene

Cálculo da massa de ar para combustão estequiométrica

Major constituents of dry air, by volume[6]

Gas		Volume(A)	
Name	Formula	in ppmv(B)	in %
Nitrogen	N_2	780,840	78.084
Oxygen	O_2	209,460	20.946
Argon	Ar	9,340	0.9340
Carbon dioxide	CO_2	397	0.0397
Neon	Ne	18.18	0.001818
Helium	He	5.24	0.000524
Methane	CH_4	1.79	0.000179
Not included in above dry atmosphere:			
Water vapor(C)	H_2O	10–50,000(D)	0.001%–5%(D)

notes:
(A) volume fraction is equal to mole fraction for ideal gas only, also see volume (thermodynamics)
(B) ppmv: parts per million by volume
(C) Water vapor is about 0.25% *by mass* over full atmosphere
(D) Water vapor strongly varies locally[4]

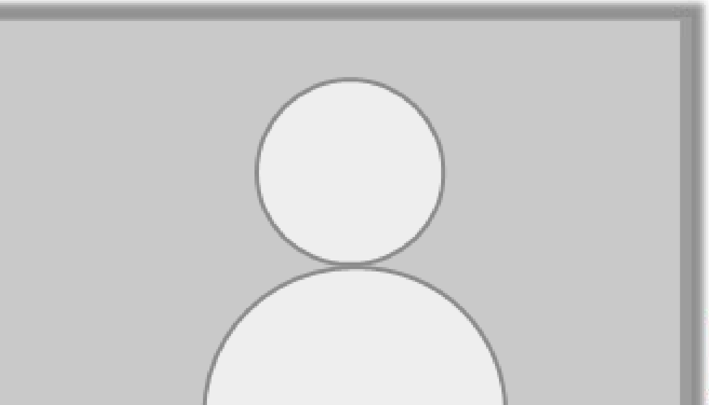
$$0{,}78084 \cdot N_2 + 0{,}20946 \cdot O_2 + 0{,}00934 \cdot Ar = 1mol$$

28g/mol ↓ 21,86g ↓ 0,7555kg +

32g/mol ↓ 6,70g ↓ 0,2316kg +

40g/mol ↓ 0,37g ↓ 0,0129kg

$$0{,}7555kg + 0{,}2316kg + 0{,}0129kg = 1kg$$



Determinação das propriedades em (3)

Cálculo da massa de ar que contém 1,181kg de oxigênio

1 kg de ar ⟶ 0,232kg de oxigênio

x kg de ar ⟶ 1,184kg de oxigênio

⇨ 5,112kg de ar

Cálculo da razão ar/combustível

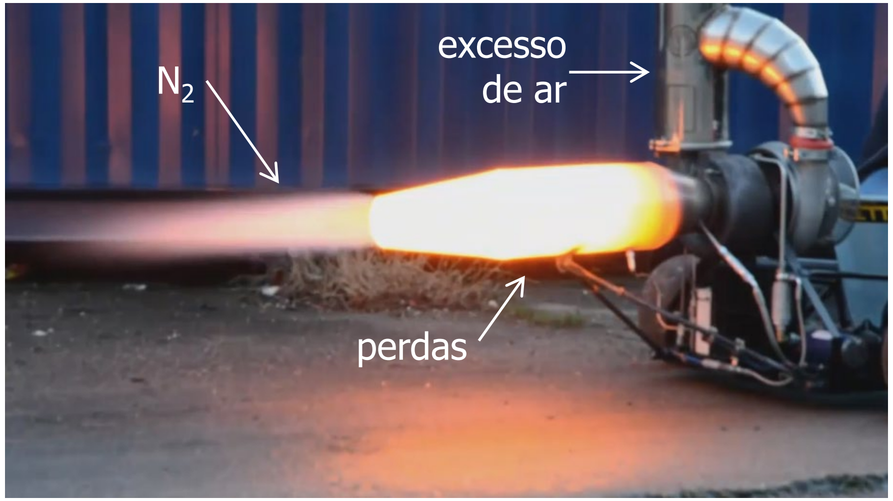
$$\frac{\dot{m}_{comb}}{\dot{m}_{ar}} = \frac{0{,}341\text{kg}}{5{,}112\text{kg}} = 0{,}066705$$

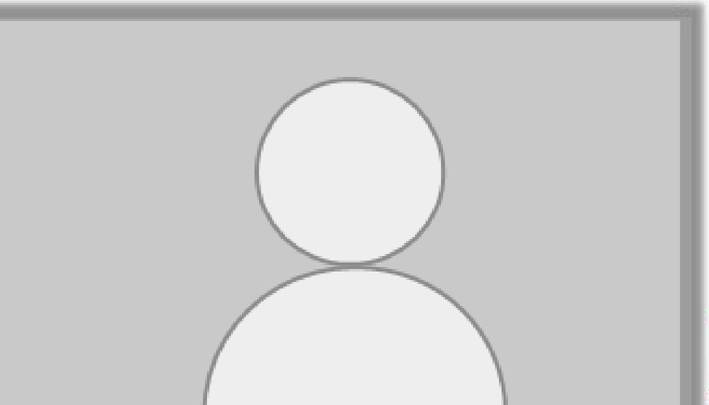
Rendimento da combustão

$$\eta_{comb} = PCI/\dot{Q}_{útil}$$

$$\eta_{comb} \overset{arb}{=} 0{,}333$$

A ser elaborado em uma aula específica...





Determinação das propriedades em (3)

Cálculo do salto entálpico

$$h_3 - h_2 = \dot{m}_{comb} / \dot{m}_{ar} \cdot \eta_{comb} \cdot PCI_{comb}$$

$$h_3 - 703{,}05 kJ/kg = 0{,}066705 \cdot 0{,}333 \cdot 44{,}19 \cdot 10^3 kJ/kg$$

$$h_3 = 1684{,}644 \text{ kJ/kg}$$

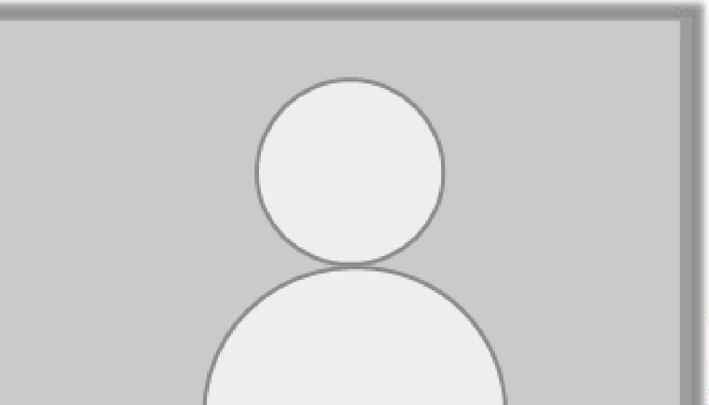
P3=10bar

h3=1684,644kJ/kg

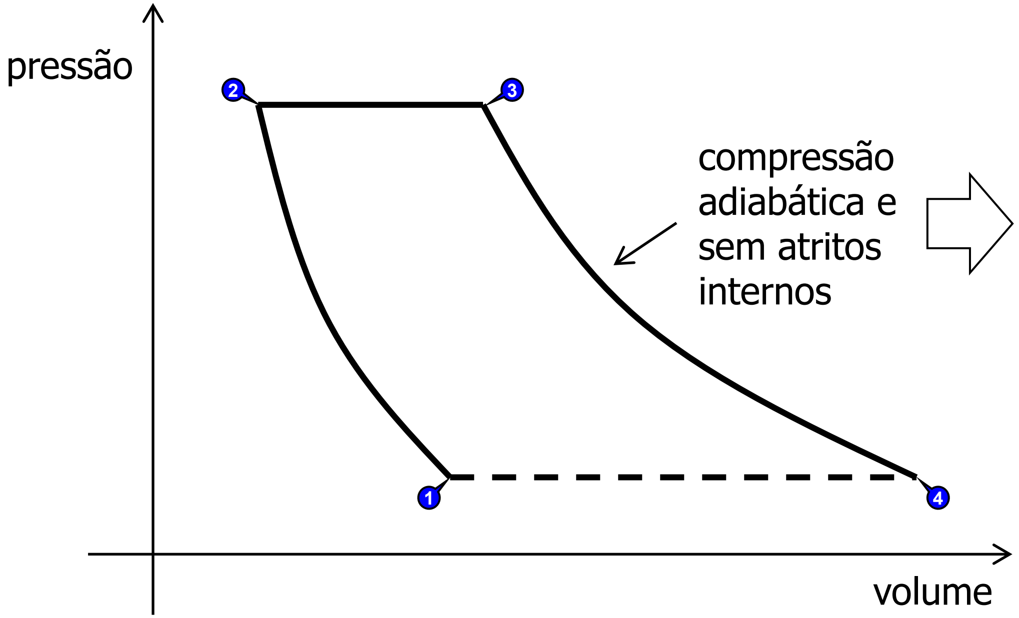
⇩

T3=1161,6ºC → **estimado: T3≈1094ºC**

s3=4,9208kJ/kg/K



Determinação das propriedades em (4)

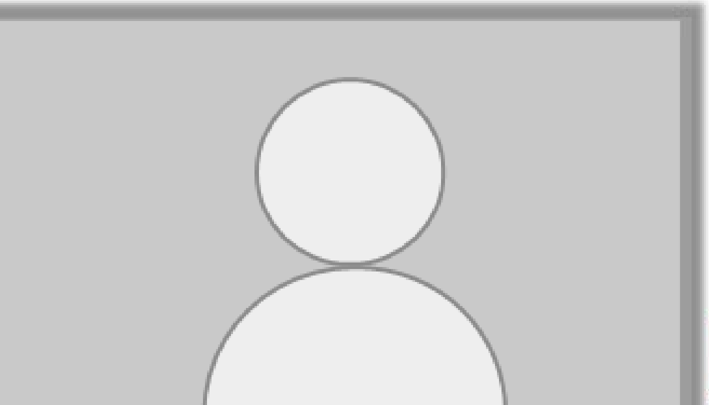


compressão adiabática e sem atritos internos ⇒ processo isentrópico

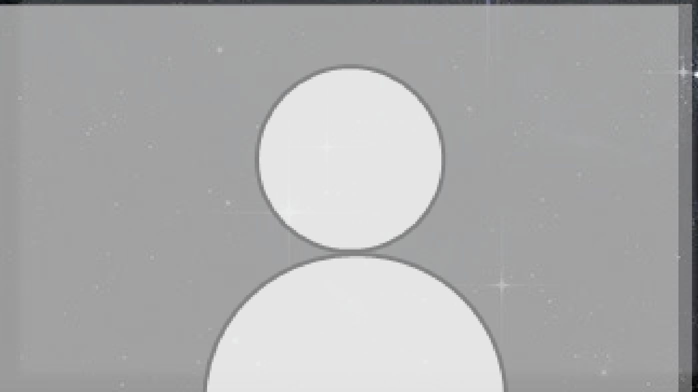
P3=10bar
h3=1684,644kJ/kg
⇓
T3=1161,6ºC
s3=4,9208kJ/kg/K

→

P4=1bar
s4=4,9208kJ/kg/K
⇓
T4=535,9ºC → estimado: T3≈570ºC
h4=958,6kJ/kg

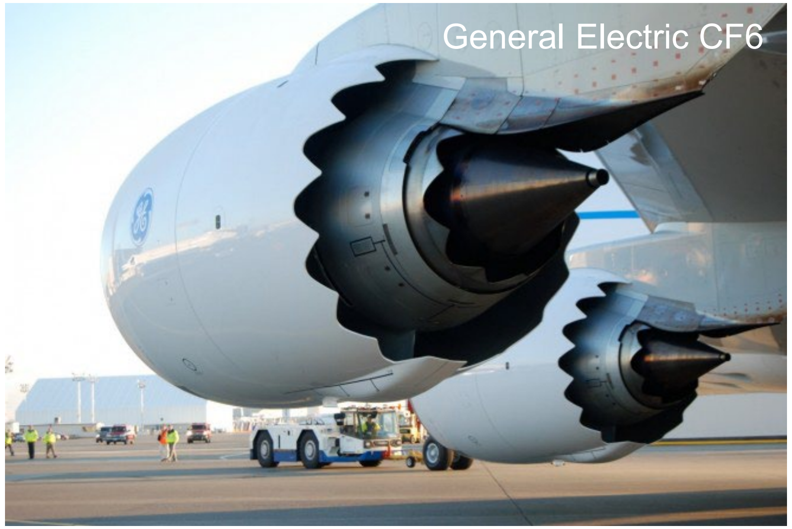


Comparando com o Boeing 747 ...



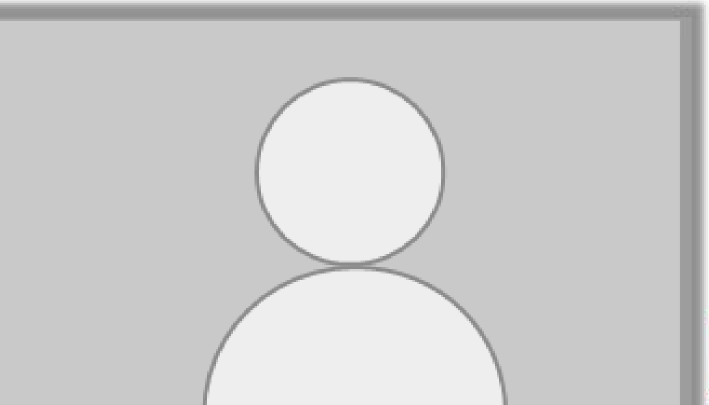
Configurações e motores que equipam o Boeing 747

Pratt & Whitney JT9D

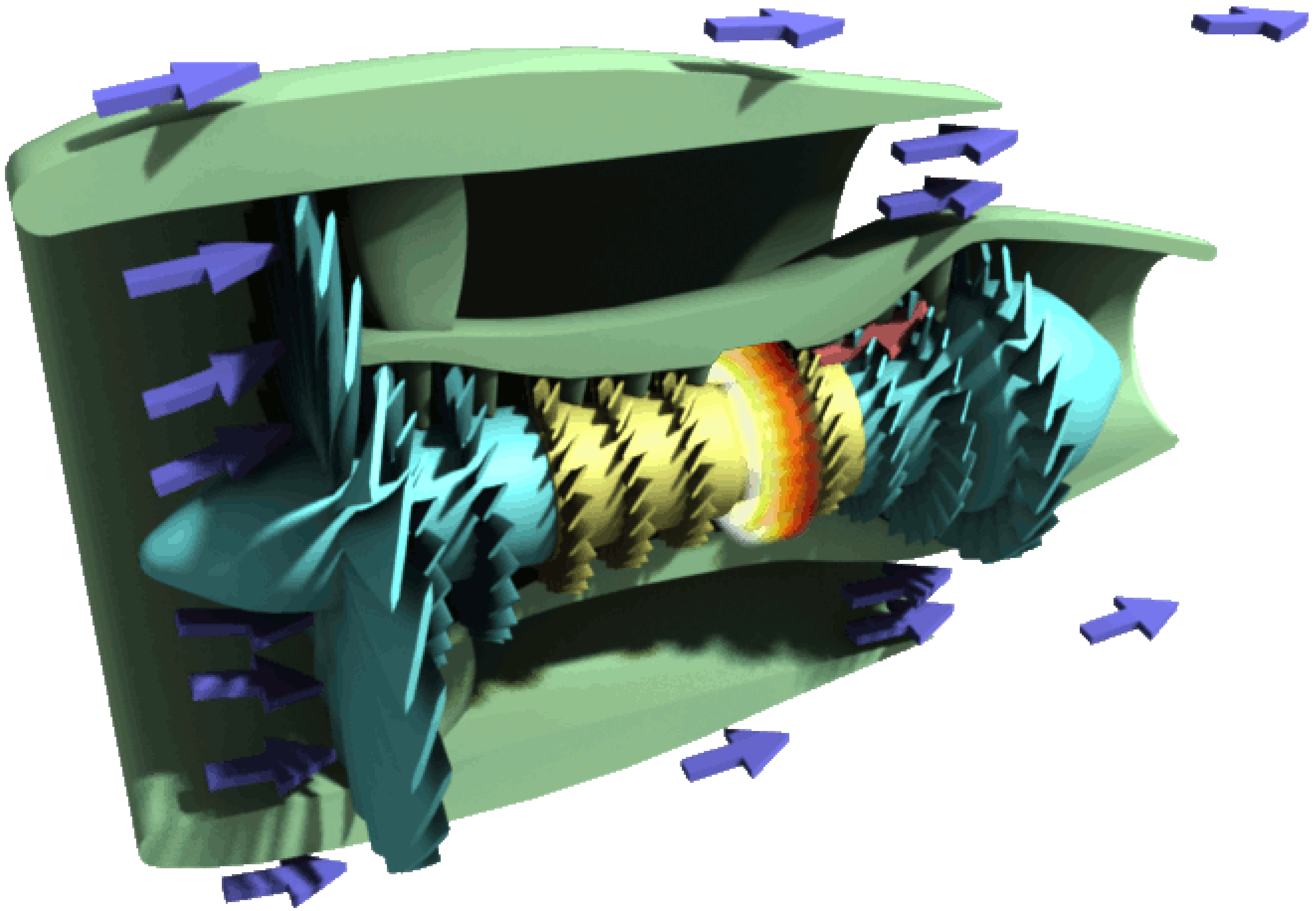


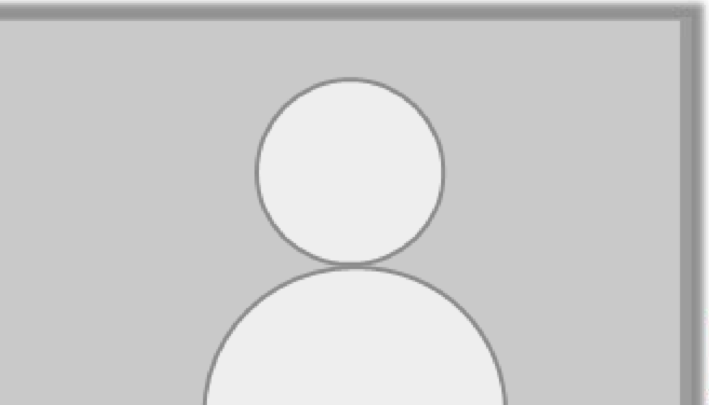
General Electric CF6

Rolls-Royce RB211

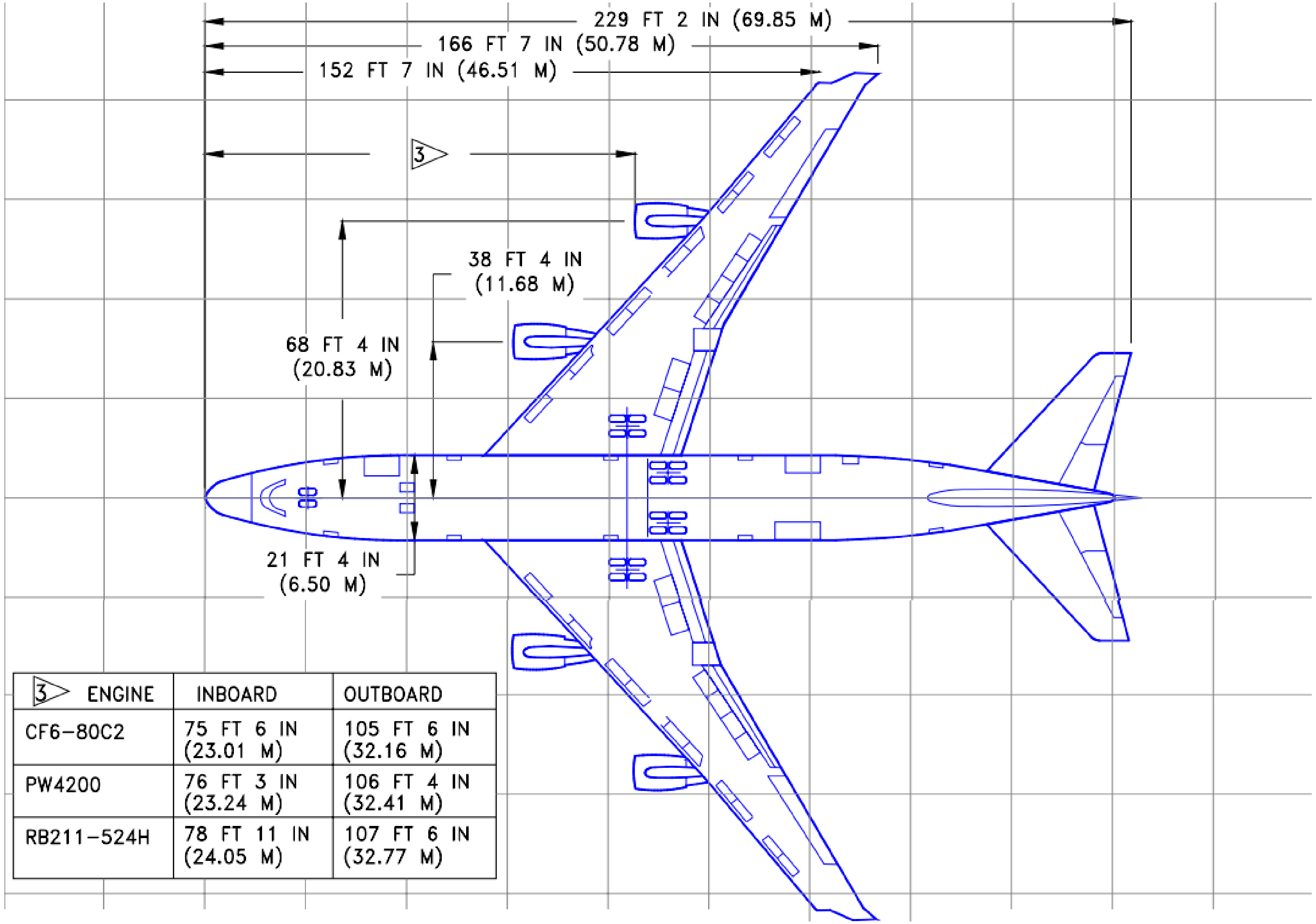


Configurações e motores que equipam o Boeing 747

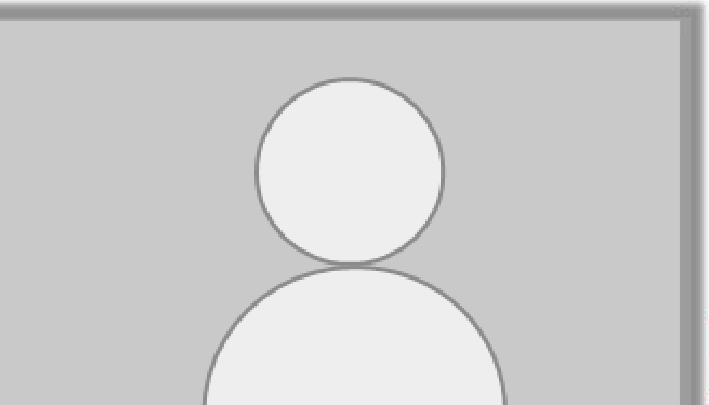




Configurações e motores que equipam o Boeing 747



3 ENGINE	INBOARD	OUTBOARD
CF6-80C2	75 FT 6 IN (23.01 M)	105 FT 6 IN (32.16 M)
PW4200	76 FT 3 IN (23.24 M)	106 FT 4 IN (32.41 M)
RB211-524H	78 FT 11 IN (24.05 M)	107 FT 6 IN (32.77 M)



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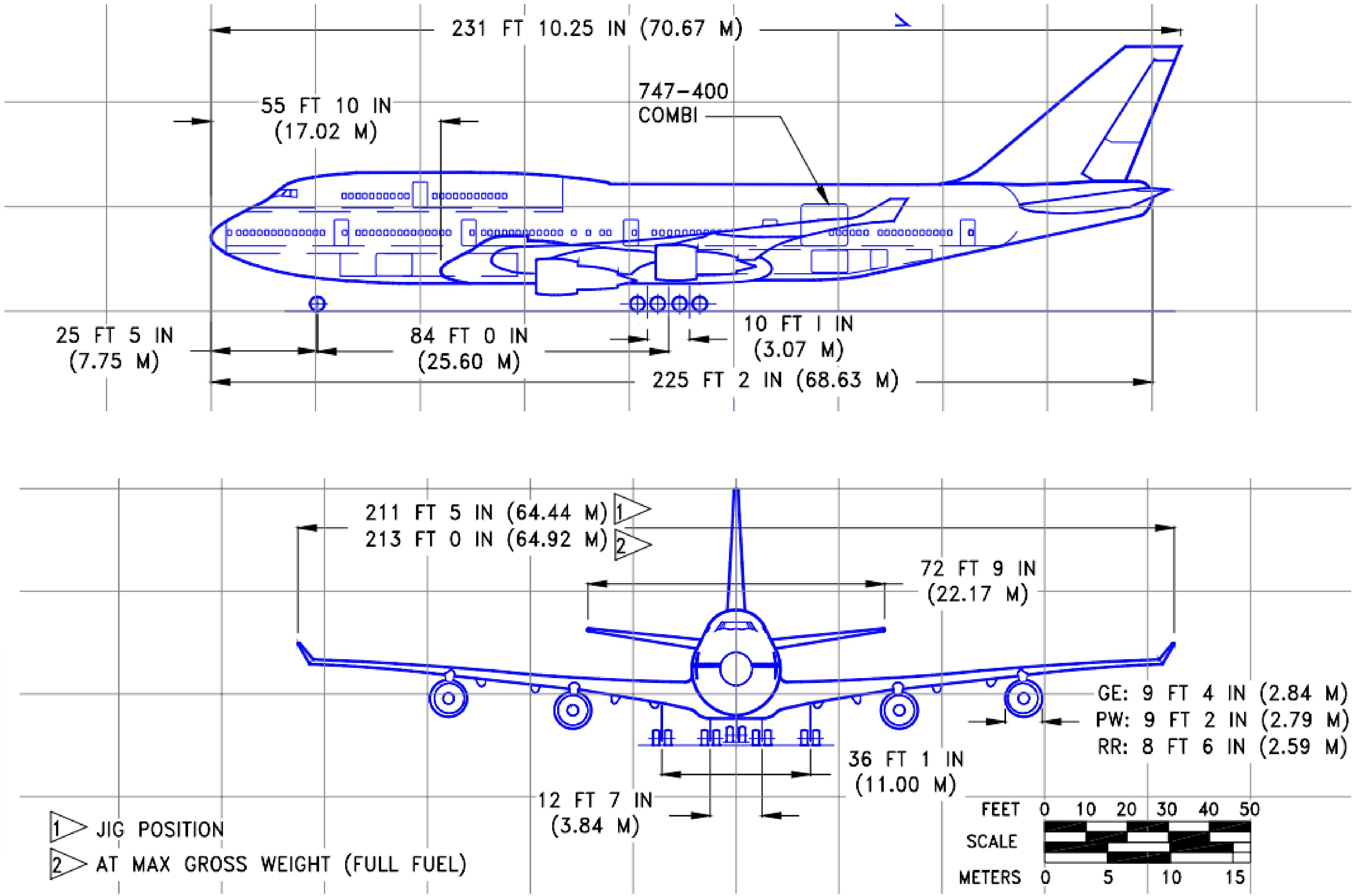
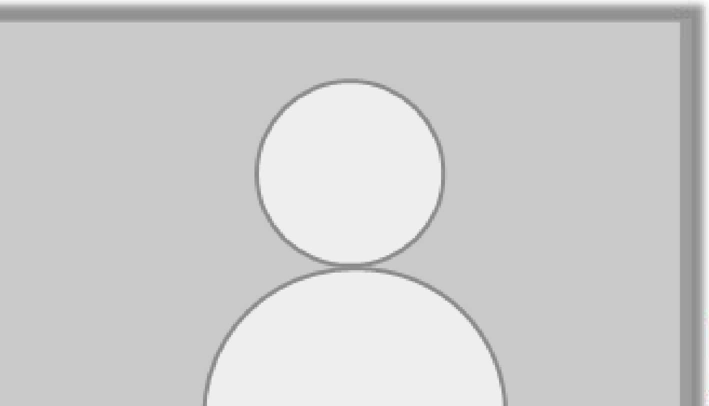
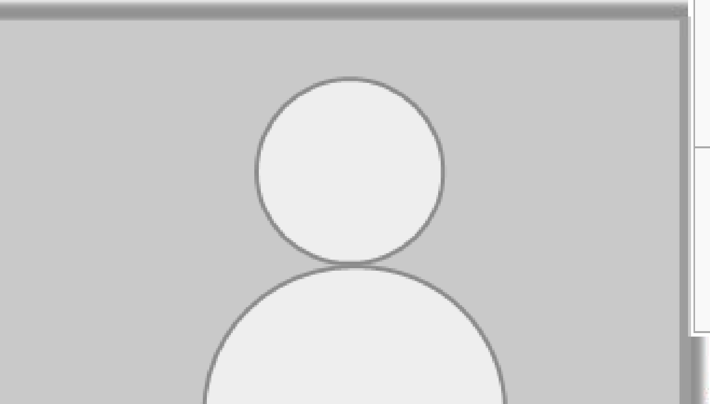
Configurações e motores que equipam o Boeing 747

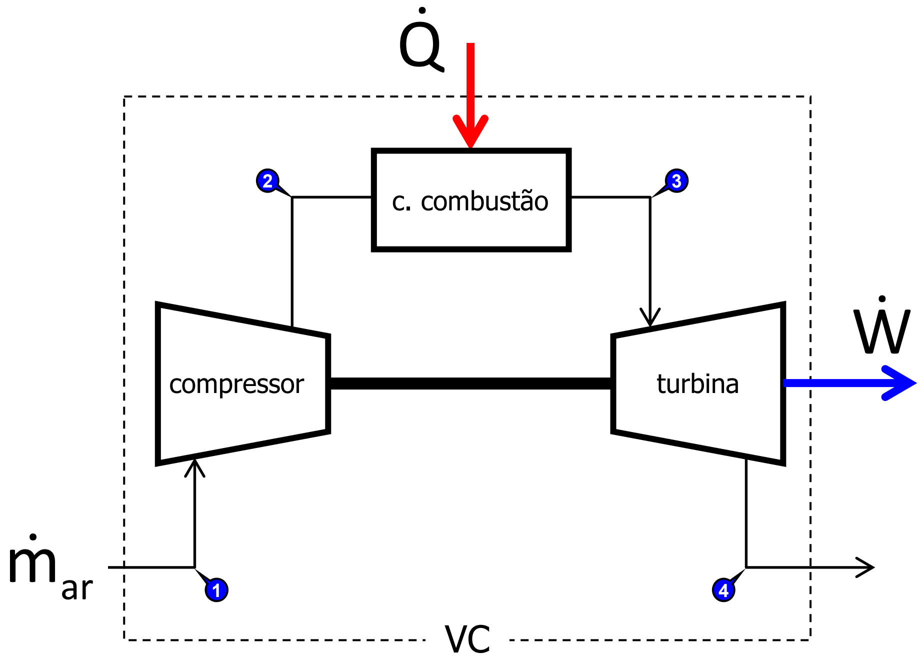




Configurações e motores que equipam o Boeing 747

Measurement	747-100B	747-200B	747-300	747-400 747-400ER	747-8I
Maximum cargo capacity	6,190 ft^3 (175.3 m^3) = 30xLD1			6,025 ft^3 (170.5 m^3) **ER:** 5,599 ft^3 (158.6 m^3)	5,705 ft^3 (161.5 m^3)
Operating empty weight	358,000 lb (162,400 kg)	383,000 lb (174,000 kg)	392,800 lb (178,100 kg)	393,263 lb (178,756 kg) **ER:** 406,900 lb (184,600 kg)	472,900 lb (214,503 kg)
Maximum takeoff weight	735,000 lb (333,390 kg)	833,000 lb (377,842 kg)		875,000 lb (396,890 kg) **ER:** 910,000 lb (412,775 kg)	987,000 lb (447,696 kg)
Cruising speed (at 35,000 ft (11,000 m) altitude)	Mach 0.84 (555 mph, 893 km/h, 481 knots)			Mach 0.85 (567 mph, 913 km/h, 493 kn) **ER:** Mach 0.855 (570 mph, 918 km/h, 495 kn)	Mach 0.855 (570 mph, 918 km/h, 495 kn)
Maximum speed	Mach 0.89 (594 mph, 955 km/h, 516 kn)			Mach 0.92 (614 mph, 988 km/h, 533 kn)	
Maximum fuel capacity	48,445 U.S. gal (40,339 imp gal/183,380 L)	52,410 U.S. gal (43,640 imp gal/199,158 L)		57,285 U.S. gal (47,700 imp gal/216,840 L) **ER:** 63,705 U.S. gal (53,045 imp gal/241,140 L)	64,225 U.S. gal (53,478 imp gal/243,120 L)
Engine models (x 4)	PW JT9D-7A/-7F/-7J RR RB211-524B2 GE CF6-45A2 (747SR)	PW JT9D-7R4G2 GE CF6-50E2 RR RB211-524D4	PW JT9D-7R4G2 GE CF6-80C2B1 RR RB211-524D4	PW 4062 GE CF6-80C2B5F RR RB211-524G/H **ER:** GE CF6-80C2B5F	GEnx-2B67
Engine thrust (per engine) estático	PW 46,500 lbf (207 kN) RR 50,100 lbf (223 kN)	PW 54,750 lbf (244 kN) GE 52,500 lbf (234 kN) RR 53,000 lbf (236 kN)	PW 54,750 lbf (244 kN) GE 55,640 lbf (247 kN) RR 53,000 lbf (236 kN)	PW 63,300 lbf (282 kN) GE 62,100 lbf (276 kN) RR 59,500/60,600 lbf (265/270 kN) **ER:** GE 62,100 lbf (276 kN)	66,500 lbf (296 kN)





Consumo de um motor: 0,8kg/s de querosene

$$\dot{Q} = \dot{m}_{comb} \cdot (\eta_{comb} PCI_{comb})$$

$$\dot{Q} = 0{,}8kg/s \cdot (0{,}333 \cdot 44{,}19MJ/kg)$$

$$\dot{Q} = 11{,}7722MW$$

Inventário de energia no volume de controle

$$\dot{Q} - \dot{W} = \dot{m}_{ar} \cdot \left[\left(h + \cancel{gz} + \cancel{\frac{V^2}{2}} \right)_s - \left(h + \cancel{gz} + \cancel{\frac{V^2}{2}} \right)_e \right]$$

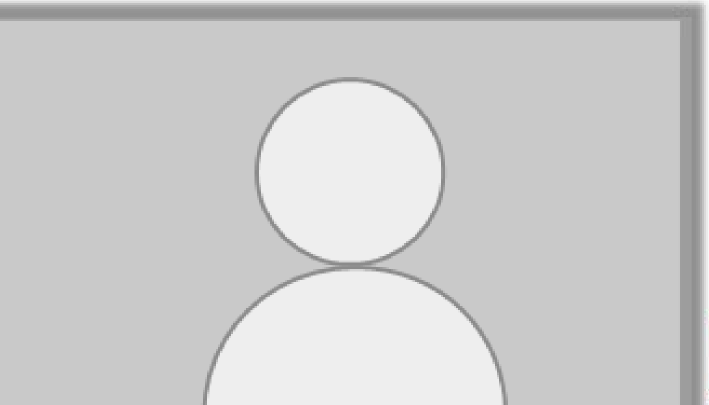
$$\dot{Q} - \dot{W} = \dot{m}_{ar} \cdot (h_4 - h_1) \qquad m_{C_{12}H_{26}} = 0{,}066705 \cdot m_{ar}$$

$$11{,}7722MW - \dot{W} = \frac{0{,}8kg/s}{0{,}066705} \cdot (958{,}6 - 424{,}5) \cdot 10^{-3} MJ/kg$$

$$\dot{W} = 5{,}367MW$$

$$\eta = \dot{W}/\dot{Q}$$

$$\eta = 45{,}6\%$$



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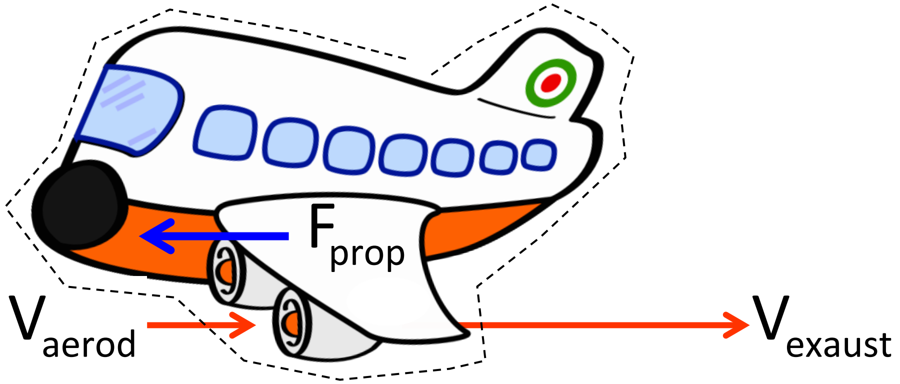
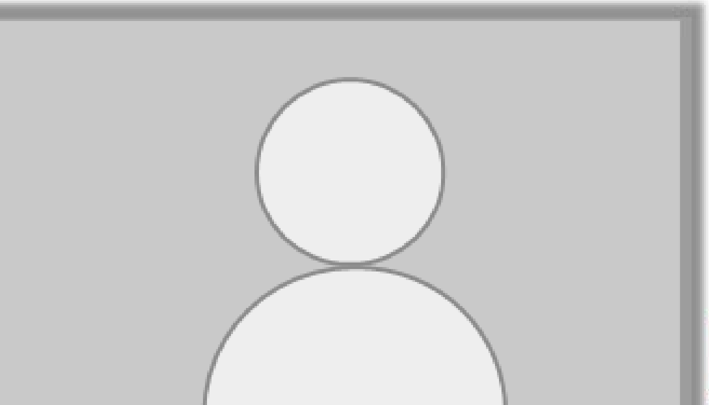
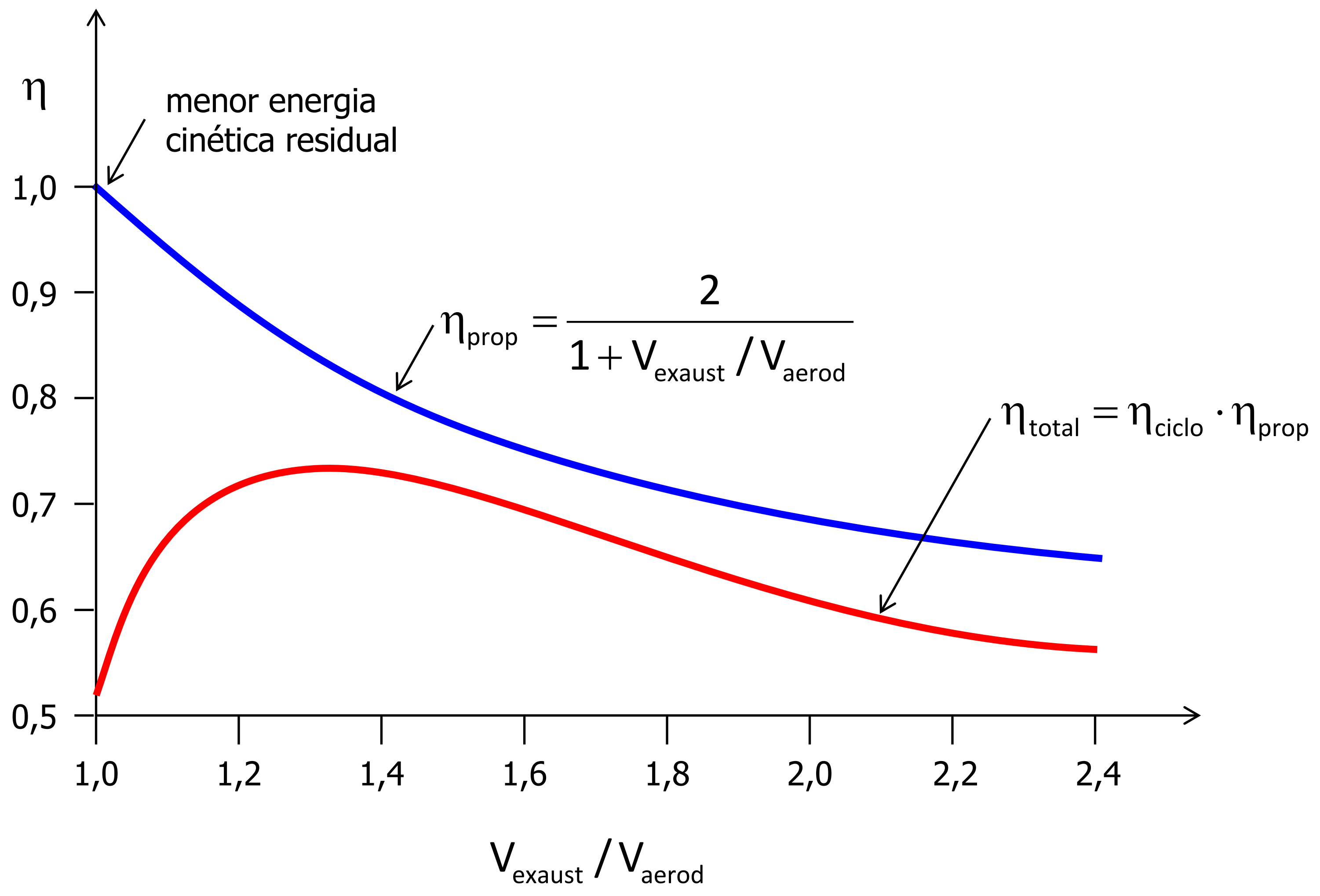


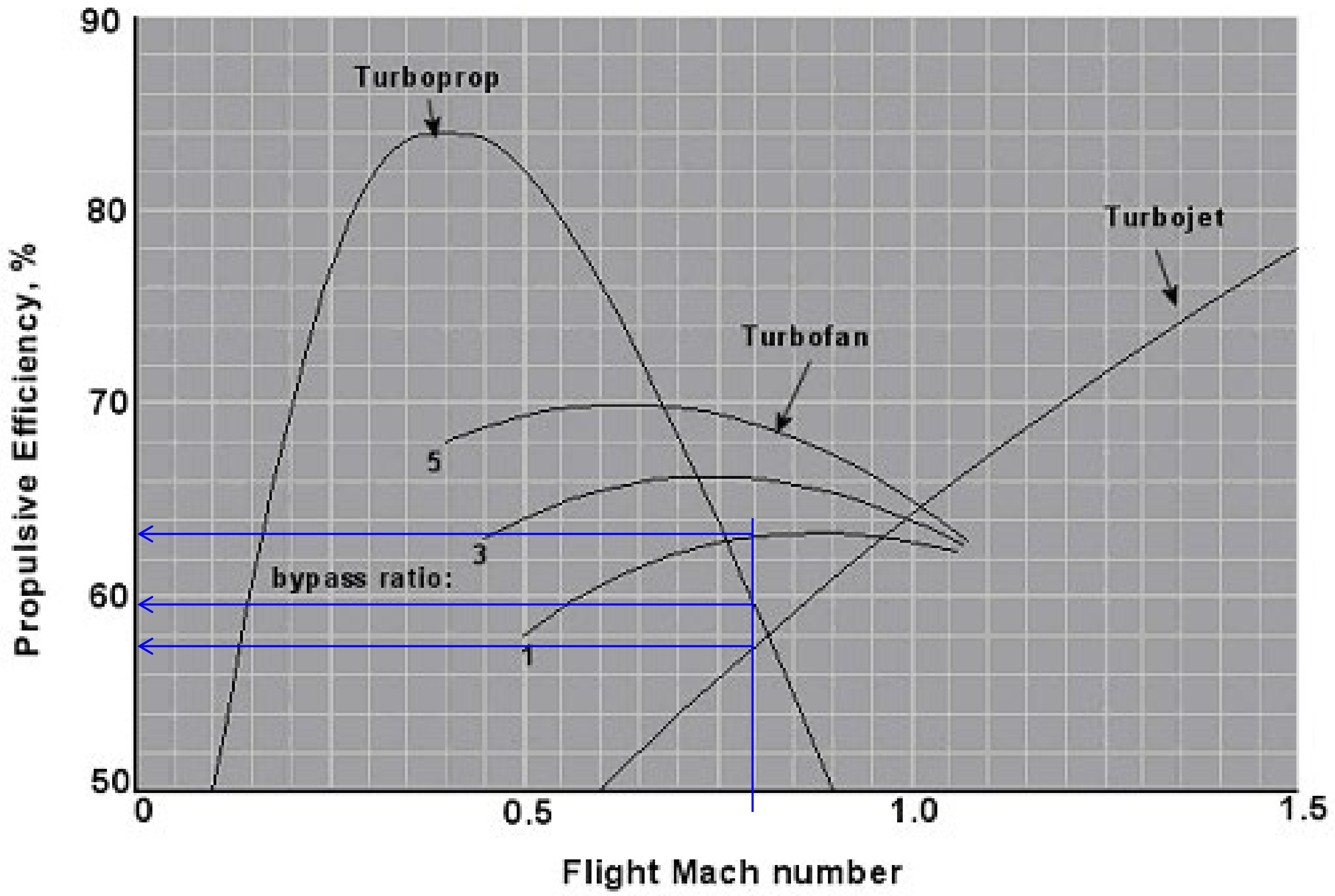
$$\eta_{prop} = \frac{F_{prop} \cdot V_{aerod}}{\frac{\dot{m}_{exaust} V_{exaust}^2}{2} - \frac{\dot{m}_{aspirac} V_{aerod}^2}{2}}$$

$$F_{prop} \cong \dot{m}_{ar} \left(V_{exaust} - V_{aerod}\right) \qquad \dot{m}_{aspirac} \cong \dot{m}_{ar} \cong \dot{m}_{exaust}$$

$$\eta_{prop} = \frac{2}{1 + \frac{V_{exaust}}{V_{aerod}}}$$

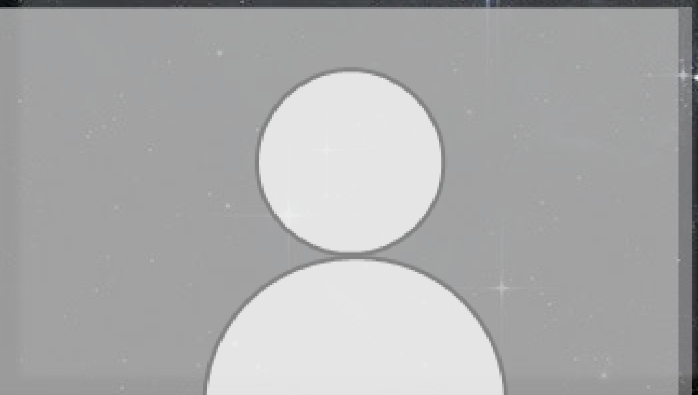



η
menor energia
cinética residual
1,0
0,9
0,8
0,7
0,6
0,5
$\eta_{prop} = \frac{2}{1 + V_{exaust} / V_{aerod}}$
$\eta_{total} = \eta_{ciclo} \cdot \eta_{prop}$
1,0
1,2
1,4
1,6
1,8
2,0
2,2
2,4
V_{exaust} / V_{aerod}


Turboprop
Turbojet
Turbofan
5
3
bypass ratio:
1
90
80
70
60
50
0
0.5
1.0
1.5
Propulsive Efficiency, %
Flight Mach number

Balanço de Energia em VC em regime transiente....

Lançamento do Saturno V / Apollo



https://youtu.be/f3NhpIu10T8