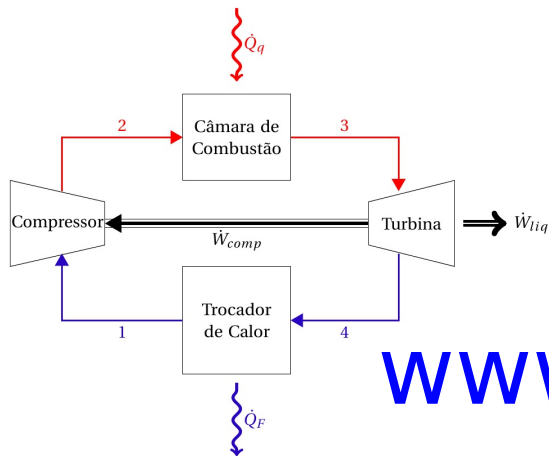
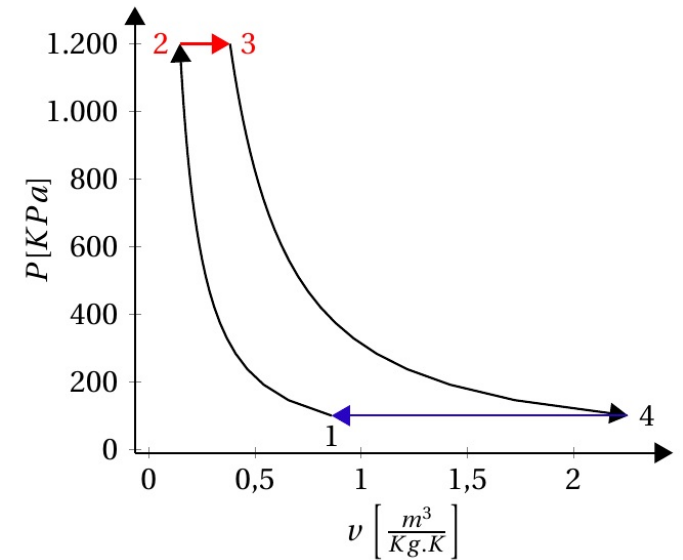
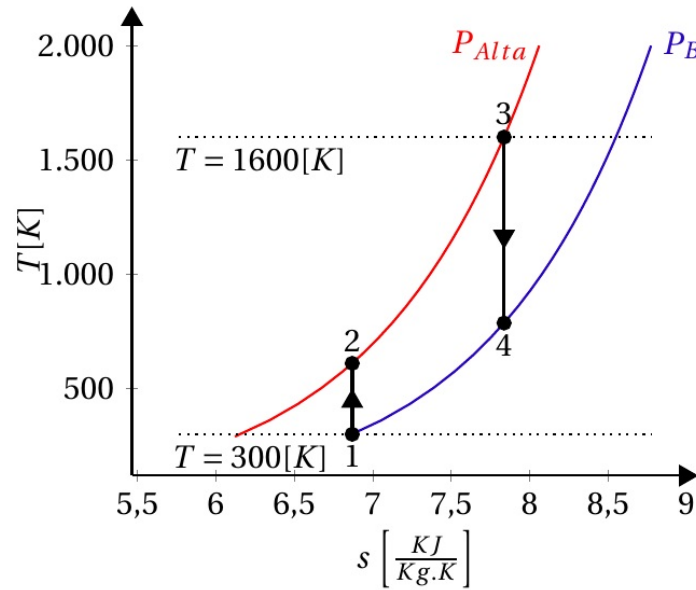
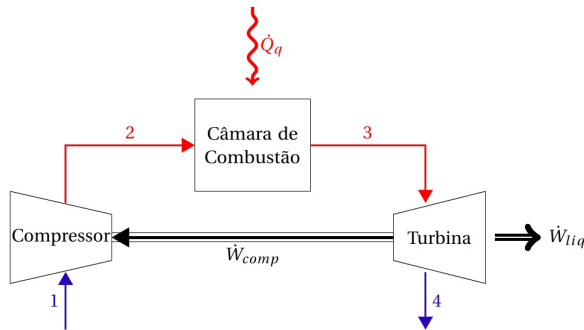


Ciclo de Potência a gás BRAYTON

TEORIA E PROCEDIMENTO DE SOLUÇÃO



www.cienciaastermicas.com

Sistemas de Potência a gás: ciclo Brayton

Objetivos da aula:

1. Identificar os componentes do ciclo Brayton ideal
2. Desenhar o diagrama $T - s$ e $P - v$
3. Fazer balanço de energia em cada componente para calcular trabalhos, calores e rendimento do ciclo
4. Identificar a diferença entre os Ciclos de potência a gás e a vapor

Representa a operação de sistemas motores com turbina a gás

Sistemas de propulsão

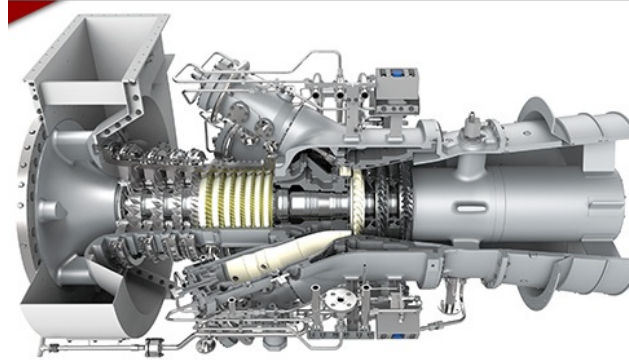
Sistemas de geração de potência

<https://web.mit.edu/16.unified/www/SPRING/propulsion/notes/node27.html>

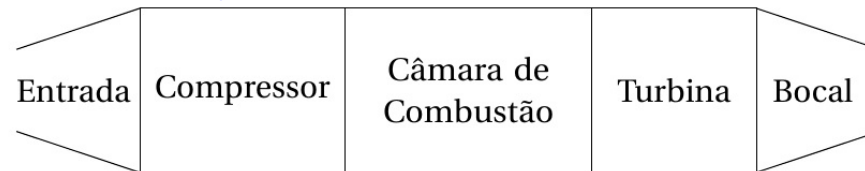
COMPONENTES

Representa a operação de sistemas motores com turbina a gás
Sistemas de propulsão
Sistemas de geração de potência

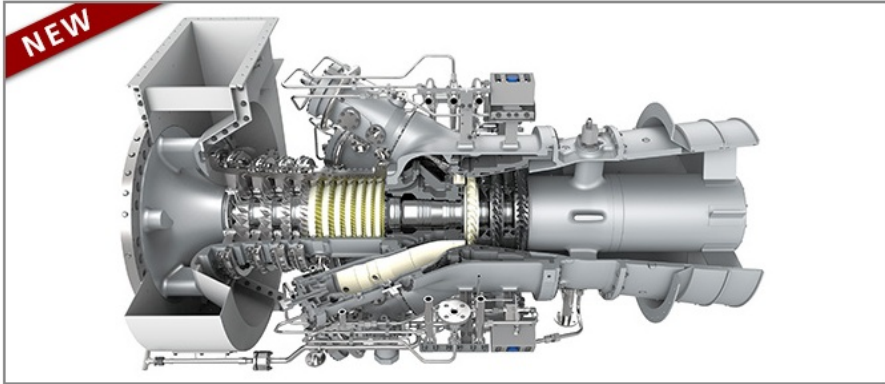
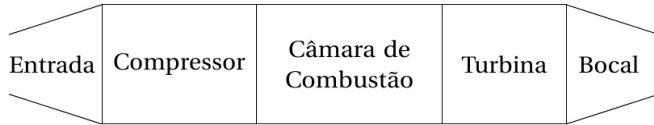
<https://web.mit.edu/16.unified/www/SPRING/propulsion/notes/node27.html>



<https://www.kawasaki-gasturbine.de/en/products/turbine-generator-sets?id=159><https://www.opensuse.org/searchPage/>

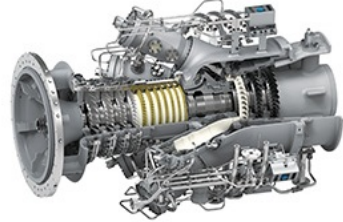


1. Compressão adiabática na entrada e compressor
Compressão isoentrópica no ciclo ideal
2. Combustão à pressão constante
Adição de calor à pressão constante no ciclo ideal
3. Expansão adiabática na turbina e bocal de exaustão
Expansão isoentrópica no ciclo ideal
[*]Parte do trabalho da turbina é utilizado para alimentar o compressor
[*]O restante do trabalho é utilizado para: acelerar o fluido em sistemas de propulsão a jato ou girar o gerador para geração de eletricidade
4. Resfriamento do ar à pressão constante para suas condições iniciais



Gas Turbine Type M5A-01

Electrical power	4,720 kW
Fuel input	14,500 kW
Efficiency	32.6 %
Exhaust gas mass flow	17.4 kg/s
Exhaust gas temperature	511°C
Generator voltage	6.3 kV / 10.5 kV
Steam mass flow 8 bar(g) saturated	11 t/h
Fuel type	Natural Gas
Emissions	DLE, NOx: 15ppm CO: 25ppm



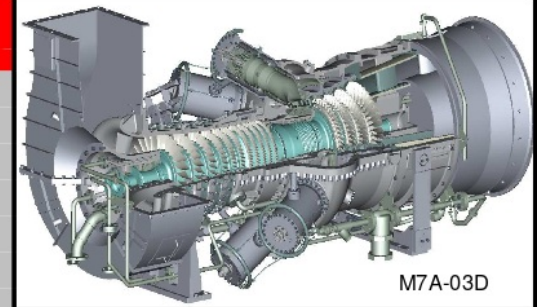
Performance under ISO-conditions w/o duct losses at Generator Terminal

<https://www.kawasaki-gasturbine.de/en/products/turbine-generator-sets?id=159>

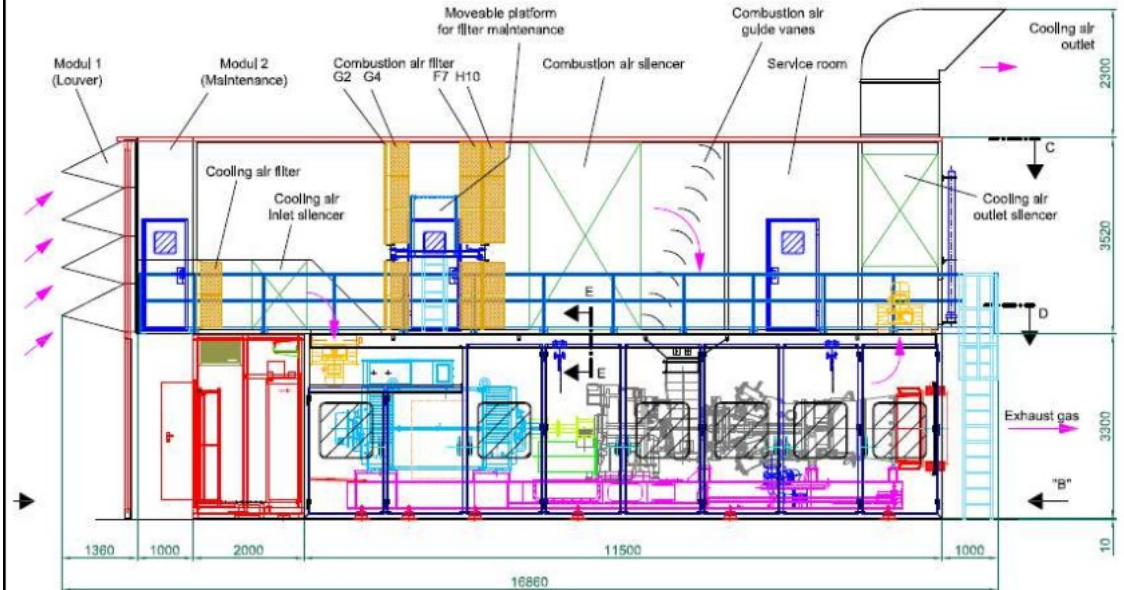
Gas Turbine Type M7A-03D

Electrical power	7,810 kW
Fuel input	23,273 kW
Efficiency	33.6 %
Exhaust gas mass flow	27.3 kg/s
Exhaust gas temperature	523 °C
Generator voltage	6.3 kV / 10.5 kV
Steam mass flow 8 bar(g) saturated	16.4 t/h
Fuel type	Natural Gas
Emissions	Single digit < 9ppm NOx / CO 25ppm

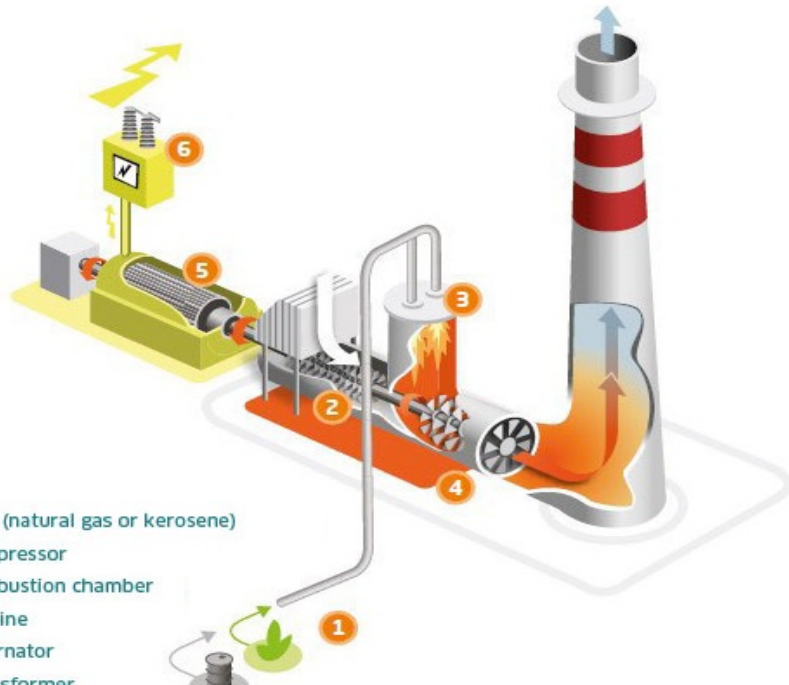
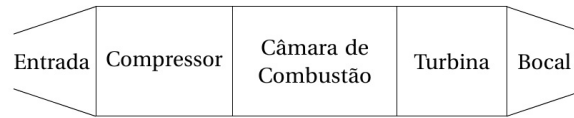
Performance at ISO-conditions w/o duct losses at Generator Terminal



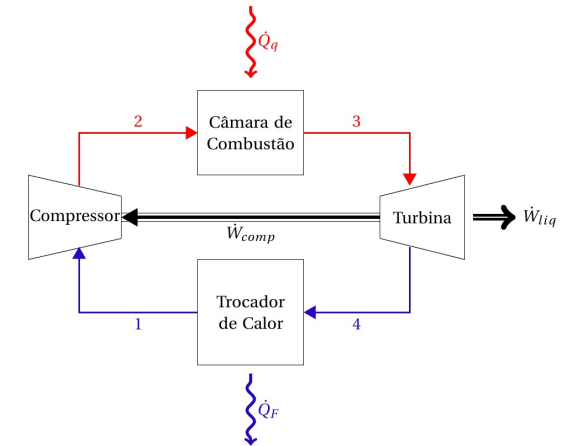
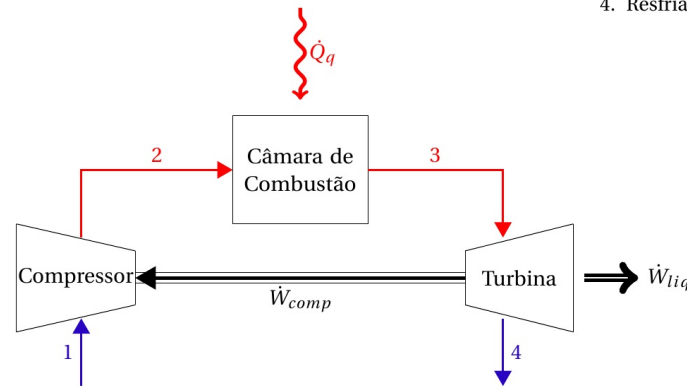
Typical Layout drawing for outdoor installation:



Ciclo Brayton para geração de potência

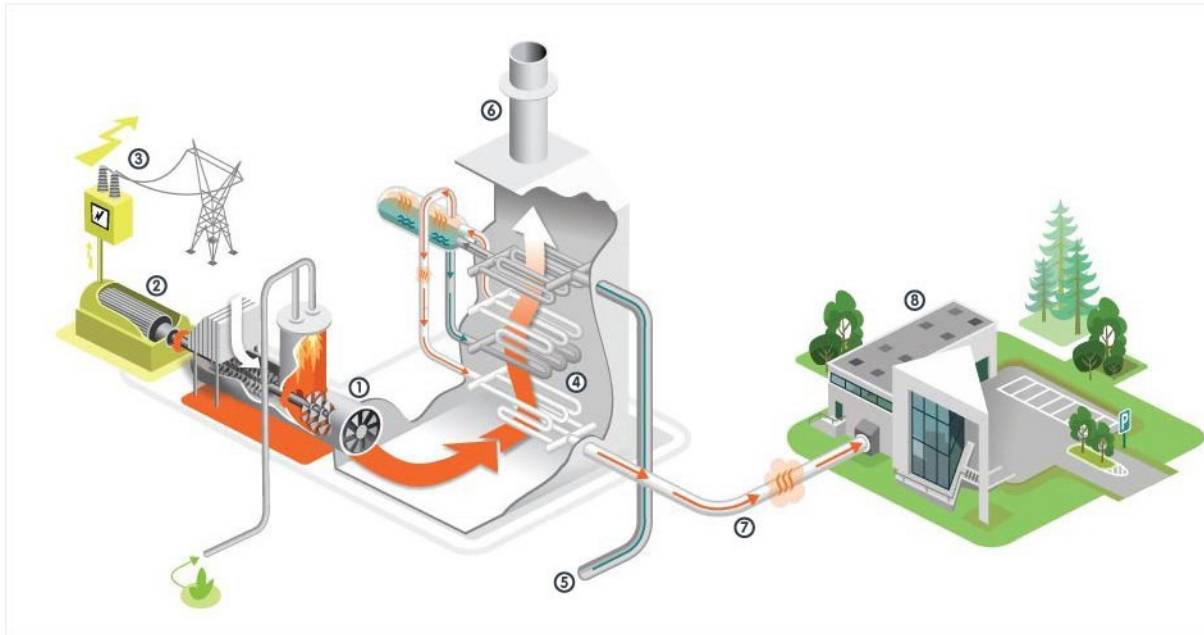


<https://www.engie.com/en/businesses/electricity/thermal-electricity/>



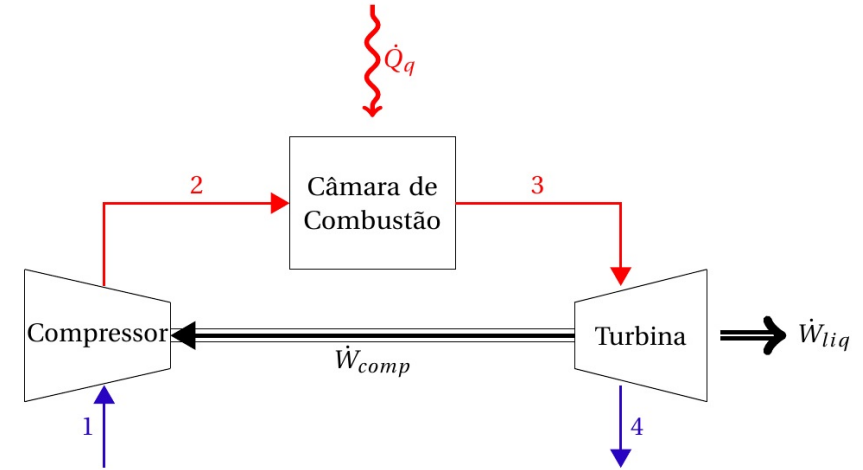
1. Compressão adiabática na entrada e compressor
Compressão isoentrópica no ciclo ideal
2. Combustão à pressão constante
Adição de calor à pressão constante no ciclo ideal
3. Expansão adiabática na turbina e bocal de exaustão
Expansão isoentrópica no ciclo ideal
[*]Parte do trabalho da turbina é utilizado para alimentar o compressor
[*]O restante do trabalho é utilizado para: acelerar o fluido em sistemas de propulsão a jato ou girar o gerador para geração de eletricidade
4. Resfriamento do ar à pressão constante para suas condições iniciais

Ciclo Brayton para geração de potência: co-geração



- ① Gas turbine
- ② Alternator
- ③ Transformer
- ④ Condensing boiler
- ⑤ Water supply
- ⑥ Flue
- ⑦ Steam line
- ⑧ Customer heat

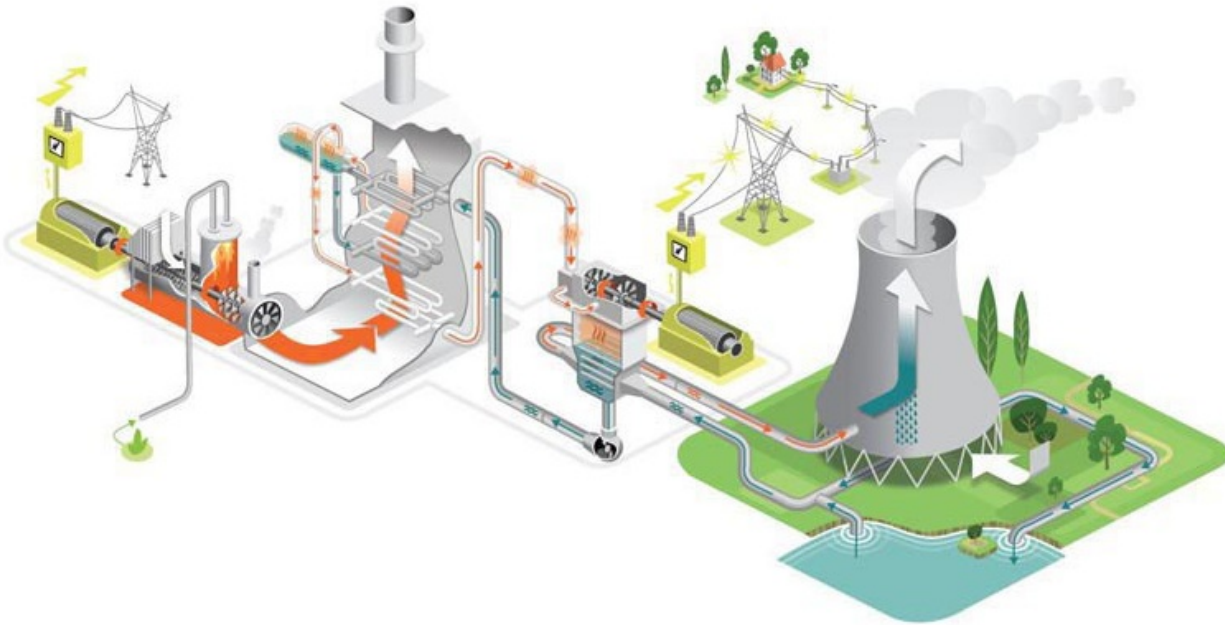
<https://www.engie.com/en/businesses/electricity/thermal-electricity/>



https://cset.mnsu.edu/engagethermo/systems_gtpp.html

Ciclos Brayton+Rankine

Steam-gas turbine plant



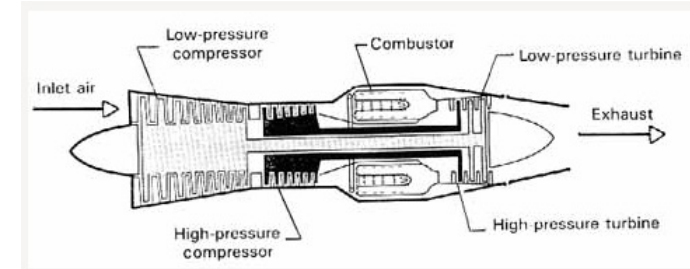
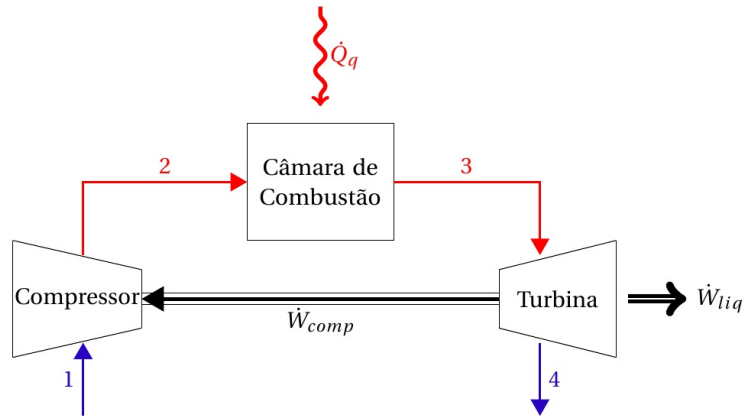
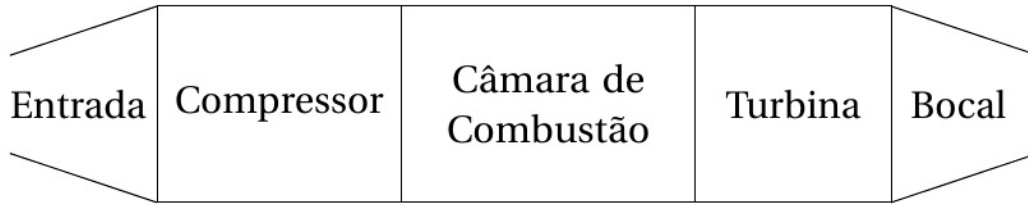
<https://www.greentechmedia.com/articles/read/ges-digital-power-plant-the-natural-gas-contender-to-grid-batteries>



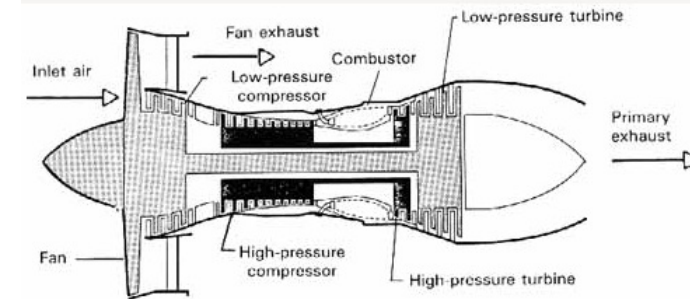
<https://siemensusa.synapticdigital.com/images-and-videos/featured-multimedia-stories/power-and-gas/new-el-segundo-energy-center-b-roll/a/2bae458c-9da5-4cae-8e81-878d1fb90c65>

<https://www.engie.com/en/businesses/electricity/thermal-electricity/>

Sistemas de Propulsão em aeronaves a jato



(a) Turbojet



(b) High-bypass-ratio turbofan

[226] Figure 10.1 - Two types of jet propulsion systems.

<https://history.nasa.gov/SP-468/ch10-3.htm>

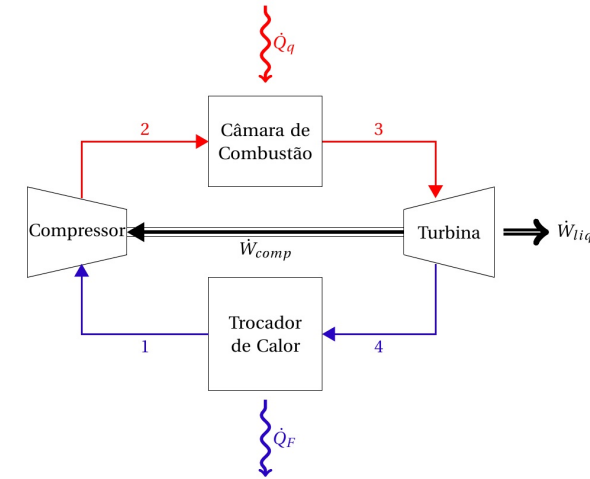
$\dot{m} (V_s - V_E)$

Ciclo de Potência a Gás Brayton ideal

Para o ciclo ideal, devemos destacar:

- os efeitos de irreversibilidade não serão considerados
 - os processos no compressor e turbina são considerados isoentrópicos (reversíveis e adiabáticos)
- Sempre ar (não há produtos de combustão)
 - Processo de combustão substituído por transferência de calor de uma fonte externa
- Sempre gás ideal
 - Equação dos gases ideais aplicáveis
- Processo de exaustão substituídos por transferência de calor para uma fonte externa
- Análise a ar frio: calores específicos constantes e avaliados à 298K

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_2}{v_1}\right)^{1-k}$$



$$ds = \int \frac{\delta Q}{T}$$

$$Tds = du + Pdv$$

$$Tds = dh - vdp$$

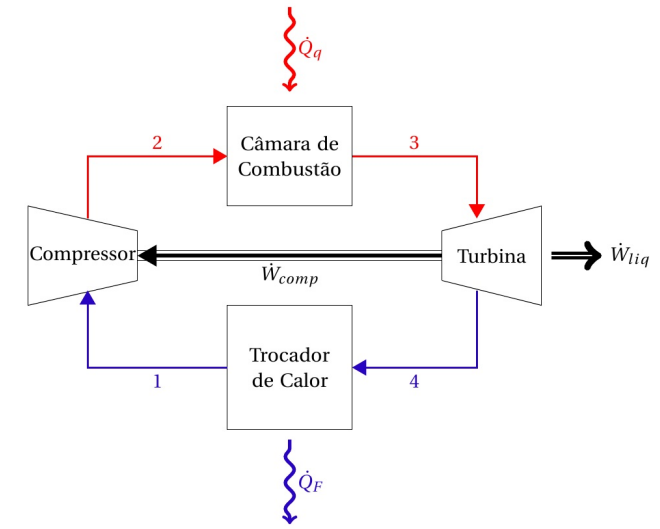
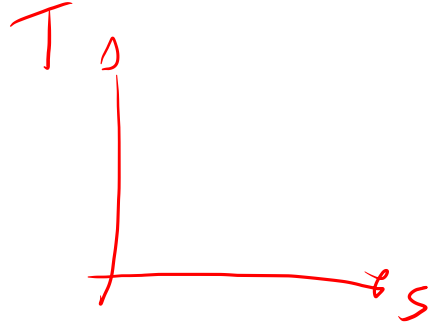
para gases ideais

Considerando calor específico constante:

$$s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

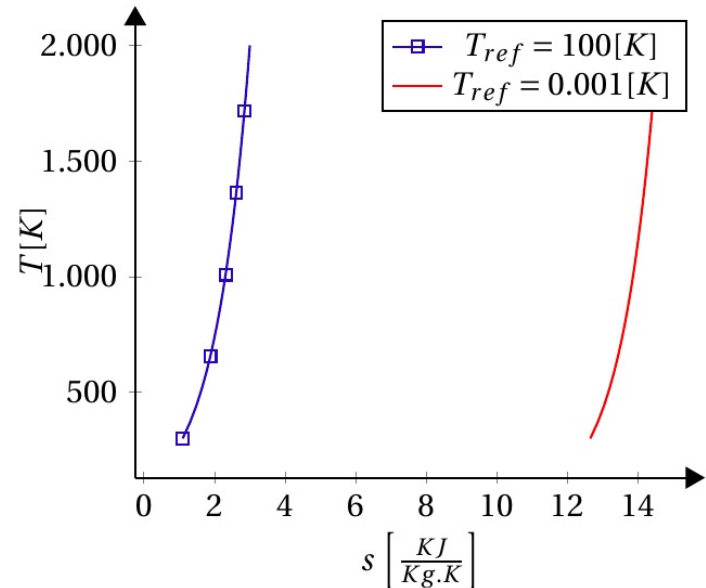
$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

O gráfico Temperatura - Entropia



Valor da entropia calculado para a pressão de 100[KPa] e temperaturas de 300[K] e 400 [K], com entropia de referência considerada nula em $T = 100[k], P = 100[KPa]$ e $T = 0,001[k], P = 100[KPa]$. O valor absoluto da entropia altera mas a diferença no valor não.

	$T_1 = 100[k]$	$T_1 = 0,001[K]$
T[K]	s[KJ/Kg.K]	s[KJ/Kg.K]
300	1,1030	12,6619
400	1,3918	12,95
dif	0,288832	0,288832

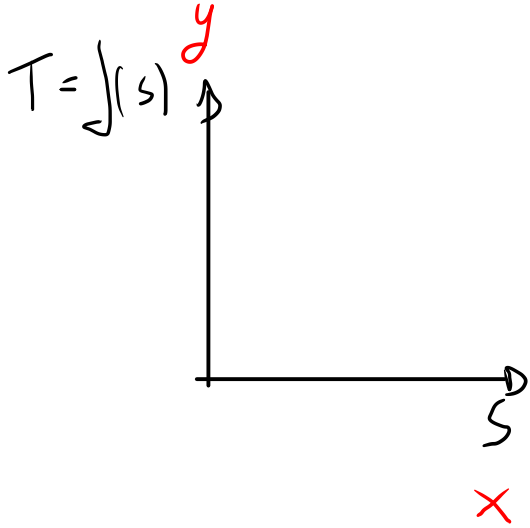


Vamos considerar a entropia de referência no valor de $T_1 = 300[K]$ e $P_1 = 100[KPa]$ como sendo igual à entropia $s_t^0 = 6,86926[KJ/Kg.K]$. A entropia para as demais pressões e temperaturas pode ser calculada por:

$$s_2 = 6,86926[KJ/Kg.K] + 1,004[KJ/Kg.K] \ln\left(\frac{T_2}{300}\right) - 0,287[KJ/Kg.K] \ln\left(\frac{P_2}{100}\right)$$

$$P_2 = 100$$

$$P_2 = 200$$



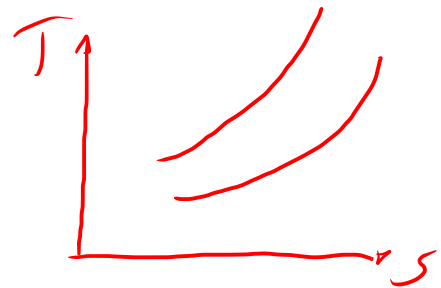
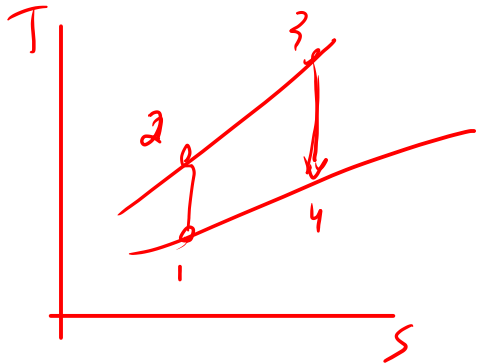
$$s_2 - 6,86926 + 0,287 \ln\left(\frac{P_2}{100}\right) = 1,004 \ln\left(\frac{T}{300}\right)$$

$$\ln\left(\frac{T}{300}\right) = \frac{1}{1,004} \left[s - 6,86926 + 0,287 \ln\left(\frac{P}{100}\right) \right]$$

$$T = 300 \times \exp\left\{ \frac{1}{1,004} \left[s - 6,86926 + 0,287 \ln\left(\frac{P}{100}\right) \right] \right\}$$

$$T = 300 \times \exp \left\{ \frac{1}{1,004} \left[s - 6,86926 + 0,287 \ln \left(\frac{P}{100} \right) \right] \right\}$$

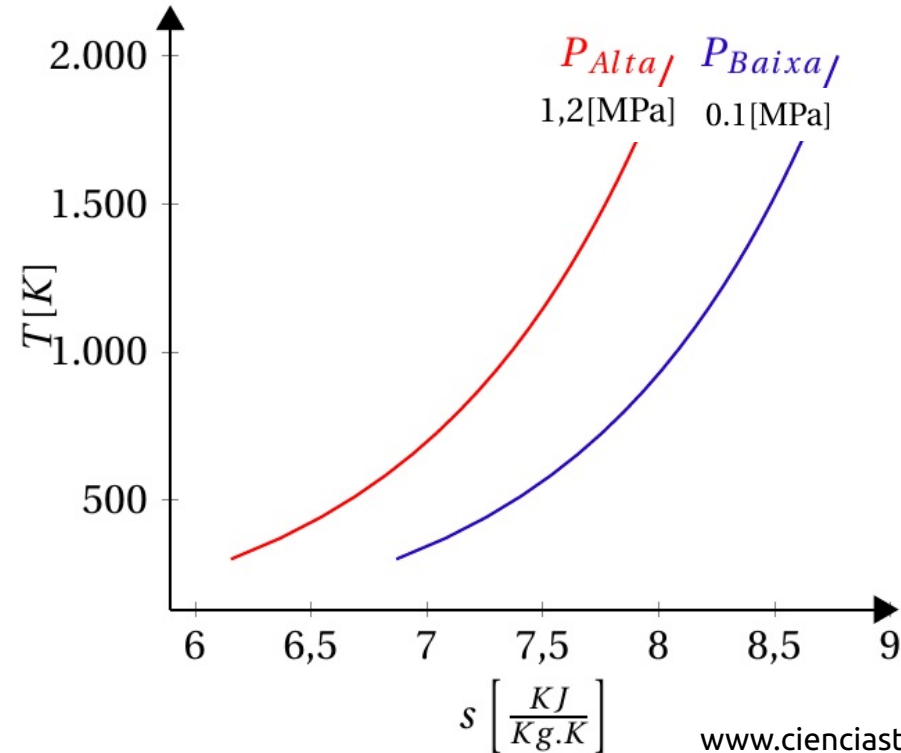
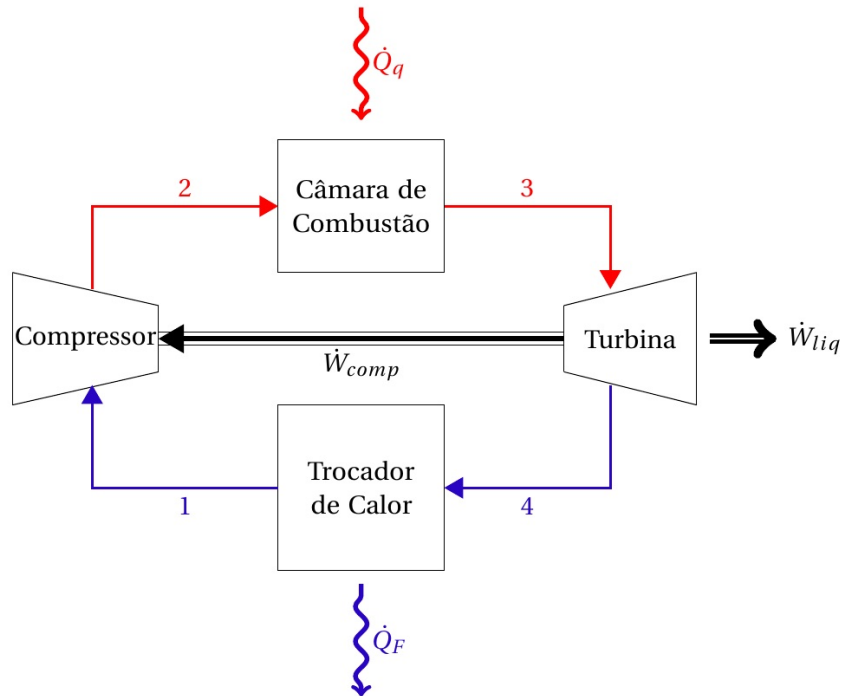
$$\sqrt{1X} = 300 \times \exp \left\{ \frac{1}{1,004} \left[X - 6,86926 + 0,287 \ln \left(\frac{P}{100} \right) \right] \right\}$$



O gráfico Temperatura - Entropia

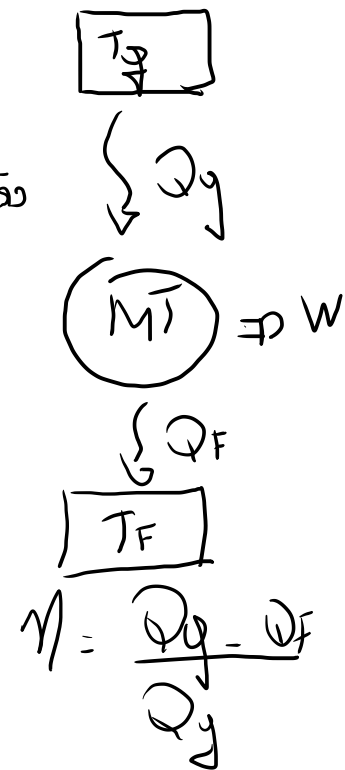
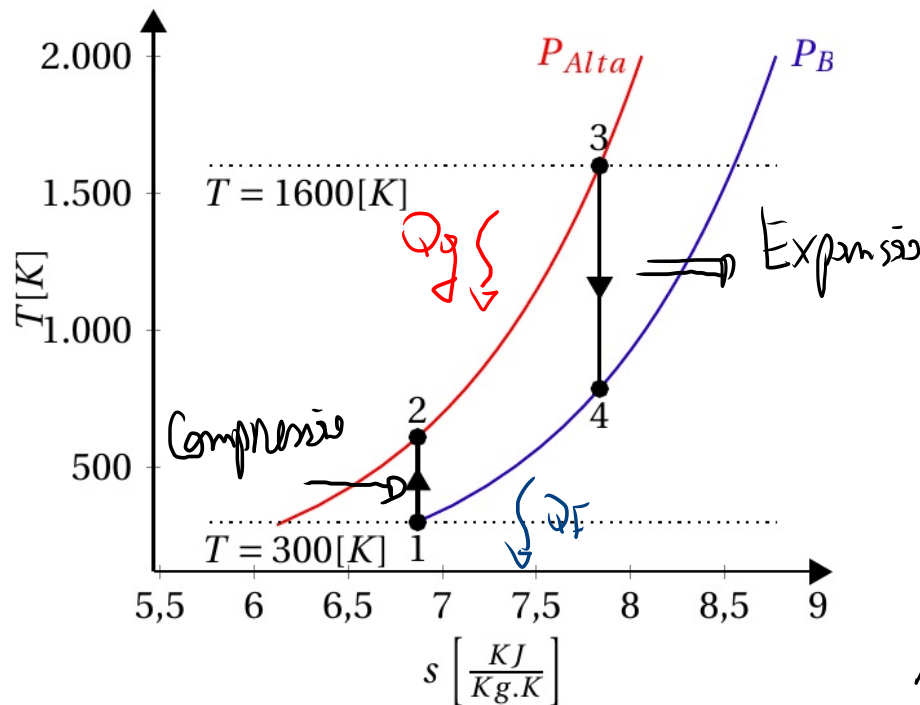
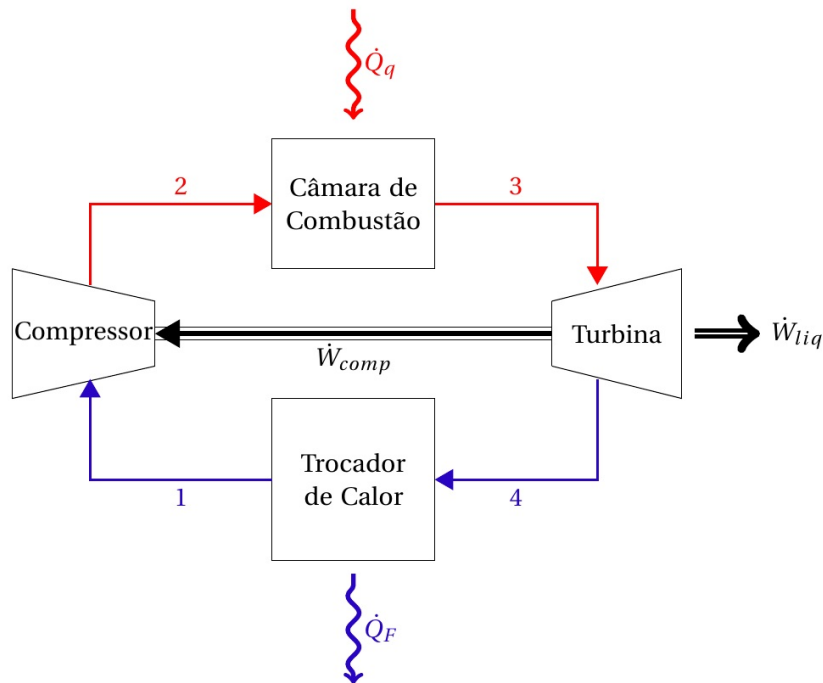
Vamos considerar a entropia de referência no valor de $T_1 = 300[K]$ e $P_1 = 100[KPa]$ como sendo igual à entropia $s_t^0 = 6,86926[KJ/Kg.K]$. A entropia para as demais pressões e temperaturas pode ser calculada por:

$$s_2 = 6,86926[KJ/Kg.K] + 1,004[KJ/Kg.K] \ln\left(\frac{T_2}{300}\right) - 0,287[KJ/Kg.K] \ln\left(\frac{P_2}{100}\right)$$



O gráfico Temperatura - Entropia

$$s_2 = 6,86926[\text{KJ}/\text{Kg}\cdot\text{K}] + 1,004[\text{KJ}/\text{Kg}\cdot\text{K}] \ln\left(\frac{T_2}{300}\right) - 0,287[\text{KJ}/\text{Kg}\cdot\text{K}] \ln\left(\frac{P_2}{100}\right)$$

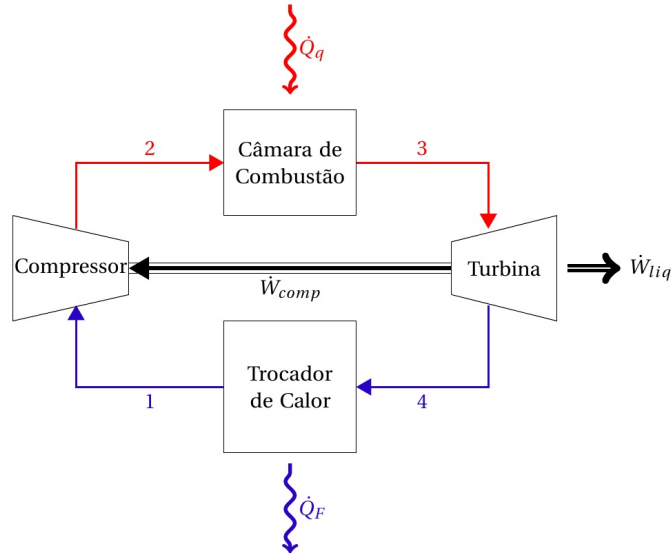


O gráfico Pressão - Volume

$$P_1 = 100[\text{KPa}] \text{ e } T_1 = 300[\text{K}]$$

Curva de compressão isoentrópica

$$v_1 = \frac{R \cdot T_1}{P_1} = \frac{0,287[\text{KJ}/\text{Kg} \cdot \text{K}] \cdot 300[\text{K}]}{100[\text{KPa}]} = 0,861[\text{m}^3/\text{Kg}]$$



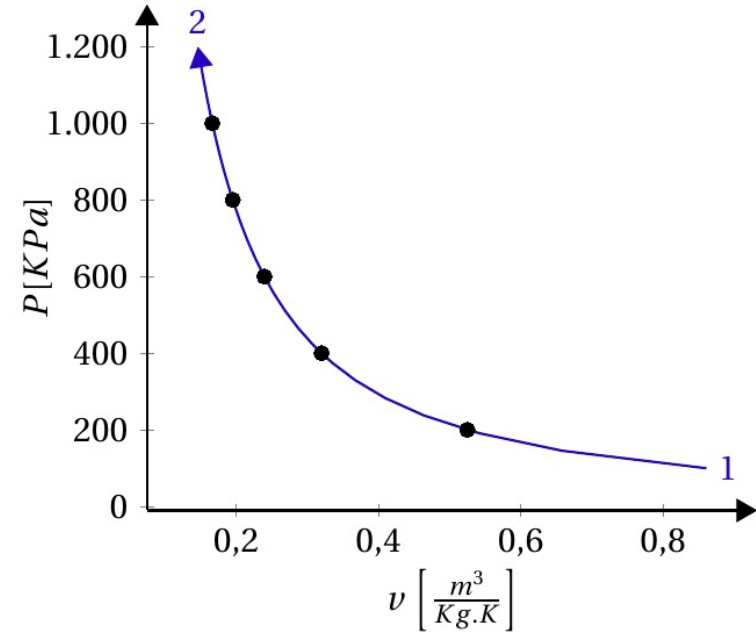
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_2}{v_1}\right)^{1-k}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right) \cdot \left(\frac{1}{1-k}\right)}$$

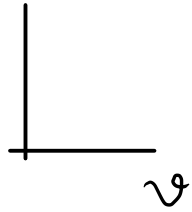
$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right) \cdot \left(\frac{-1}{k-1}\right)}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{-\frac{1}{k}}$$

$$v_2 = 0,861 \left(\frac{P_2}{100}\right)^{-\frac{1}{1,4}}$$



$$P = f(v)$$



$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_2}{v_1}\right)^{1-k}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right) \cdot \left(\frac{1}{1-k}\right)}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right) \cdot \left(\frac{-1}{k-1}\right)}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{-\frac{1}{k}}$$

$$\left(\frac{v_2}{v_1}\right)^{-k} = \frac{P_2}{P_1}$$

$$P_2 = P_1 \left(\frac{v_2}{v_1}\right)^{-k}$$

$$v_1 = 0,861 \text{ m}^3/\text{kg}$$

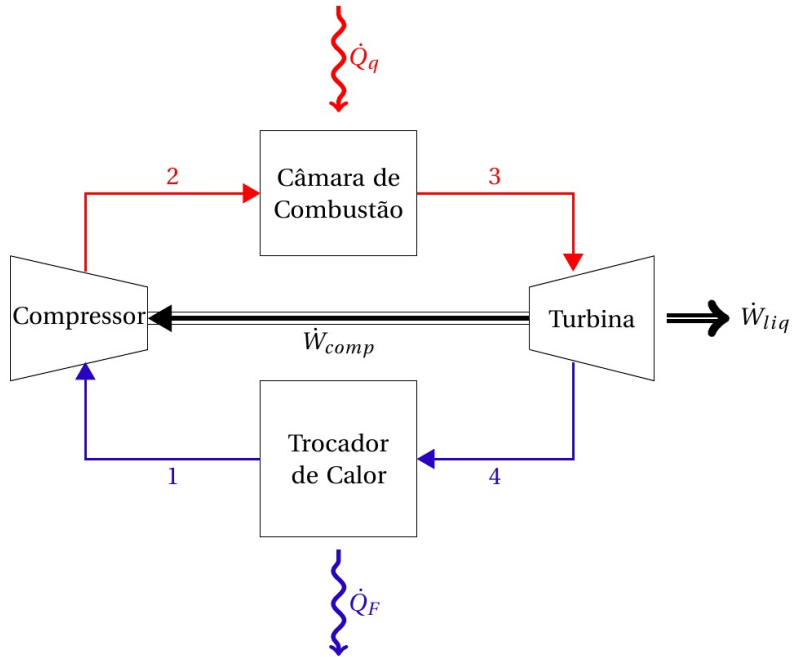
$$P_1 = 100 \text{ kPa}$$

$$\left. \begin{array}{l} P_2 = P_1 \left(\frac{v_2}{v_1}\right)^{-k} \\ v_1 = 0,861 \text{ m}^3/\text{kg} \\ P_1 = 100 \text{ kPa} \end{array} \right\} \downarrow (x) = 100 \left(\frac{x}{0,861}\right)^{-1,4}$$

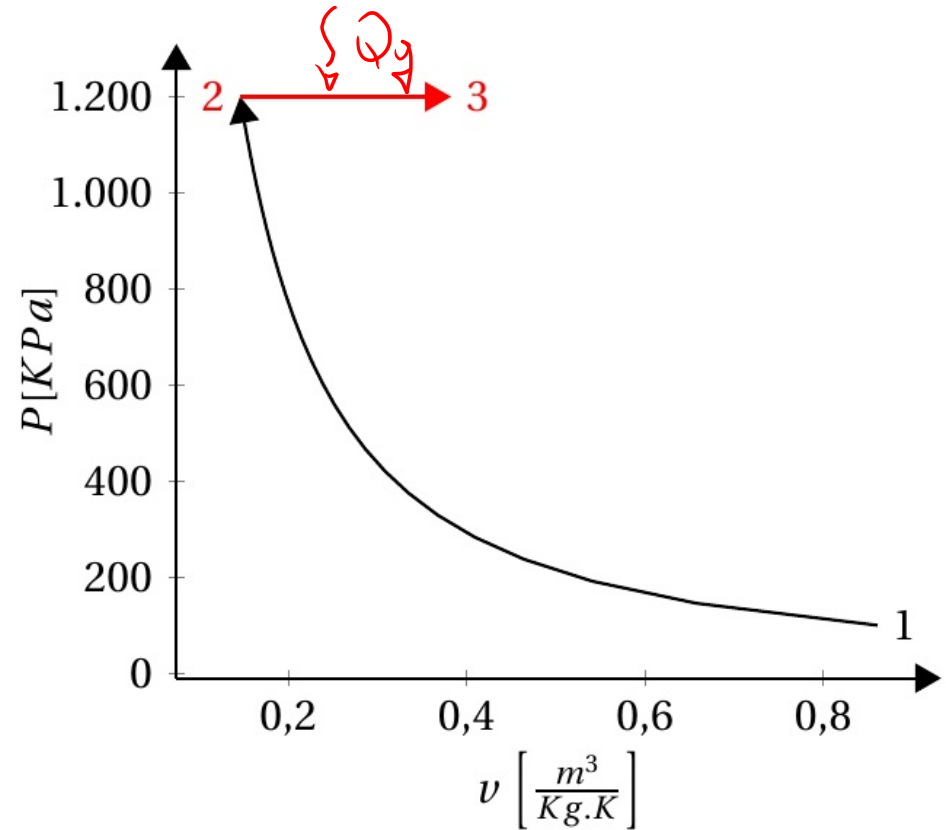
O gráfico Pressão - Volume
adição de calor.

$$P_3 = 1200[\text{KPa}]$$

$$T_3 = 1600[\text{K}]$$



$$v_3 = \frac{R \cdot T_3}{P_3} = \frac{0,287[\text{KJ}/\text{Kg} \cdot \text{K}] \cdot 1600[\text{K}]}{1200[\text{KPa}]} = 0,38267[\text{m}^3/\text{Kg}]$$



$$Q = h_3 - h_2 = c_p (T_3 - T_2)$$

O gráfico Pressão - Volume

$$P_4 = 100[\text{KPa}]$$

$$\frac{v_4}{v_3} = \left(\frac{P_4}{P_3}\right)^{-\frac{1}{k}}$$

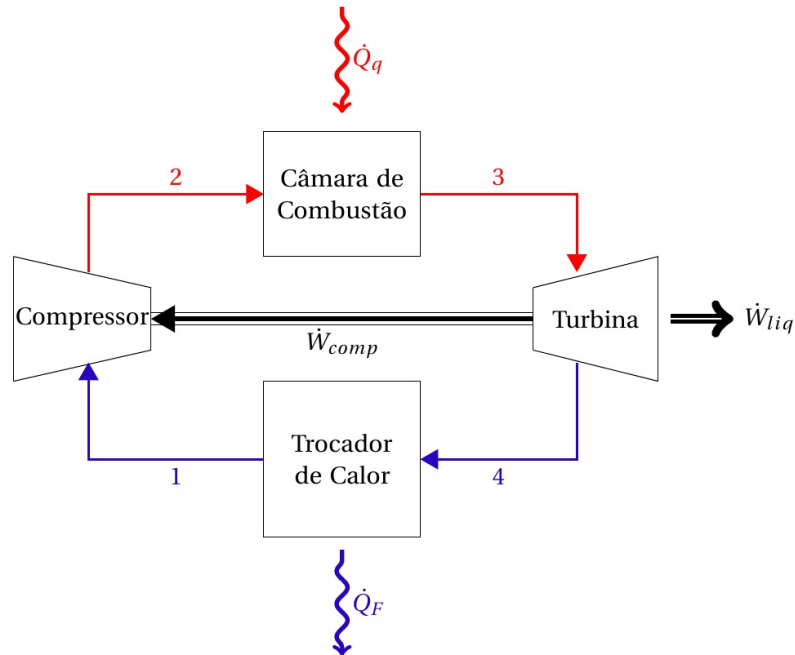
$$v_4 = 0,38267 \left(\frac{P_4}{1200}\right)^{-\frac{1}{1,4}}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_2}{v_1}\right)^{1-k}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right) \cdot \left(\frac{1}{1-k}\right)}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right) \cdot \left(\frac{-1}{k-1}\right)}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{-\frac{1}{k}}$$

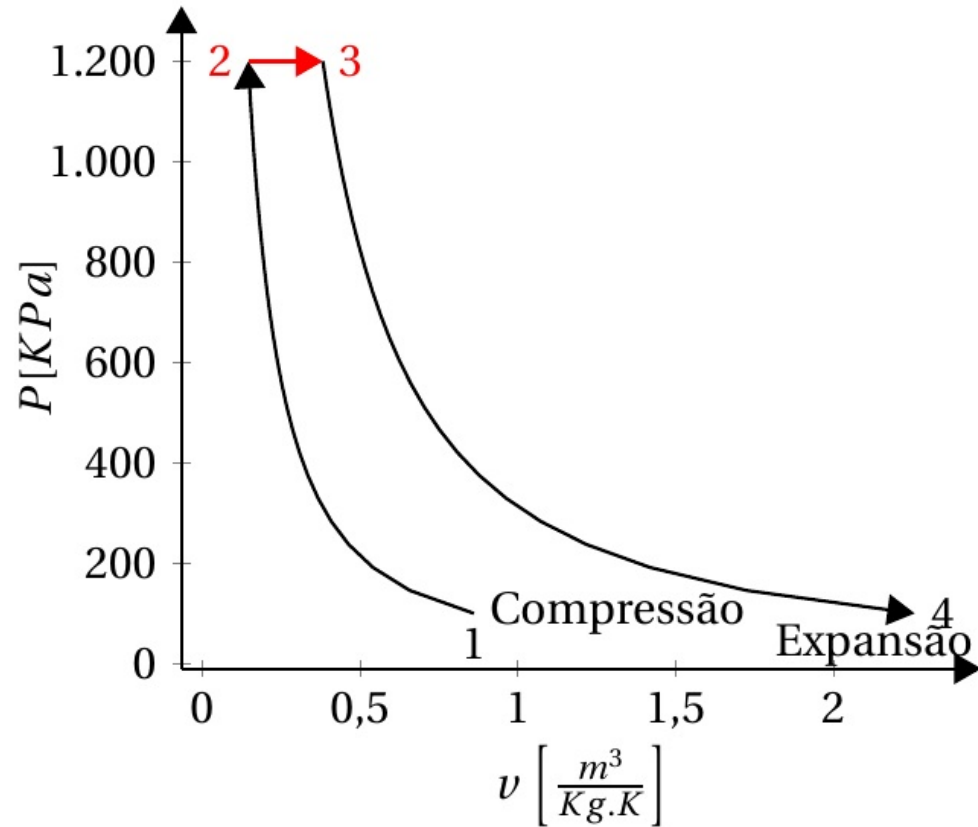
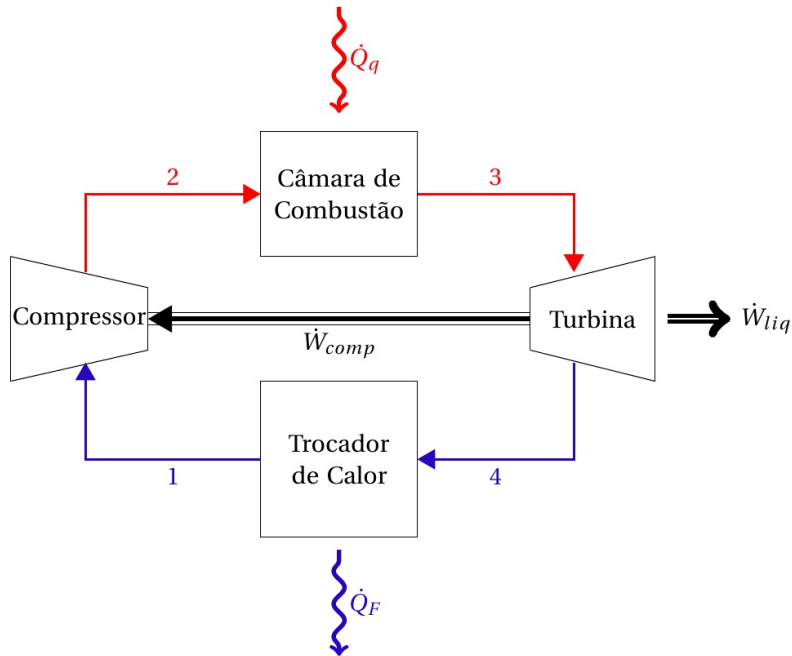


O gráfico Pressão - Volume

$$P_4 = 100[\text{KPa}]$$

$$\frac{v_4}{v_3} = \left(\frac{P_4}{P_3}\right)^{-\frac{1}{k}}$$

$$v_4 = 0,38267 \left(\frac{P_4}{1200}\right)^{-\frac{1}{1,4}}$$



$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_2}{v_1}\right)^{1-k}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right) \cdot \left(\frac{1}{1-k}\right)}$$

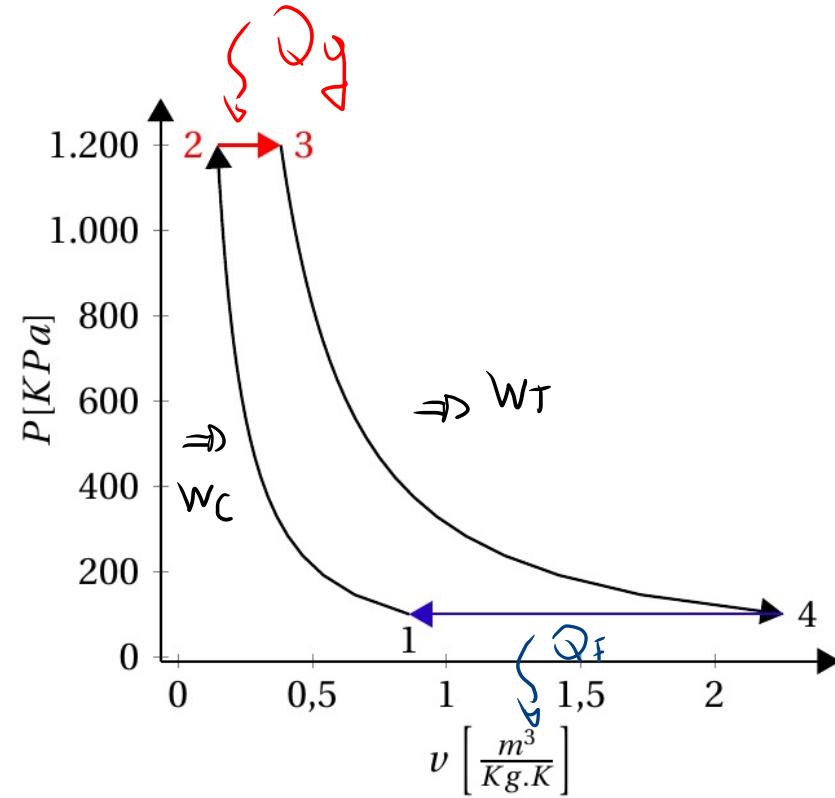
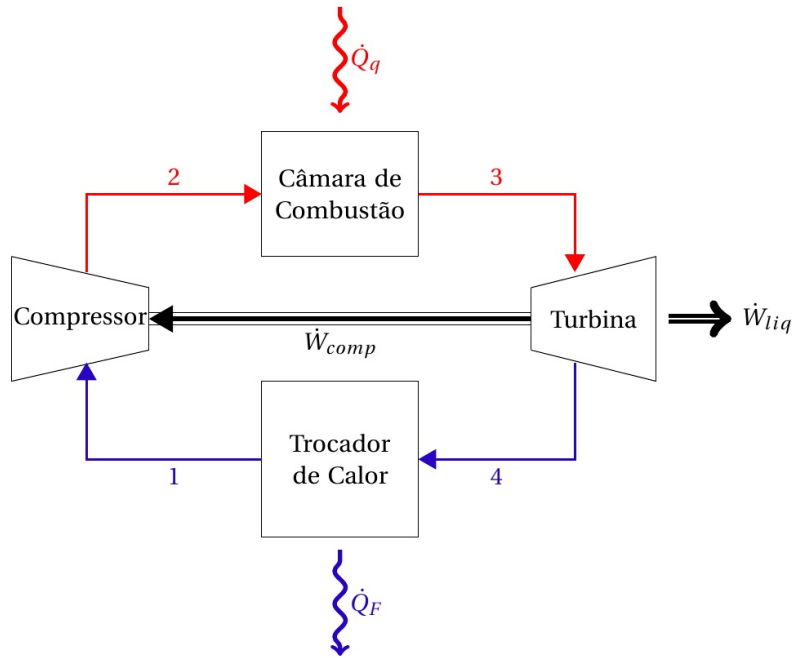
$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right) \cdot \left(\frac{-1}{k-1}\right)}$$

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{P_2}{P_1}\right)^{-\frac{1}{k}}$$

$$\eta = \frac{P_2}{P_1}$$

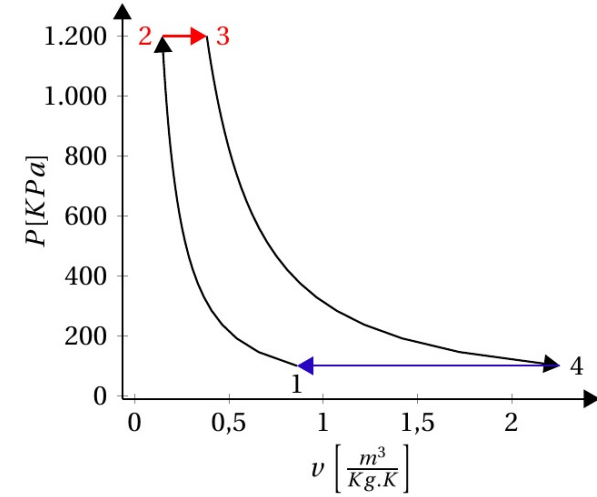
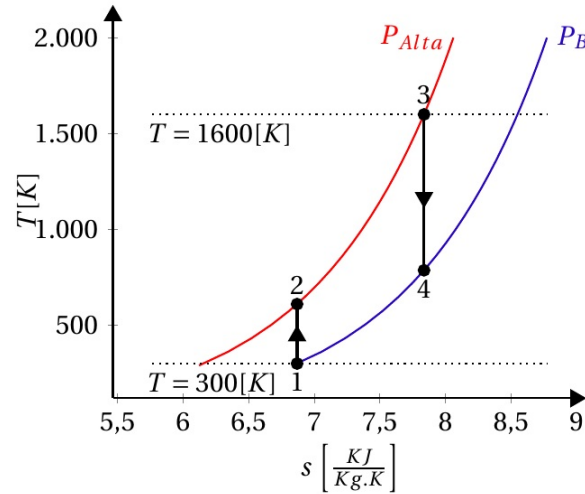
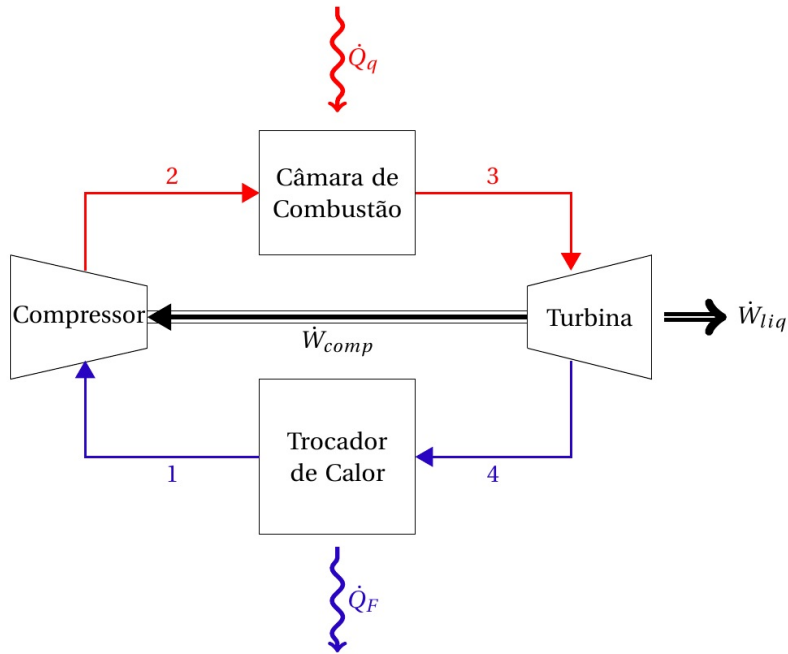
$$\frac{T_2}{T_1} = \eta^{\frac{k-1}{k}} \quad \left(\frac{v_2}{v_1}\right)^{1-k} = \eta^{\frac{k-1}{k}}$$

O gráfico Pressão - Volume rejeição de calor

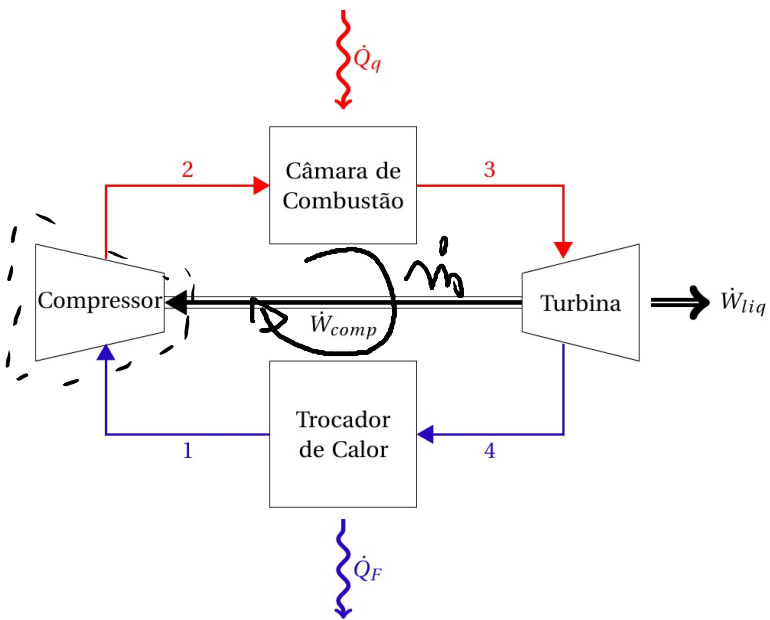


Procedimento de Solução

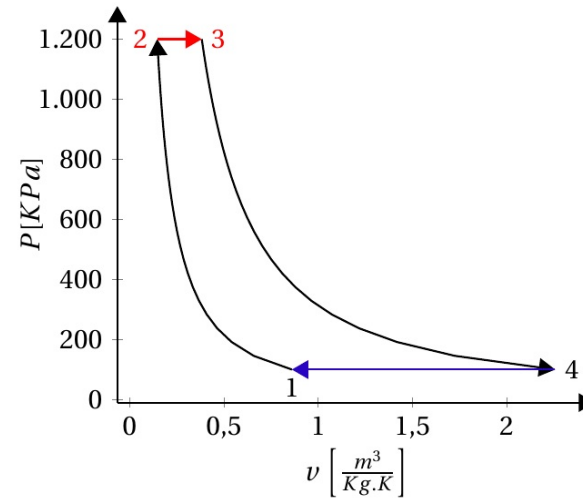
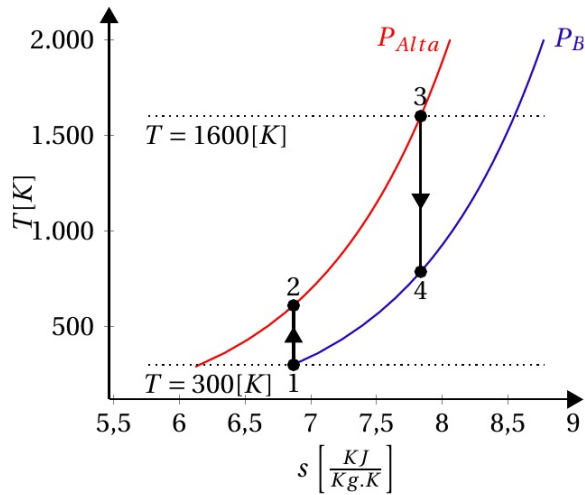
1. Desenhe os componentes do ciclo
2. Faça os gráficos T-S e P-V
3. Faça a tabela dos estados termodinâmicos e preencha os valores conhecidos.



Ponto	P [KPa]	T [K]
1	P_B	T_1
2	P_A	
3	P_A	T_3
4	P_B	



Procedimento de Solução



Faça a tabela dos estados termodinâmicos

Ponto	P [KPa]	T [K]
1	P_B	T_1
2	P_A	
3	P_A	
4	P_B	

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}}$$

Faça a tabela dos componentes.

Componente	w [KJ/Kg]	q [KJ/Kg]
Compressor	$h_2 - h_1 = c_p(T_2 - T_1)$	0
Câmara de combustão	0	$h_3 - h_2 = c_p(T_3 - T_2)$
Turbina	$h_4 - h_3 = c_p(T_4 - T_3)$	0
Trocador de Calor	0	$h_1 - h_4 = c_p(T_1 - T_4)$
Σ	w_{liq}	q_{liq}

$$\eta = \frac{|w_{liq}|}{q_{CC}}$$

$$bwr = \frac{|w_{compressor}|}{|w_{Turbina}|}$$

$$de_{ciclo} = 0 = q_{liq} + w_{liq}$$

$$\eta_c = 1 - \frac{T_D}{T_A}$$

$$de = \delta q + \delta w$$