Exergia

Parte 2

Balanço de exergia para um VC

$$\underbrace{\frac{d\mathsf{E}_{cv}}{dt}}_{\substack{\text{rate of}\\ \text{exergy}\\ \text{change}}} = \underbrace{\sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \left(\dot{W}_{cv} - p_0\frac{dV_{cv}}{dt}\right) + \sum_i \dot{m}_i \mathsf{e}_{fi} - \sum_e \dot{m}_e \mathsf{e}_{fe}}_{\substack{\text{rate of}\\ \text{exergy}\\ \text{transfer}}} - \underbrace{\dot{\mathsf{E}}_d}_{\substack{\text{rate of}\\ \text{exergy}\\ \text{destruction}}}$$

$$\mathsf{e}_f = h - h_0 - T_0(s - s_0) + \frac{V^2}{2} + gz$$

R.P. e 2 Portas

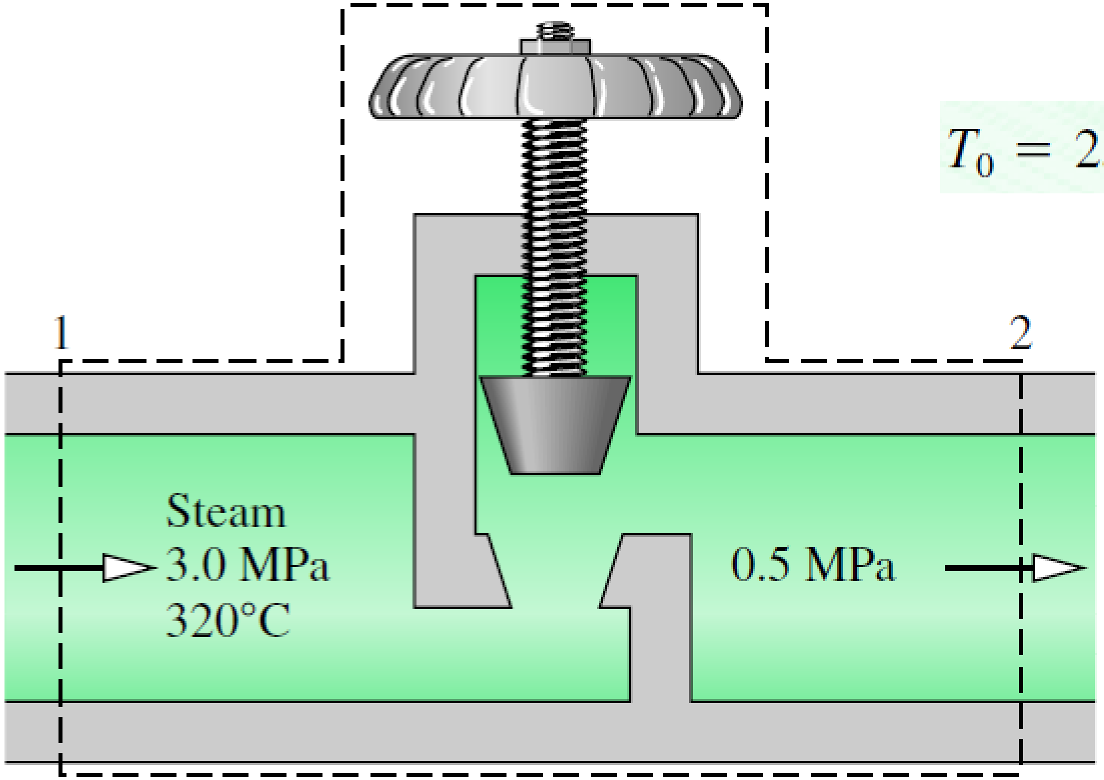
$$0 = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{cv} + \dot{m}(\mathsf{e}_{f1} - \mathsf{e}_{f2}) - \dot{\mathsf{E}}_d$$

Onde,

$$\mathsf{e}_{f1} - \mathsf{e}_{f2} = (h_1 - h_2) - T_0(s_1 - s_2) + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)$$

Exemplo 1 (livro M.S.)

Superheated water vapor enters a valve at 3.0 MPa, 320°C and exits at a pressure of 0.5 MPa. The expansion is a throttling process. Determine the specific flow exergy at the inlet and exit and the exergy destruction per unit of mass flowing, each in kJ/kg. Let $T_0 = 25°C$, $p_0 = 1$ atm.



$T_0 = 25°C$, $p_0 = 1$ atm.

Determinar:

specific flow exergy at the inlet and exit

exergy destruction per unit of mass

1ª Lei:

$$h_2 = h_1$$

From Table A-4, $h_1 = 3043.4$ kJ/s, $s_1 = 6.6245$ kJ/kg · k.

0.5 MPa with $h_2 = h_1$, the specific entropy at the exit is $s_2 = 7.4223$ kJ/kg · k.

Table A-2 gives $h_0 = 104.89$ kJ/kg, $s_0 = 0.3674$ kJ/kg · k.

E, utilizando $e_f = h - h_0 - T_0(s - s_0)$

$$e_{f1} = (3043.4 - 104.89) - 298(6.6245 - 0.3674) = 1073.89 \text{ kJ/kg}$$

$$e_{f2} = (3043.4 - 104.89) - 298(7.4223 - 0.3674) = 836.15 \text{ kJ/kg}$$

$$0 = \sum_j \cancelto{0}{\left(1 - \frac{T_0}{T_j}\right)} \dot{Q}_j - \cancelto{0}{\dot{W}_{cv}} + \dot{m}(e_{f1} - e_{f2}) - \dot{E}_d$$

$$\frac{\dot{E}_d}{\dot{m}} = (e_{f1} - e_{f2}) = 1073.89 - 836.15 = 237.7 \text{ kJ/kg}$$

OBS1: como $h_1 = h_2$

$$\frac{\dot{E}_d}{\dot{m}} = T_0(s_2 - s_1)$$

Notar que, da 2ª Lei em processo adiabático:

$$T_0(s_2 - s_1)\ \dot{m} = T_0\dot{\sigma}_{cv}$$

Logo, do balanço de exergia:

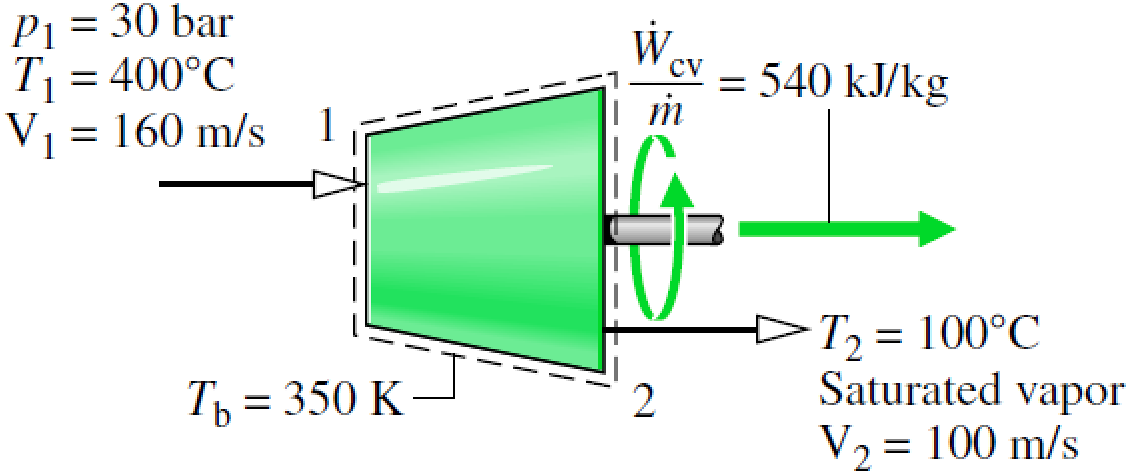
$$\dot{E}_d = T_0\dot{\sigma}_{cv} \quad \Rightarrow \quad \frac{\dot{E}_d}{\dot{m}} = T_0(s_2 - s_1)$$

Que, obviamente, dá o mesmo resultado

OBS2: embora a energia se conserve, exergia é destruída pela expansão na válvula

Exemplo2 (livro M.S.)

Steam enters a turbine with a pressure of 30 bar, a temperature of 400°C, a velocity of 160 m/s. Steam exits as saturated vapor at 100°C with a velocity of 100 m/s. At steady state, the turbine develops work at a rate of 540 kJ per kg of steam flowing through the turbine. Heat transfer between the turbine and its surroundings occurs at an average outer surface temperature of 350 K. Develop a full accounting of the *net* exergy carried in by the steam, per unit mass of steam flowing. Neglect the change in potential energy between inlet and exit. Let $T_0 = 25°C$, $p_0 = 1$ atm.



$T_0 = 25°C$, $p_0 = 1$ atm.

$$e_{f1} - e_{f2} = (h_1 - h_2) - T_0(s_1 - s_2) + \left(\frac{V_1^2 - V_2^2}{2}\right)$$

Table A-4, $h_1 = 3230.9$ kJ/kg, $s_1 = 6.9212$ kJ/kg · K.

Table A-2, $h_2 = 2676.1$ kJ/kg, $s_2 = 7.3549$ kJ/kg · K.

$$\begin{aligned} e_{f1} - e_{f2} &= \left[(3230.9 - 2676.1) - 298(6.9212 - 7.3549) + \frac{(160)^2 - (100)^2}{2|10^3|}\right] \\ &= 691.84 \text{ kJ/kg} \end{aligned}$$

Da 1ª lei:

$$\frac{\dot{Q}_{cv}}{\dot{m}} = \frac{\dot{W}_{cv}}{\dot{m}} + (h_2 - h_1) + \left(\frac{V_2^2 - V_1^2}{2}\right)$$

$$\frac{\dot{Q}_{cv}}{\dot{m}} = 540 - 554.8 - 7.8 = -22.6 \text{ kJ/kg}$$

E assim:

$$\frac{\dot{E}_q}{\dot{m}} = \left(1 - \frac{T_0}{T_b}\right)\left(\frac{\dot{Q}_{cv}}{\dot{m}}\right) = \left(1 - \frac{298}{350}\right)\left(-22.6\frac{\text{kJ}}{\text{kg}}\right) = -3.36\frac{\text{kJ}}{\text{kg}}$$

E, do balanço de exergia:

$$\frac{\dot{E}_d}{\dot{m}} = \left(1 - \frac{T_0}{T_b}\right)\left(\frac{\dot{Q}_{cv}}{\dot{m}}\right) - \frac{\dot{W}_{cv}}{\dot{m}} + (e_{f1} - e_{f2}) = 148.48 \text{ kJ/kg}$$

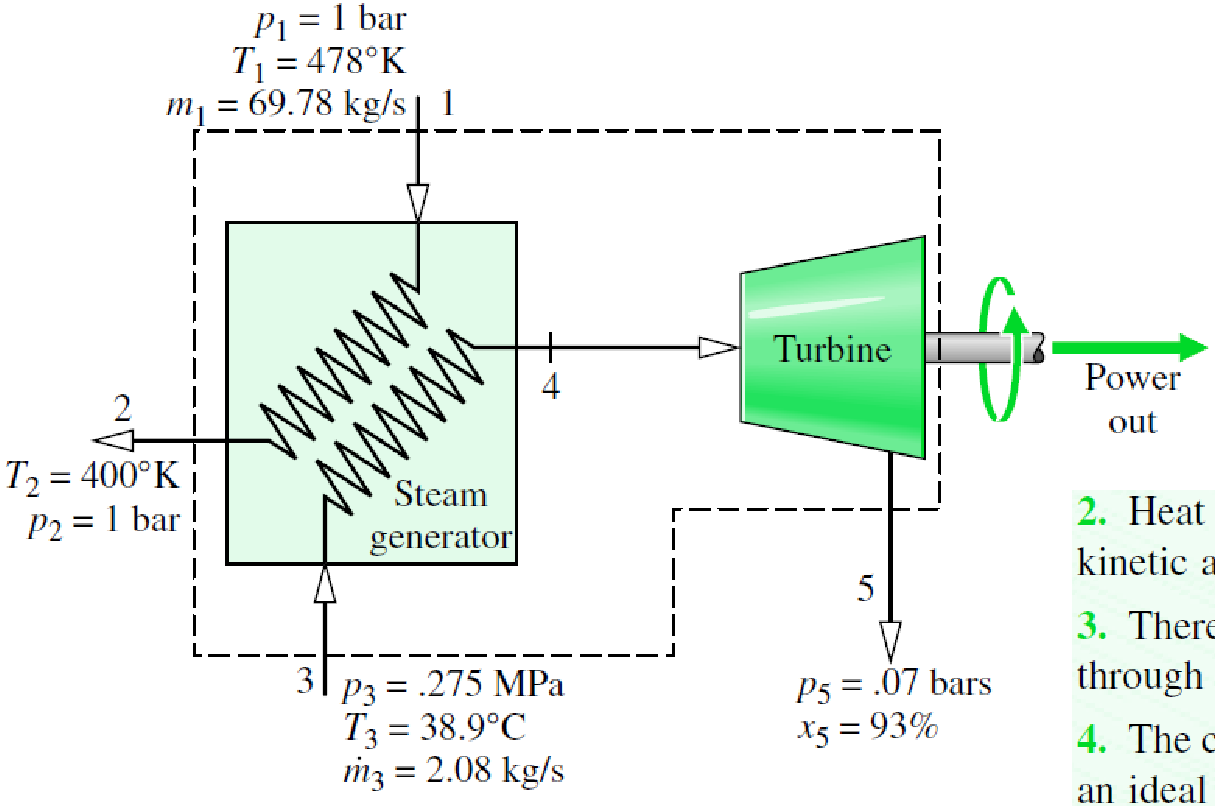
Net rate of exergy in:	691.84 kJ/kg (100%)
Disposition of the exergy:	
• Rate of exergy out	
work	540.00 kJ/kg (78.05%)
heat transfer	3.36 kJ/kg (0.49%)
• Rate of exergy destruction	148.48 kJ/kg (21.46%)
	691.84 kJ/kg (100%)

Exemplo3 (livro M.S.)

An industrial process discharges gaseous combustion products at 478°K, 1 bar with a mass flow rate of 69.78 kg/s. As shown in Fig. E4.10, a proposed system for utilizing the combustion products combines a heat-recovery steam generator with a turbine. At steady state, combustion products exit the steam generator at 400°K, 1 bar and a separate stream of water enters at .275 MPa, 38.9°C with a mass flow rate of 2.079 kg/s. At the exit of the turbine, the pressure is 0.07 bars and the quality is 93%. Heat transfer from the outer surfaces of the steam generator and turbine can be ignored, as can the changes in kinetic and potential energies of the flowing streams. There is no significant pressure drop for the water flowing through the steam generator. The combustion products can be modeled as air as an ideal gas.

(a) Develop a full accounting of the *net* exergy carried in by the combustion products.

(b) Discuss the design implications of the results.



2. $T_0 = 298$°K.

2. Heat transfer is negligible, and changes in kinetic and potential energy can be ignored.

3. There is no pressure drop for water flowing through the steam generator.

4. The combustion products are modeled as air as an ideal gas.

Balanço de massa

$$\dot{m}_1 = \dot{m}_2, \qquad \dot{m}_3 = \dot{m}_5$$

1ª Lei

$$0 = \underline{\dot{Q}_{cv}} - \dot{W}_{cv} + \dot{m}_1\left(h_1 + \underline{\frac{V_1^2}{2} + gz_1}\right) + \dot{m}_3\left(h_3 + \underline{\frac{V_3^2}{2} + gz_3}\right)$$
$$- \dot{m}_2\left(h_2 + \underline{\frac{V_2^2}{2} + gz_2}\right) - \dot{m}_5\left(h_5 + \underline{\frac{V_5^2}{2} + gz_5}\right)$$

$$\dot{W}_{cv} = \dot{m}_1(h_1 - h_2) + \dot{m}_3(h_3 - h_5)$$

where $\dot{m}_1 = 69.78$ kg/s, $\dot{m}_3 = 2.08$ kg/s

Table A-22: At 478 K, $h_1 = 480.35$ kJ/kg, and at 400 K, $h_2 = 400.98$ kJ/kg.

Table A-2E, $h_3 \approx h_f(39°C) = 162.82$ kg/s, $s_3 \approx s_f(39°C) = 0.5598$ kJ/kg · °K.

Table A-3 with $x_5 = 0.93$ gives $h_5 = 2403.27$ kJ/kg and $s_5 = 7.739$ kJ/kg · °K

$$\begin{aligned}\dot{W}_{cv} &= (69.78 \text{ kg/s})(480.3 - 400.98) \text{ kJ/kg} \\ &\quad + (2.079 \text{ kg/s})(162.9 - 2403) \text{ kJ/kg} \\ &= 876.8 \text{ kJ/s} = 876.8 \text{ kW}\end{aligned}$$

Para o VC englobando apenas o regenerador:

$$0 = \dot{m}_1(h_1 - h_2) + \dot{m}_3(h_3 - h_4)$$

$$h_4 = h_3 + \frac{\dot{m}_1}{\dot{m}_3}(h_1 - h_2) = 2825 \text{ kJ/kg}$$

Table A-4. $s_4 = 7.2196$ kJ/kg · °K

Exergia líquida sendo reaproveitada pelos produtos da combustão (disponível para uso do ciclo a vapor)

$$\dot{m}_1[\mathrm{e}_{f1} - \mathrm{e}_{f2}] = \dot{m}_1[h_1 - h_2 - T_0(s_1 - s_2)]$$
$$= \dot{m}_1\left[h_1 - h_2 - T_0\left(s_1^\circ - s_2^\circ - R\ln\frac{p_1}{p_2}\right)\right]$$

Table A-22, $h_1 = 480.35$ kJ/kg, $h_2 = 400.97$ kJ/kg, $s_1^\circ = 2.173$ kJ/kg · °K, $s_2^\circ = 1.992$ kJ/kg · °K

and $p_2 = p_1$

$$\dot{m}_1[\mathrm{e}_{f1} - \mathrm{e}_{f2}] = 1775.78 \text{ kJ/s}$$

Fluxo líquido de exergia carregado pelo vapor (incremento de exergia do vapor. i.e., o que não é aproveitado pela turbina)

$$\dot{m}_3[\mathrm{e}_{f5} - \mathrm{e}_{f3}] = \dot{m}_3[h_5 - h_3 - T_0(s_5 - s_3)]$$

$$\dot{m}_3[\mathrm{e}_{f5} - \mathrm{e}_{f3}] = 209.66 \text{ kJ/s}$$

Exergia deixando o sistema como trabalho de eixo

$$\dot{W}_{cv} = 876.8\ \text{kW}$$

Taxa de destruição de exergia no regenerador (balanço aplicado ao VC englobando apenas o regenerador):

$$0 = \sum_j \cancelto{0}{\left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j} - \cancelto{0}{\dot{W}_{cv}} + \dot{m}_1(\mathsf{e}_{f1} - \mathsf{e}_{f2}) + \dot{m}_3(\mathsf{e}_{f3} - \mathsf{e}_{f4}) - \dot{\mathsf{E}}_d$$

$$\dot{\mathsf{E}}_d = \dot{m}_1(\mathsf{e}_{f1} - \mathsf{e}_{f2}) + \dot{m}_3[h_3 - h_4 - T_0(s_3 - s_4)] = 366.1\ \text{kJ/s}$$

Taxa de destruição de exergia na turbina (balanço aplicado ao VC englobando apenas a turbina)

$$0 = \sum_j \cancelto{0}{\left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j} - \dot{W}_{cv} + \dot{m}_4(\mathsf{e}_{f4} - \mathsf{e}_{f5}) - \dot{\mathsf{E}}_d$$

$$\dot{\mathsf{E}}_d = -\dot{W}_{cv} + \dot{m}_4[h_4 - h_5 - T_0(s_4 - s_5)] = 320.2\ \text{kJ/s}$$

Net rate of exergy in:	1772.8 kJ/s (100%)
Disposition of the exergy:	
• Rate of exergy out	
power developed	876.8 kJ/s (49.5%)
water stream	209.66 kJ/s (11.8%)
• Rate of exergy destruction	
heat-recovery steam generator	366.12 kJ/s (20.6%)
turbine	320.2 kJ/s (18%)

Eficiência exergética

- Útil na avaliação da eficiência na utilização de recursos energéticos
  - Também conhecida como eficiência da 2ª Lei
- ε = eficiência exergética
  - Razão entre exergia utilizada e exegia recebida
  - Não confundir com rendimento térmico
- Sistemas termodinâmicos recebem e fornecem exergia
  - Quanto maior for ε, mais eficiente será a utilização da energia

Turbinas

- Adiabática, RP, 2 portas, ΔKE = ΔPE = 0

$$0 = \cancelto{0}{\sum_j \left(1 - \frac{T_0}{T_j}\right)} \dot{Q}_j - \dot{W}_{cv} + \dot{m}(\mathsf{e}_{f1} - \mathsf{e}_{f2}) - \dot{\mathsf{E}}_d$$

$$\mathsf{e}_{f1} - \mathsf{e}_{f2} = \frac{\dot{W}_{cv}}{\dot{m}} + \frac{\dot{\mathsf{E}}_d}{\dot{m}}$$

$$\varepsilon = \frac{\dot{W}_{cv}/\dot{m}}{\mathsf{e}_{f1} - \mathsf{e}_{f2}}$$

Compressores

- Adiabático, RP, 2 portas, ΔKE = ΔPE = 0

$$0 = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j^{\,0} - \dot{W}_{cv} + \dot{m}(\mathsf{e}_{f1} - \mathsf{e}_{f2}) - \dot{\mathsf{E}}_d$$

$$\left(-\frac{\dot{W}_{cv}}{\dot{m}}\right) = \mathsf{e}_{f2} - \mathsf{e}_{f1} + \frac{\dot{\mathsf{E}}_d}{\dot{m}}$$

$$\varepsilon = \frac{\mathsf{e}_{f2} - \mathsf{e}_{f1}}{(-\dot{W}_{cv}/\dot{m})}$$

Trocadores de calor sem mistura

- 1 = entrada quente, 2 = saída quente, 3 = entrada frio, 4 = saída frio

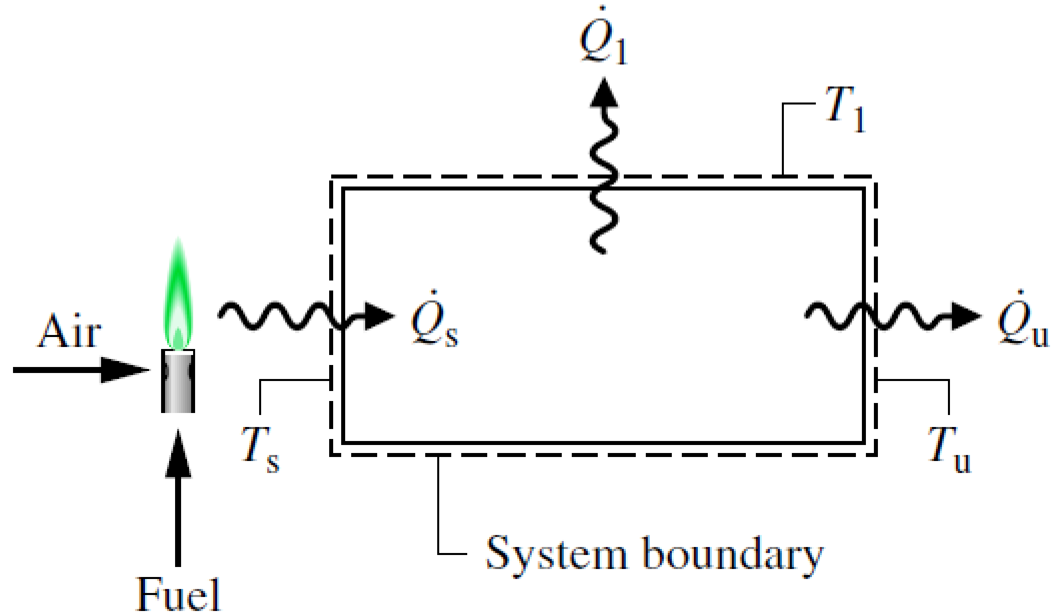
$$0 = \cancelto{0}{\sum_j \left(1 - \frac{T_0}{T_j}\right)} \dot{Q}_j - \cancelto{0}{\dot{W}_{cv}} + (\dot{m}_h \mathrm{e}_{f1} + \dot{m}_c \mathrm{e}_{f3}) - (\dot{m}_h \mathrm{e}_{f2} + \dot{m}_c \mathrm{e}_{f4}) - \dot{\mathrm{E}}_d$$

$$\dot{m}_h(\mathrm{e}_{f1} - \mathrm{e}_{f2}) = \dot{m}_c(\mathrm{e}_{f4} - \mathrm{e}_{f3}) + \dot{\mathrm{E}}_d$$

$$\varepsilon = \frac{\dot{m}_c(\mathrm{e}_{f4} - \mathrm{e}_{f3})}{\dot{m}_h(\mathrm{e}_{f1} - \mathrm{e}_{f2})}$$

Exemplo

- Seja o SF, em RP:



$$\cancel{\frac{dE}{dt}}^{\,0} = (\dot{Q}_s - \dot{Q}_u - \dot{Q}_1) - \cancel{\dot{W}}^{\,0}$$

$$\cancel{\frac{d\mathsf{E}}{dt}}^{\,0} = \left[\left(1 - \frac{T_0}{T_s}\right)\dot{Q}_s - \left(1 - \frac{T_0}{T_u}\right)\dot{Q}_u - \left(1 - \frac{T_0}{T_1}\right)\dot{Q}_1\right] - \left[\cancel{\dot{W}}^{\,0} - p_0 \cancel{\frac{dV}{dt}}^{\,0}\right] - \dot{\mathsf{E}}_d$$

Exemplo

$$\dot{Q}_s = \dot{Q}_u + \dot{Q}_l$$

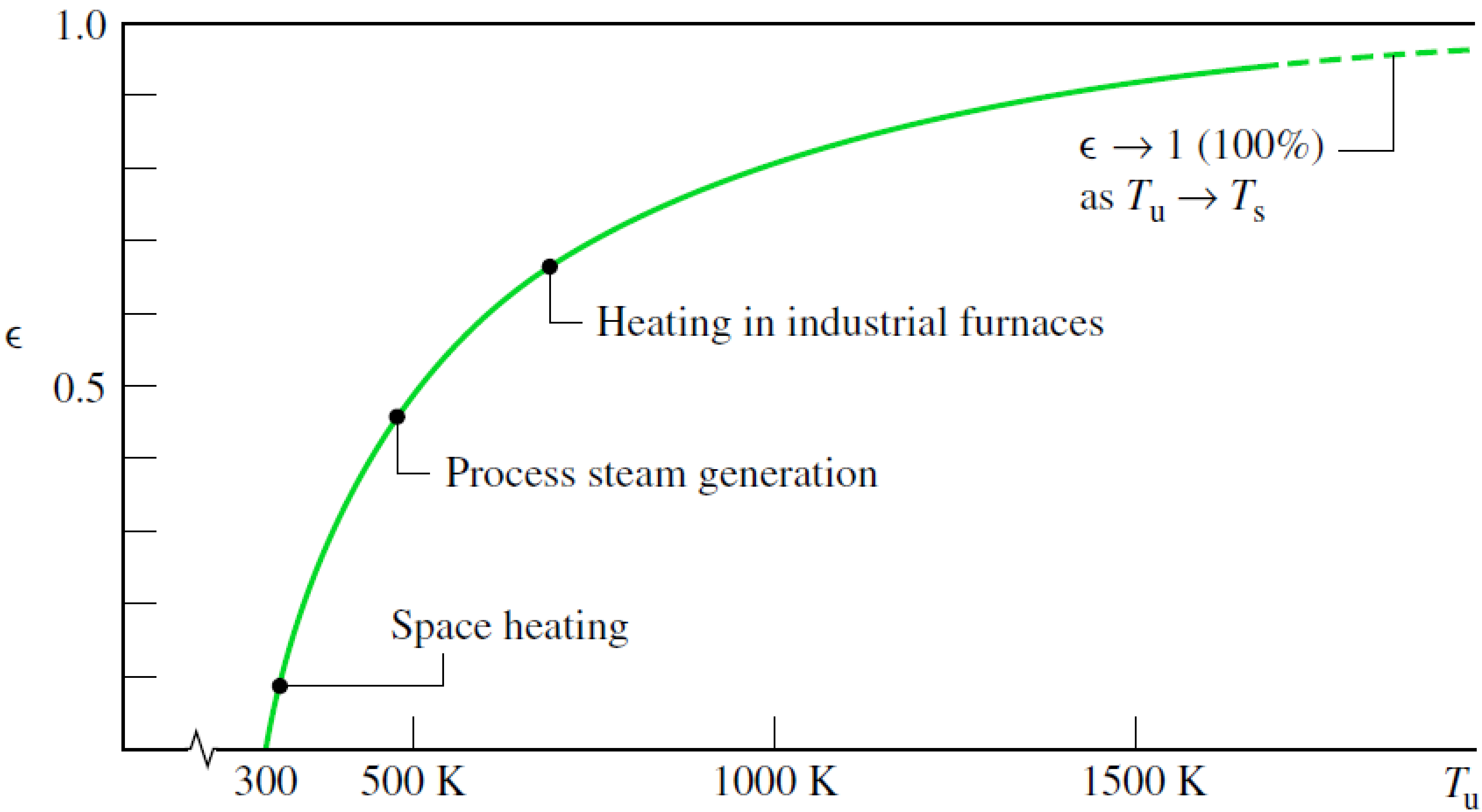
$$\left(1 - \frac{T_0}{T_s}\right)\dot{Q}_s = \left(1 - \frac{T_0}{T_u}\right)\dot{Q}_u + \left(1 - \frac{T_0}{T_l}\right)\dot{Q}_l + \dot{E}_d$$

$$\eta = \frac{\dot{Q}_u}{\dot{Q}_s}$$

$$\varepsilon = \frac{(1 - T_0/T_u)\dot{Q}_u}{(1 - T_0/T_s)\dot{Q}_s} \qquad \varepsilon = \eta\left(\frac{1 - T_0/T_u}{1 - T_0/T_s}\right)$$

Mesmo se $\eta=1$, ε pode ser menor do que 1

Exemplo (cont)



▲ **Figure 7.8** Effect of use temperature T_u on the exergetic efficiency ε (T_s = 2200 K, η = 100%).