Steady-State, Steady Flow (SSSF) Processes - II

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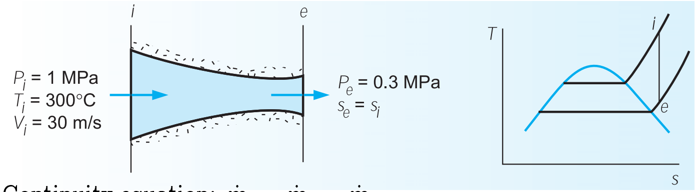
ME 203: Engineering Thermodynamics

▷ [Borgnakke Ex. 7.2]: Reversible adiabatic flow of steam through nozzle, $V_e = ?$



T185

- Continuity equation: $\dot{m}_i = \dot{m}_e = \dot{m}$
- First law: $0 = 0 - 0 + (h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + 0$
- Second law: $s_i = s_e$.

$\Rightarrow h_i = h(steam,\ P_i = 1\ MPa,\ T_i = 300^o C) = \checkmark$

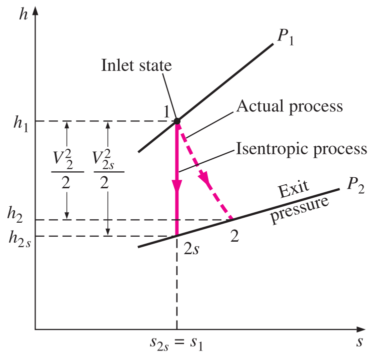
$\Rightarrow s_i = s(steam,\ P_i = 1\ MPa,\ T_i = 300^o C) = \checkmark$

$\Rightarrow s_e = s_i$ & $P_e = 0.3$ MPa: state 'e' defined.

$\Rightarrow h_e = h(P_e = 0.3\ MPa,\ s_e = \checkmark) = \checkmark$

$\Longrightarrow \frac{V_e^2}{2} = (h_i - h_e) + \frac{V_i^2}{2} \Longrightarrow V_e = 736.7$ m/s$\triangleleft$

Isentropic Nozzle Efficiency

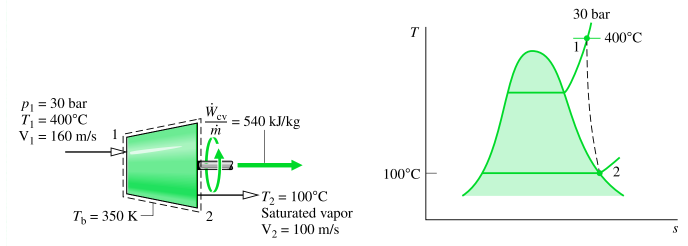


T181

- For nozzle: $w = 0,\ \Delta(PE) = 0,\ V_1 \sim 0 \Rightarrow h_1 = h_2 + \frac{V_2^2}{2}$

$$\Longrightarrow \boxed{\eta_N = \frac{\text{Actual KE at nozzle exit}}{\text{Isentropic KE at nozzle exit}} = \frac{V_2^2}{V_{2s}^2} \approx \frac{h_1 - h_2}{h_1 - h_{2s}}}$$

▷ [Moran Ex. 6.6]: Entropy production in a steam turbine



T178

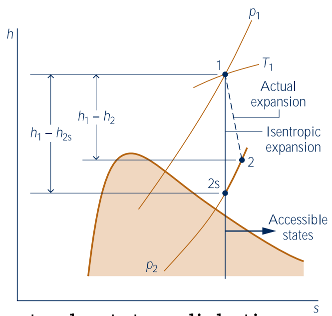
- Continuity equation: $\dot{m}_i = \dot{m}_e = \dot{m}$
- First law: $0 = q - w + (h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + 0$
- Second law: $(s_e - s_i) = \frac{\dot{q}}{T_b} + \frac{\dot{\sigma}_{cv}}{\dot{m}}$.

$\Rightarrow P_1 = 30$ bar, $T_1 = 400^o C :\Longrightarrow h_1 = \checkmark,\ s_1 = \checkmark$

$\Rightarrow T_2 = 100^o C,\ x_2 = 1.0 :\Longrightarrow h_2 = \checkmark,\ s_2 = \checkmark$

$\Longrightarrow q = -23.92$ kJ/kg $\Longrightarrow \frac{\dot{\sigma}_{cv}}{\dot{m}} = 0.499$ kJ/kg.K $\triangleleft$.

Isentropic Turbine Efficiency

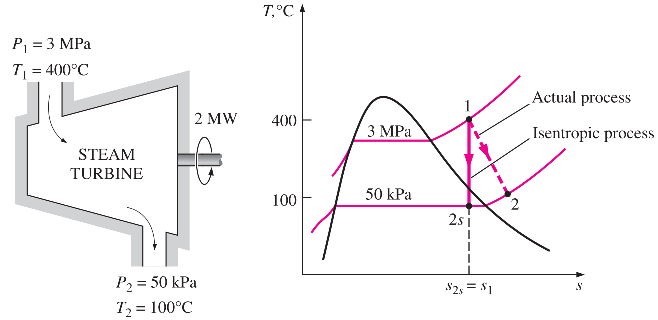


T176

- $\dot{w}_t = h_1 - h_2$: for steady-state, adiabatic expansion.
- $\frac{\dot{\sigma}_{cv}}{\dot{m}} = s_2 - s_1 \geqq 0$: states with $s_2 < s_1$ is not attainable with adiabatic expansion.
- $\dot{w}_t|_s = h_1 - h_{2s}$: state '2s' is for internally reversible expansion.

$\Rightarrow$ Isentropic turbine efficiency, $\boxed{\eta_t = \frac{\dot{w}_t}{\dot{w}_t|_s} = \frac{h_1 - h_2}{h_1 - h_{2s}}}$

▷ [Cengel Ex.7.14]: Isentropic Efficiency of a Steam Turbine



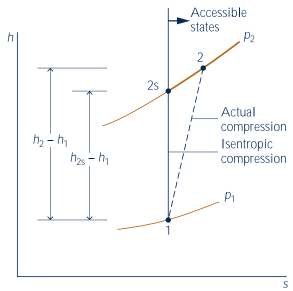
T179

- $(P_1 = 3 \text{ MPa}, T_1 = 400^o C) :\Rightarrow h_1 = \checkmark, s_1 = \checkmark$
- $(P_2 = 50 \text{ kPa}, T_2 = 100^o C) :\Rightarrow h_2 = \checkmark$
- $(P_{2s} = 50 \text{ kPa}, s_{2s} = s_1) :\Rightarrow h_{2s} = \checkmark$

$\Longrightarrow \eta_t = \frac{h_1 - h_2}{h_1 - h_{2s}} = 66.7\% \triangleleft$

$\Longrightarrow \dot{m} = \frac{Power}{h_1 - h_{2s}} = 3.64 \text{ kg/s} \triangleleft$

Isentropic Compressor and Pump Efficiencies

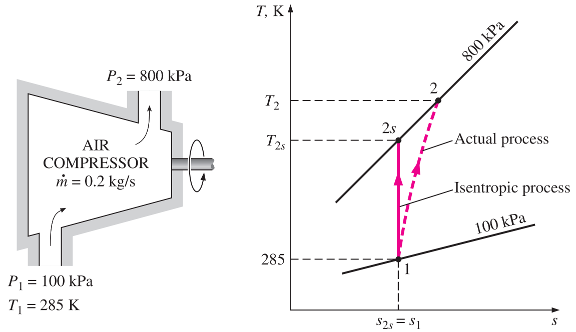


T177

- $\dot{w}_c = h_1 - h_2 = -(h_2 - h_1)$: for steady-state, adiabatic compression.
- $\frac{\dot{\sigma}_{cv}}{\dot{m}} = s_2 - s_1 \geq 0$: states with $s_2 < s_1$ is not attainable with adiabatic compression.
- $\dot{w}_c|_s = h_1 - h_{2s} = -(h_{2s} - h_1)$

$\Rightarrow$ Isentropic compressor/pump efficiency, $\boxed{\eta_c = \frac{-\dot{w}_c|_s}{-\dot{w}_c} = \frac{h_{2s} - h_1}{h_2 - h_1}}$

▷ [Cengel Ex. 7.15]: Effect of efficiency on compressor power, if $\eta_c = 80\%$



T180

- $T_{2s} = T_1 (P_2/P_1)^{(k-1)/k} = 516.5$ K
- $\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{c_P(T_{2s} - T_1)}{c_P(T_2 - T_1)} \Rightarrow T_2 = 574.8$ K

$\Rightarrow W_c|_s = -\dot{m}(h_{2s} - h_1) = \dot{m} c_P (T_{2s} - T_1) = -46.5 \text{ kW} \triangleleft$

$\Rightarrow W_c = -\dot{m}(h_2 - h_1) = -\dot{m} c_P (T_2 - T_1) = -58.1 \text{ kW} \triangleleft$

Steady-state Flow Process

- First Law: CM system & reversible process:

$\Rightarrow$ $\delta q = du + \delta w = d(h - Pv) + Pdv = dh - vdP$

- Second Law: $\delta q = Tds \Rightarrow Tds = dh - vdP$

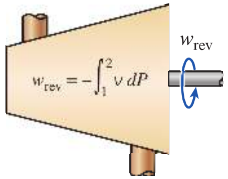
$\Rightarrow$ $\int_1^2 Tds = \int_1^2 (dh - vdP) = (h_2 - h_1) - \int_1^2 vdP$

- First Law: CV system & reversible process:

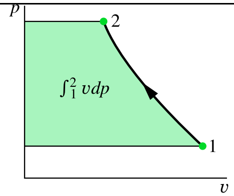
$\Rightarrow$ $0 = q_{12} - w_{12} + (h_1 - h_2) - \Delta(ke) - \Delta(pe)$

$\Longrightarrow$ $w_{12} = q_{12} + (h_1 - h_2) - 0 - 0 = \int_1^2 Tds + (h_1 - h_2) = -\int_1^2 vdP$

$$\boxed{w_{sf} = w_{12} = -\int_1^2 vdP}$$



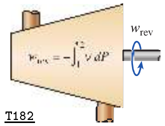
T182



T183

$$\boxed{Pv^n = \text{constant}}$$

$$\boxed{w_{sf} = w_{12} = -\int_1^2 vdP}$$



T182

$$w_{12}: \begin{cases} = \frac{n}{1-n}(P_2v_2 - P_1v_1) & = \frac{nR(T_2-T_1)}{1-n} \quad : n \neq 1 \\ = RT\ln\left(\frac{v_2}{v_1}\right) & = -RT\ln\left(\frac{P_2}{P_1}\right) \quad : n = 1 \end{cases}$$

$$q_{12} = h_2 - h_1 + w_{12}$$

▷ Example: A compressor operates at steady state with nitrogen entering at 100 kPa and 20°C and leaving at 500 kPa. During this compression process, the relation between pressure and volume is $Pv^{1.3}$ =constant.

- $R = (8.314/28) = 0.2969$ kJ/kg.K, $c_P = 1.0$ kJ/kg.K

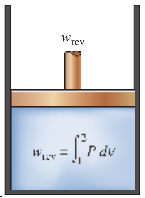
$\Rightarrow$ $T_2/T_1 = (P_2/P_1)^{(n-1)/n} \Longrightarrow T_2 = 425$ K.

$\Rightarrow$ $w_{12} = \frac{nR(T_2-T_1)}{1-n} = -169.5$ kJ/kg $\triangleleft$

$\Rightarrow$ $q_{12} = c_P(T_2 - T_1) + w_{12} = -37.5$ kJ/kg $\triangleleft$

$$\boxed{Pv^n = \text{constant}}$$

$$\boxed{w_b = w_{12} = \int_1^2 Pdv}$$



T192

$$w_{12}: \begin{cases} = \frac{P_2v_2 - P_1v_1}{1-n} & = \frac{R(T_2-T_1)}{1-n} \quad : n \neq 1 \\ = RT\ln\left(\frac{v_2}{v_1}\right) & = -RT\ln\left(\frac{P_2}{P_1}\right) \quad : n = 1 \end{cases}$$

$$q_{12} = u_2 - u_1 + w_{12}$$

▷ Example: In a reversible process, nitrogen is compressed in a cylinder from 100 kPa and 20°C to 500 kPa. During this compression process, the relation between pressure and volume is $Pv^{1.3}$ =constant.

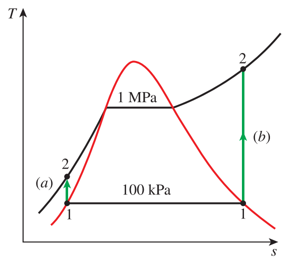
- $R = (8.314/28) = 0.2969$ kJ/kg.K, $c_v = R/(1.4-1) = 0.742$ kJ/kg.K

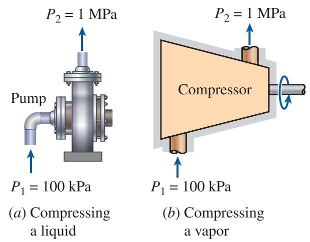
$\Rightarrow$ $T_2/T_1 = (P_2/P_1)^{(n-1)/n} \Longrightarrow T_2 = 425$ K.

$\Rightarrow$ $w_{12} = \frac{R(T_2-T_1)}{1-n} = -130.4$ kJ/kg $\triangleleft$

$\Rightarrow$ $q_{12} = c_V(T_2 - T_1) + w_{12} = -32.2$ kJ/kg $\triangleleft$

▷ [Cengel Ex.7.12]: Compression & Pumping Works





T191

$\Rightarrow$ $w_P = -\int_1^2 vdP \simeq -v_f(P_2 - P_1) = -0.939$ kJ/kg $\triangleleft$

$\Rightarrow$ $w_C = h_1 - h_2 = -518.6$ kJ/kg $\triangleleft$

$\Longrightarrow$ $w_c >> w_p$