第8章 热力过程与热力学循环

本章内容

- □8.1 基本热力过程
- □8.2 蒸汽动力循环
- □8.3 制冷循环

8.1 基本热力过程

流体输送

$$\Delta h + g\Delta z + \frac{1}{2}\Delta u^2 = q + w_s$$

$$\Delta h = \Delta U + \Delta(pV) = 0 + \Delta p/\rho \qquad q = w_s = 0$$

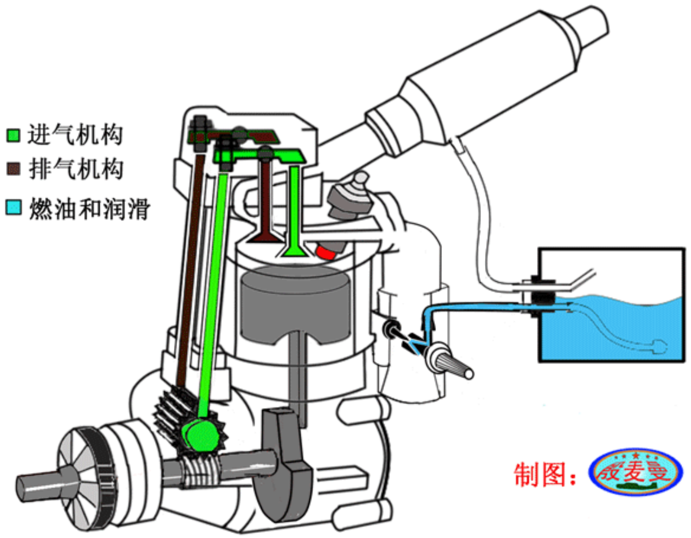
$$\boxed{\frac{\Delta P}{\rho} + g\Delta z + \frac{1}{2}\Delta u^2 = 0}$$ 伯努利方程

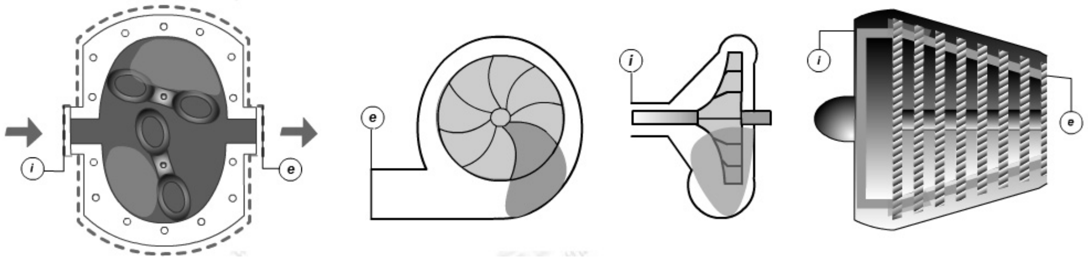
- **泵(Pump)** $W_{s(R)} = \int V\mathrm{d}p$

对于绝大多数液体: $W_{s(R)} = V\Delta p$

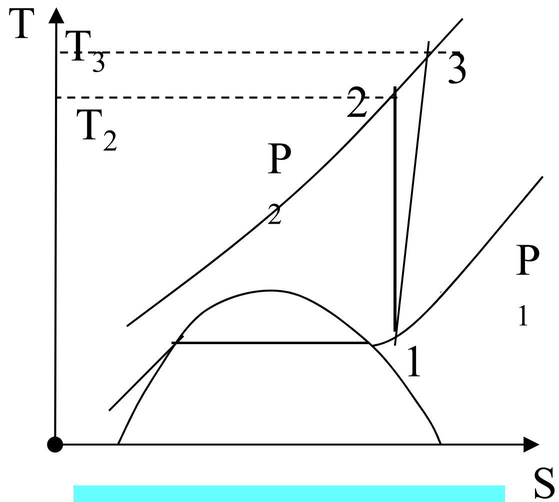
压缩过程

四行程发动机工作原理





$$\Delta H = H_2 - H_1 = \int_{T_1}^{T_2} C_P dT + H_2^R - H_1^R$$



$$\eta_s = \frac{W_{s(R)}}{W_s} = \frac{H_2 - H_1}{H_3 - H_1}$$

$$W_s = W_{s(R)} / \eta_s$$

例：状态为-8℃和0.304MPa下的NH_3经绝热压缩至压力为1.419MPa的状态. 已知η_s=0.8. 试求$W_{s(R)}$=?, W_s=? ΔS_g=?

解：**a.** 可逆压缩过程

由**T-S**图可得，H_1=1443.5kJ/kg, H_2=1665.2kJ/kg, S_1=S_2=5.5438 kJ/(kg.K),

因此有, $W_{s(R)}=H_2-H_1$=1665.2-1443.5=221.7 kJ/kg

b. 热效率为η_s=**0.8**的不可逆过程

$$W_s = W_{s(R)} / \eta_s = 221.7/0.8 = 277.1 kJ/kg$$

$$\Delta H = H_2 - H_1 = W_s$$

$$H_2 = W_s + H_1 = 277.1 + 1443.5 = 1720.6 kJ/kg$$

由**T-S**图可得，S_2=5.6484 kJ/(kg·K)

$$\Delta S_g = S_2 - S_1 = 5.6484 - 5.5438 = 0.1046 kJ/kg$$

- 可逆轴功

热力学第一定律： $\mathrm{d}H=\delta q+\delta w_s$

基本热力学关系式：$\mathrm{d}H=T\mathrm{d}S+V\mathrm{d}p$

可逆过程： $dq=TdS$

于是有： $\mathrm{d}W_s=V\mathrm{d}p$ $\boxed{w_{s(R)}=\int V\mathrm{d}p}$

对于理想气体的等温压缩过程：

$$W_{S(R)}=\int_{p_1}^{p_2}V\mathrm{d}p=\int_{p_1}^{p_2}\frac{nRT}{p}\mathrm{d}p=n\int_{p_1}^{p_2}\frac{RT}{p}\mathrm{d}p$$

$$W_{S(R)}=nRT_1\ln\frac{p_2}{p_1}$$

对于理想气体的绝热压缩过程： $pV^{k}=const$

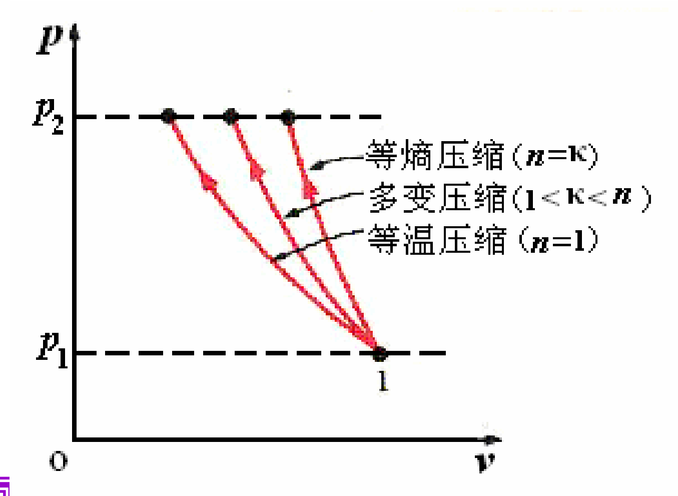
$$W_S=\frac{K}{K-1}V_1p_1[(\frac{p_2}{p_1})^{\frac{K-1}{K}}-1]=\frac{K}{K-1}nRT_1[(\frac{p_2}{p_1})^{\frac{K-1}{K}}-1]$$

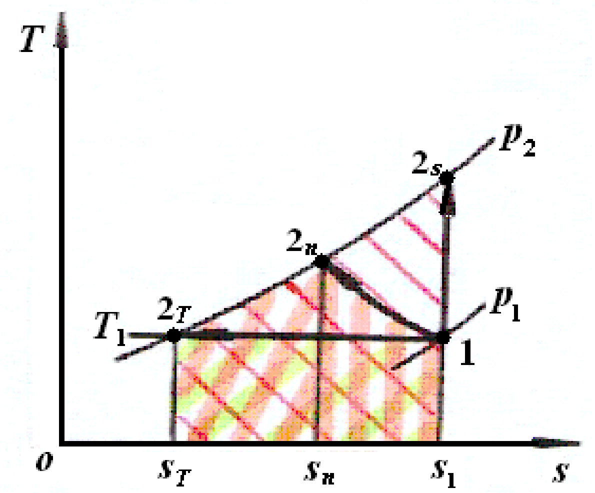
$$W_S=\frac{K}{K-1}nRT_1[(\frac{p_2}{p_1})^{\frac{K-1}{K}}-1]$$

对于理想气体的多方压缩过程： $pV^{m}=const$

$$W_S=\frac{m}{m-1}nRT_1[(\frac{p_2}{p_1})^{\frac{m-1}{m}}-1]$$

理论耗功量





$$w_C = \int_1^2 v\mathrm{d}p \qquad \pi = \frac{p_2}{p_1}$$

w_C取决于初、终态及过程特征

1.绝热压缩

$$w_{C,s} = h_{2s} - h_1 = \frac{\kappa}{\kappa-1} R_g T_1 \left(\pi^{\frac{\kappa-1}{\kappa}} - 1 \right)$$

2.等温压缩

$$w_{C,T} = R_g T_1 \ln \pi$$

3.多变压缩

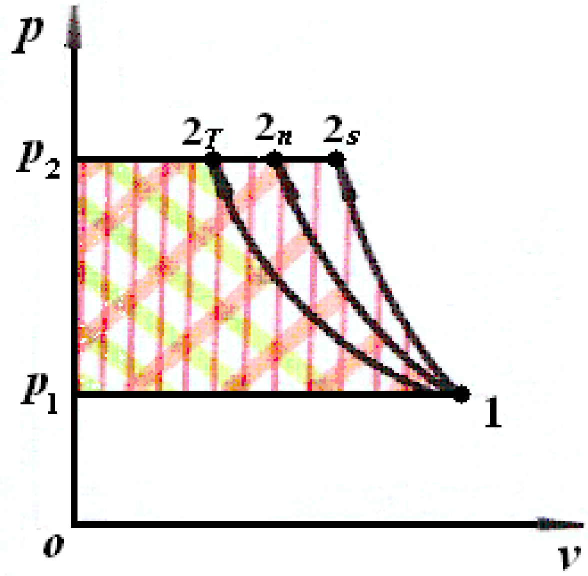
$$w_{C,n} = \frac{n}{n-1} p_1 v_1 \left(\pi^{\frac{n-1}{n}} - 1 \right)$$

讨论：

a）

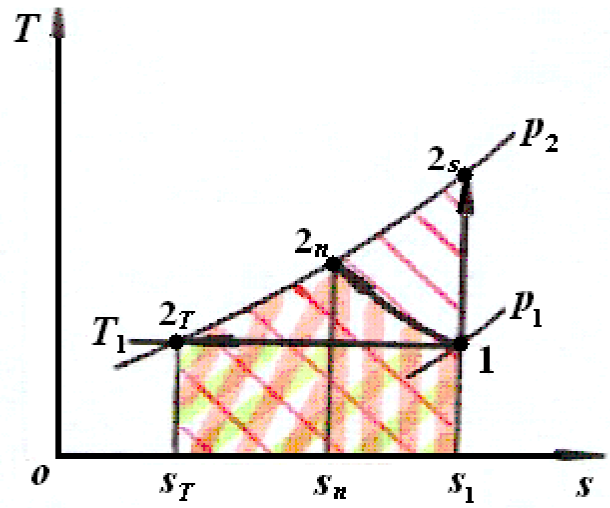
$$\left.\begin{matrix} w_{C,s} > w_{C,n} > w_{C,T} \\ T_{2s} > T_{2n} > T_{2T} \\ v_{2s} > v_{2n} > v_{2T} \end{matrix}\right\}$$

理想压缩是等温压缩



b）通常为多变压缩, $1<n<\kappa$

$$n\uparrow \left\{\begin{matrix} w_{Cn} \\ T_{2n} \\ v_{2n} \end{matrix}\right\} \uparrow$$



	理想气体	真实气体
等温压缩	$W_{S(R)} = nRT_1 \ln \frac{p_2}{p_1}$	$W_{S(R)} \approx Z_m nRT_1 \ln \frac{p_2}{p_1}$
绝热压缩	$W_S = \frac{K}{K-1} nRT_1[(\frac{p_2}{p_1})^{\frac{K-1}{K}} - 1]$	$W_S = \frac{K}{K-1} Z_m nRT_1[(\frac{p_2}{p_1})^{\frac{K-1}{K}} - 1]$
多变压缩	$W_S = \frac{m}{m-1} nRT_1[(\frac{p_2}{p_1})^{\frac{m-1}{m}} - 1]$	$W_S = \frac{m}{m-1} Z_m nRT_1[(\frac{p_2}{p_1})^{\frac{m-1}{m}} - 1]$

例：1kg的空气从0.10814MPa和288.75K变化至1.8424MPa，

试求$W_{s(R)}$ =?

解：假设空气为理想气体

a. 等温压缩过程:

$$W_{S(R)} = nRT\ \ln\frac{p_2}{p_1} = (\frac{1}{29})8.314(273+15.6)\ln\frac{1.8428}{0.10814} = 234.6kJ$$

b. 绝热压缩过程: ***K*=1.4**

$$W_{S(R)} = \frac{K}{K-1}nRT_1[(\frac{p_2}{p_1})^{\frac{K-1}{K}}-1]$$

$$= \frac{1.4}{1.4-1}\times\frac{8.314}{29}\times(273+15.6)\times[(\frac{1.8424}{0.10814})^{\frac{1.4-1}{1.4}}-1]$$

$$= \frac{1.4}{0.4}\times 0.2867\times 288.6\times(2.2481-1) = 361.44\ \mathrm{kJ}$$

c. 对于多变压缩过程：***m* =1.25**

$$W_S = \frac{m}{m-1} nRT_1[(\frac{p_2}{p_1})^{\frac{m-1}{m}} - 1]$$

$$= \frac{1.25}{1.25-1} \times 0.2867 \times 288.6 \times [(\frac{1.8424}{0.10814})^{\frac{1.25-1}{1.25}} - 1] = 315.7kJ$$

- 终态温度的计算：

绝热压缩过程：

$$T_2 = T_1(\frac{p_2}{p_1})^{\frac{K-1}{K}} = 288.6(\frac{1.8434}{0.10814})^{\frac{1.4-1}{1.4}} = 648.79K = 375.79^{\circ}\mathrm{C}$$

多变压缩过程：

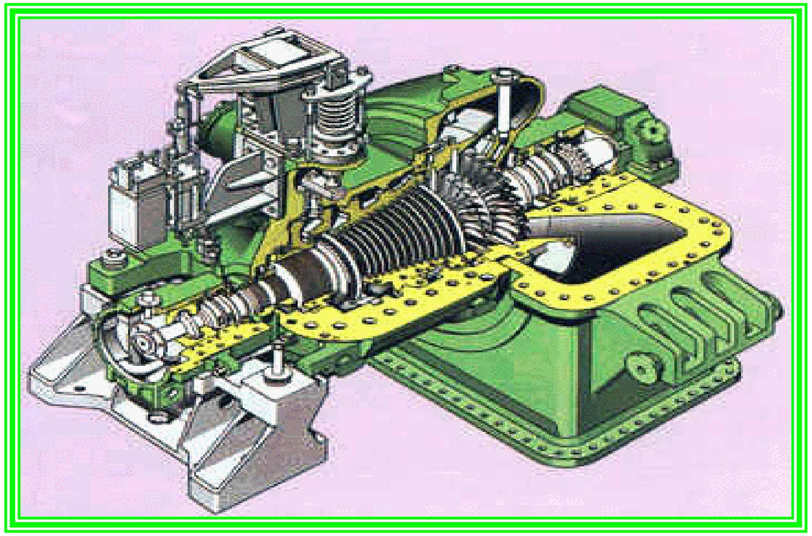
$$T_2 = T_1(\frac{p_2}{p_1})^{\frac{m-1}{m}} = 288.6(\frac{1.8434}{0.10814})^{\frac{1.25-1}{1.25}} = 508.83K = 235.83^{\circ}\mathrm{C}$$

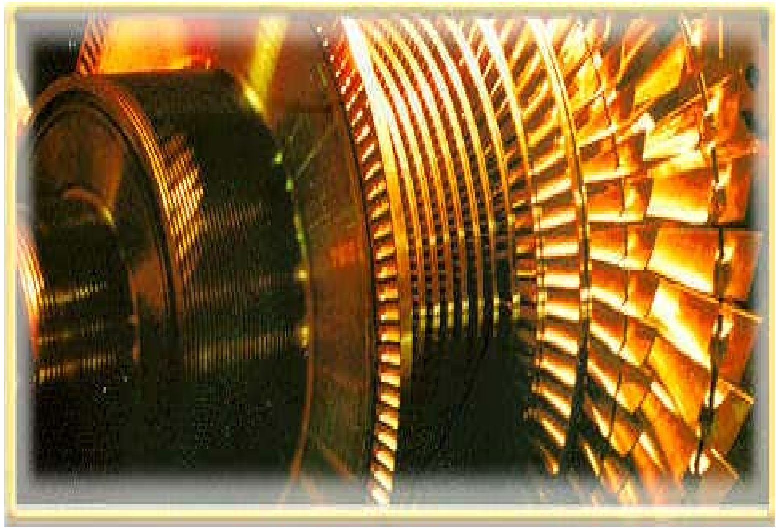
➢ 计算结果：

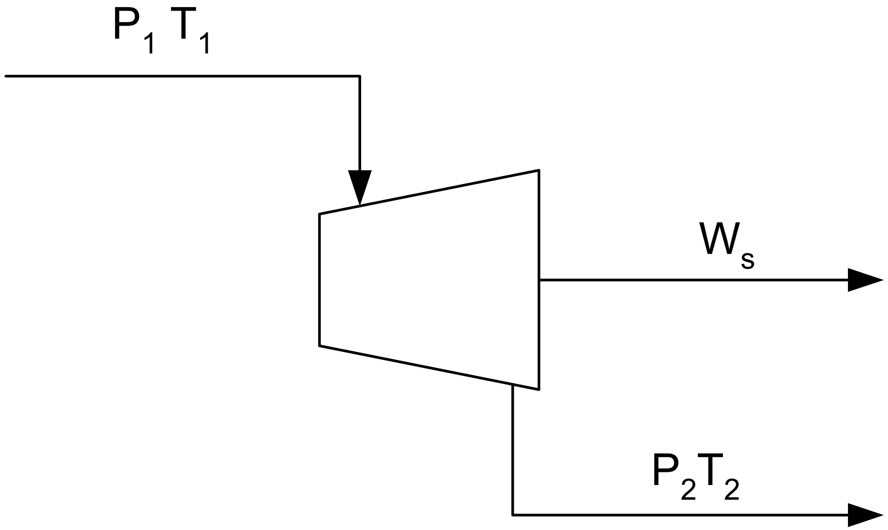
压缩过程	终态温度 (℃)	消耗功(kJ)
等温压缩	15.6	234.6
多变压缩	235.83	315.7
绝热压缩	375.79	361.44

膨胀过程

蒸汽透平







绝热

可逆

等熵

等熵效率

$$\Delta h + g\Delta z + \frac{1}{2}\Delta u^2 = q + w_s \quad \Delta h = q + w_s \quad w_s = \Delta h$$

$$\Delta H = H_2 - H_1 = \int_{T_1}^{T_2} C_P \mathrm{d}T + H_2^R - H_1^R$$

✓透平效率: $\eta = \dfrac{W_s}{W_{s,isentropic}}$

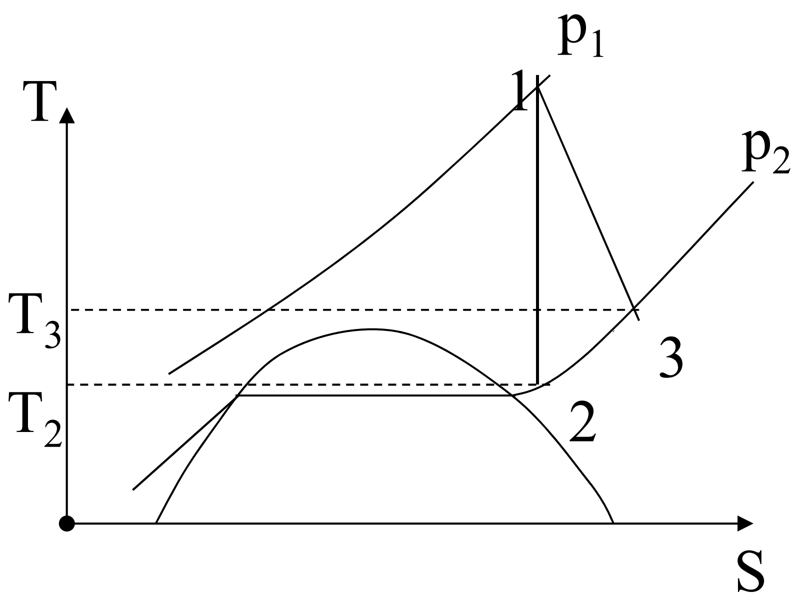
✓等熵膨胀过程, 即1→2： $Q=0,\ W_{s(R)}=\Delta H=H_2-H_1$

✓若膨胀过程不可逆, 即1→3：$W_s=\Delta H=H_3-H_1$

透平效率 (等熵效率)：

$$\eta_s=\frac{W_s}{W_{s(R)}}=\frac{H_3-H_1}{H_2-H_1}$$

$$W_s=\eta_s W_{s(R)}$$



例：在573K和4.5MPa条件下, 乙烯(C_2H_4)经绝热可逆膨胀过程至0.2 MPa, 求轴功 W_s=?

解: 对于**1mol**乙烯

$$W_s = \Delta H = \int_{T_1}^{T_2} C_p^{id} \mathrm{d}T + H_2^R - H_1^R$$

$$\Delta S = S_2 - S_1 = \int_{T_1}^{T_2} \frac{C_p^{id}}{T} \mathrm{d}T - nR\ln\frac{p_2}{p_1} + S_2^R - S_1^R = 0$$

a) 假设满足理想气体状态方程**:**

$$W_s = \Delta H = \int_{T_1}^{T_2} C_p^{id} \mathrm{d}T \qquad \Delta S = \int_{T_1}^{T_2} \frac{C_p^{id}}{T} \mathrm{d}T - nR\ln\frac{p_2}{p_1} = 0$$

$$C_{pm}^{id} = R(1.424 + 14.394\times10^{-3}T - 4.392\times10^{-6}T^2)$$

$$\int_{T_1}^{T_2} R(1.424T^{-1} + 14.394\times10^{-3} - 4.392\times10^{-6}T^1)\mathrm{d}T - R\ln\frac{p_2}{p_1} = 0$$

$$R[1.424\ln\frac{T_2}{T_1} + 14.394\times10^{-3}(T_2 - T_1) - \frac{4.392\times10^{-6}}{2}(T_2^2 - T_1^2)] - R\ln\frac{p_2}{p_1} = 0$$

首先, 采用牛顿迭代法求解$\boldsymbol{T_2}$下的焓平衡式:

$$f(T_2) = \int_{T_1}^{T_2} \frac{C_{pm}^{id}}{T} \mathrm{d}T - R\ln\frac{p_2}{p_1} = 0$$

$$f(T_2) = \int_{T_1}^{T_2} R(1.424T^{-1} + 14.394\times10^{-3} - 4.392\times10^{-6}T^{1})\mathrm{d}T - R\ln\frac{p_2}{p_1} = 0$$

$$f'(T_2) = C_{pm}^{id}/T_2 = R(1.424/T_2 + 14.394\times10^{-3} - 4.392\times10^{-6}T_2)$$

$$f(T_2) = R[1.424\ln\frac{T_2}{T_1} + 14.394\times10^{-3}(T_2 - T_1) - \frac{4.392\times10^{-6}}{2}(T_2^2 - T_1^2)] - R\ln\frac{p_2}{p_1} = 0$$

$$T_2^{(n+1)} = T_2^{(n)} - f(T_2^{(n)})/f'(T_2^{(n)})$$

迭代直至满足: $\left|\dfrac{T_2^{(n+1)} - T_2^{(n)}}{T_2^{(n)}}\right| \le \varepsilon$

$$T_2 = 370.79\mathrm{K}$$

于是有： $W_s = \Delta H_m = \int_{573.15}^{370.8} C_{pm}^{id} \mathrm{d}T$

$$= \int_{573.15}^{370.8} R(1.424 + 14.394\times10^{-3}T - 4.392\times10^{-6}T^2)\mathrm{d}T$$

$$= -12154\ \ \mathrm{J/mol}$$

b) 采用普遍化维里关系式，对于真实气体：

对于乙烯： $T_c = 282.48K,\ p_c = 5.04\mathrm{MPa},\ \omega = 0.085$

初始状态： $T_r = \dfrac{573.15}{282.4} = 2.030,\ p_r = \dfrac{4.5}{5.04} = 0.893$

采用普遍化维里关系式

$$B^0 = 0.083 - \frac{0.422}{T_r^{1.6}} = -0.053\,,\ \frac{\mathrm{d}B^0}{\mathrm{d}T_r} = \frac{0.675}{T_r^{2.6}} = 0.107$$

$$B^1 = 0.139 - \frac{0.172}{T_r^{4.2}} = 0.130\,,\ \frac{\mathrm{d}B^1}{\mathrm{d}T_r} = \frac{0.722}{T_r^{5.6}} = 0.018$$

$$\frac{H_m^R}{RT_c} = p_r[B^0 - T_r \frac{\mathrm{d}B^0}{\mathrm{d}T_r} + \omega(B^1 - T_r \frac{\mathrm{d}B^1}{\mathrm{d}T_r})]$$

$$= 0.893 \times \left[-0.053 - 2.032 \times 0.107 + 0.085 \times \left(0.13 - 2.032 \times 0.018\right)\right]$$

$$= -0.234$$

$$H_{m1}^R = -0.234 \times 8.314 \times 282.4 = -550.39 \text{ J/mol}$$

$$\frac{S_m^R}{R} = -p_r(\frac{\mathrm{d}B^0}{\mathrm{d}T_r} + \omega\frac{\mathrm{d}B^1}{\mathrm{d}T_r}) = -0.893 \times \left(0.107 + 0.085 \times 0.018\right) = -0.97$$

$$S_{m1}^R = 8.314 \times (-0.97) = -0.806 \text{ J/(mol.K)}$$

乏汽压力$p = 0.2\text{MPa}$, 实际气体(如果以理想气体为标准, 则结果会稍有不同) . 选择$\boldsymbol{T_2}$的初始值为 a)的结果：T_2=371K

$$T_r = 1.313,\ P_r = 0.04,\ \frac{\mathrm{d}B^0}{\mathrm{d}T_r} = 0.332,\ \frac{\mathrm{d}B^1}{\mathrm{d}T_r} = 0.175,\ S_{m2}^R = -0.115 \text{J/(mol.K)}$$

因此， $\Delta S = S_2 - S_1 = \int_{T_1}^{T_2} \frac{C_p^{id}}{T} \mathrm{d}T - nR \ln \frac{p_2}{p_1} + S_2^R - S_1^R = 0$

$$f(T_2) = R[1.424 \ln \frac{T_2}{573.15} + 14.394 \times 10^{-3} (T_2 - 573.15)$$

$$- \frac{4.392 \times 10^{-6}}{2} (T_2^2 - 573.15^2)] - R \ln \frac{0.2}{4.5} - 0.115 + 0.806 = 0$$

采用牛顿迭代法求解T_2, 最终可以得到: T_2=365.79K

由$\boldsymbol{T_2}$的值可得： $T_r = 1.295,\ p_r = 0.04,\ B^0 = -0.196,\ B^1 = 0.081,\ \frac{\mathrm{d}B^0}{\mathrm{d}T_r} = 0.345,\ \frac{\mathrm{d}B^1}{\mathrm{d}T_r} = 0.188$

$$H_{m2}^R = -61.11 \mathrm{J/mol},\quad S_{m2}^R = -0.120\ \mathrm{J/(mol.K)}$$

$$\int_{T_1}^{T_2} C_{pm}^{id} dT = \int_{573.15}^{365.81} R(1.424 + 14.394 \times 10^{-3} T - 4.392 \times 10^{-6} T^2) dT$$

$$= R[1.424(365.81 - 573.15) + \frac{1}{2} \times 14.394 \times 10^{-3} (365.81^2 - 573.15^2)$$

$$- \frac{1}{3} \times 4.392 \times 10^{-6} (365.81^3 - 573.15^3)] = -12407.94 \mathrm{J/mol}$$

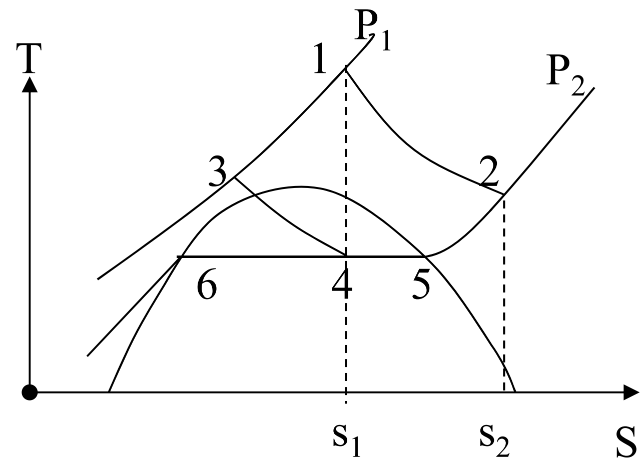
$$W_s = \Delta H = \int_{T_1}^{T_2} C_p^{id} dT + H_2^R - H_1^R$$

$$= -12407.94 - 61.11 + 550.39 = -11918.66\ \mathrm{J/mol}$$

节流过程

$$\Delta h + g\Delta z + \frac{1}{2}\Delta u^2 = q + w_s$$

节流 (Throttling)　$\Delta h = 0;\quad h_2 = h_1$



➢该过程为等焓过程，故有：

$$\Delta H = H_2 - H_1 = \int_{T_1}^{T_2} C_P \mathrm{d}T + H_2^R - H_1^R = 0$$

$$\Delta S = S_2 - S_1 = \int_{T_1}^{T_2} \frac{C_p^{id}}{T} \mathrm{d}T - nR\ln\frac{p_2}{p_1} + S_2^R - S_1^R$$

例：丙烷C_3H_8, 从状态①2MPa, 400K节流至状态②0.1MPa, T_2，试计算$T_2 = ?$ $\Delta S = ?$

解：对于节流过程, 有$\Delta H = 0$,则： $\Delta H = H_2 - H_1 = \int_{T_1}^{T_2} C_P \mathrm{d}T + H_2^R - H_1^R = 0$

ΔT 很小, 故： $\Delta H = C_P(T_2 - T_1) + H_2^R - H_1^R = 0$

对于丙烷： $T_c = 369.8K, P_c = 4.25\text{MPa}, \omega = 0.152$

初始状态有： $T_r = \dfrac{400}{369.8} = 1.0817,\ p_r = \dfrac{2}{4.25} = 0.4706$

采用普遍化维里关系式：

$$B^0 = 0.083 - \frac{0.422}{T_r^{1.6}} = -0.289,\ \frac{\mathrm{d}B^0}{\mathrm{d}T_r} = \frac{0.675}{T_r^{2.6}} = 0.55$$

$$B^1 = 0.139 - \frac{0.172}{T_r^{4.2}} = 0.015,\ \frac{\mathrm{d}B^1}{\mathrm{d}T_r} = \frac{0.722}{T_r^{5.2}} = 0.48$$

$$\frac{H_m^R}{RT_c} = p_r[B^0 - T_r\frac{\mathrm{d}B^0}{\mathrm{d}T_r} + \omega(B^1 - T_r\frac{\mathrm{d}B^1}{\mathrm{d}T_r})]$$
$$= 0.4706\times\left[-0.289 - 1.0817\times 0.55 + 0.152\times\left(0.015 - 1.0817\times 0.48\right)\right]$$
$$= -0.452$$

$$H_{m1}^R = -0.452\times 8.314\times 369.8 = -1390\ \mathrm{J/mol}$$

终态**:** 0.1MPa**, ---**可视为理想气体**,** 则**:** $H_2^R = 0,\ S_2^R = 0$

$$\Delta H = C_P(T_2 - T_1) + H_2^R - H_1^R = 0 \qquad T_2 = H_1^R / C_P + T_1$$

$$C_{pm} = R(1.213 + 28.785\times 10^{-3}T - 8.824\times 10^{-6}T^2)\Big|_{T=400K}$$
$$= 94.074\ \mathrm{J/(mol\cdot K)}$$

$$T_2 = -1390/94.074 + 400 = 385.2K$$

$$T_m = (400 + 385.2)/2 = 392.6K,\ C_{pm,m} = 92.734\ \mathrm{J/(mol \cdot K)}$$

$$T_2 = -1390/92.734 + 400 = 385.0K$$

$$\Delta S_m = S_{m2} - S_{m1} = \int_{T_1}^{T_2} \frac{C_{mp}^{id}}{T} \mathrm{d}T - R\ln\frac{p_2}{p_1} - S_{m1}^R$$

$$\frac{S_m^R}{R} = -p_r\left(\frac{\mathrm{d}B^0}{\mathrm{d}T_r} + \omega\frac{\mathrm{d}B^1}{\mathrm{d}T_r}\right) = -0.4706\times(0.55 + 0.152\times 0.48) = -0.2932$$

$$S_{m1}^R = 8.314\times(-0.2932) = -2.437\ \mathrm{J/(mol\cdot K)}$$

$$\Delta S_m = 92.734\ln\frac{385}{400} - 8.314\ln\frac{0.1}{2.0} + 2.437 = 23.8\ \mathrm{J/(mol\cdot K)}$$

已证明：节流过程是不可逆过程.

8.2 蒸汽动力循环

简单蒸汽动力装置循环—朗肯循环

一、概述

蒸汽及蒸汽动力装置(steam power plant)

1）蒸汽是历史上最早广泛使用的工质，**19**世纪后期蒸汽动力装置的大量使用，促使生产力飞速发展，促使资本主义诞生。

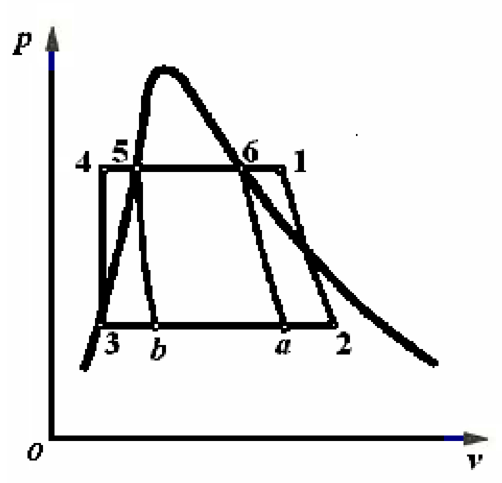
2）目前世界约**75%**电力、国内**78%**电力来自火电厂，绝大部分来自蒸汽动力。

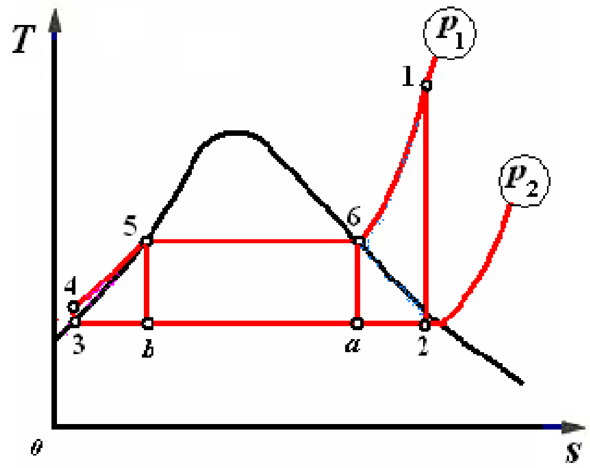
3）蒸汽动力装置可利用各种燃料。

4）蒸汽是无污染、价廉、易得的工质。

二、朗肯循环 (Rankine cycle)

1. 水蒸气的卡诺循环





水蒸气卡诺循环有可能实现，但：

1）温限小

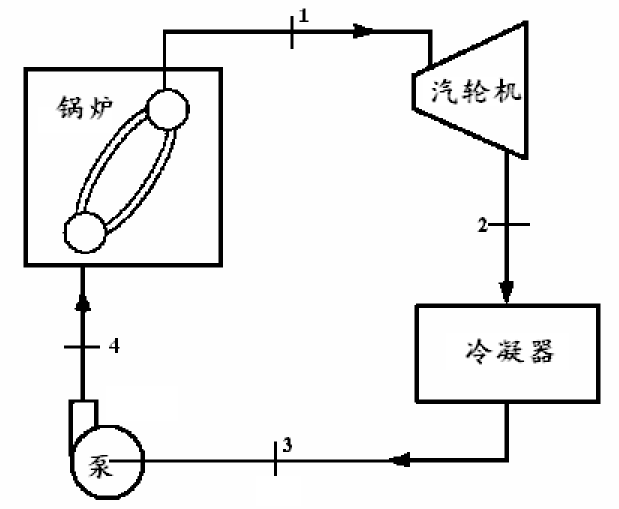
2）膨胀末端*x*太小

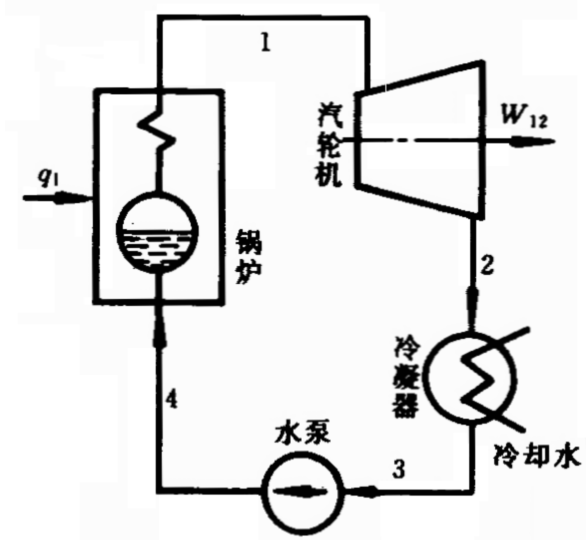
3）压缩两相物质的困难

实际并不实行卡诺循环

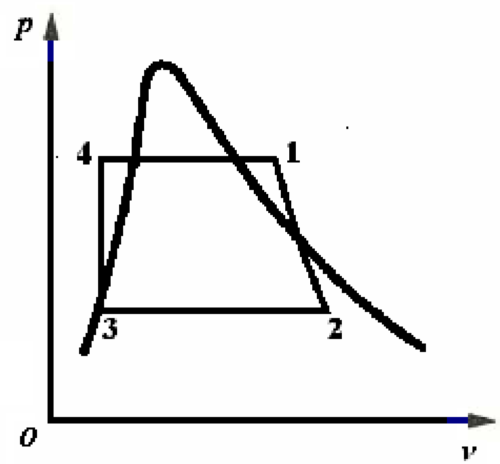
2. 水蒸气朗肯循环

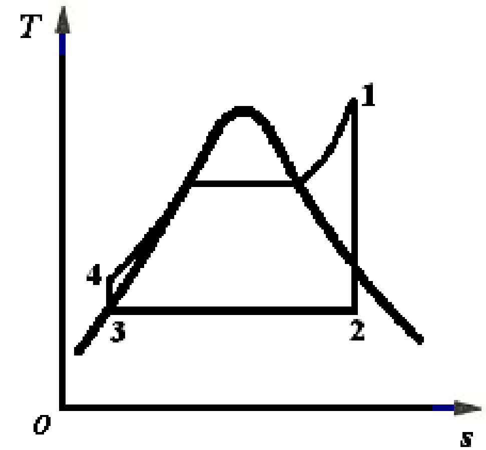
1）流程图

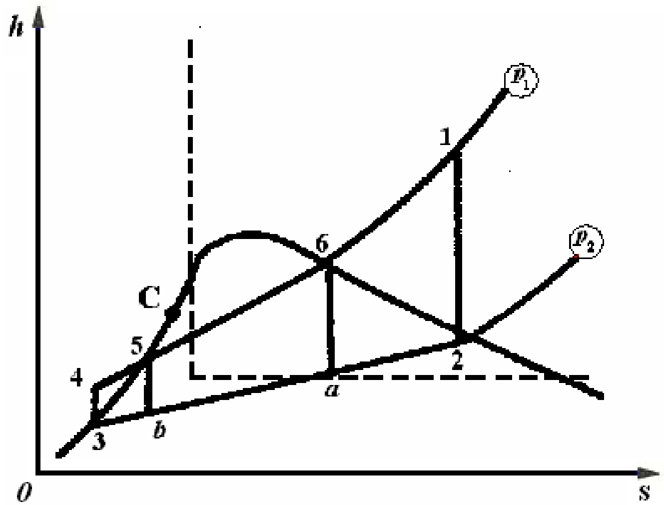




2）*p-v*，*T-s*及*h-s*图







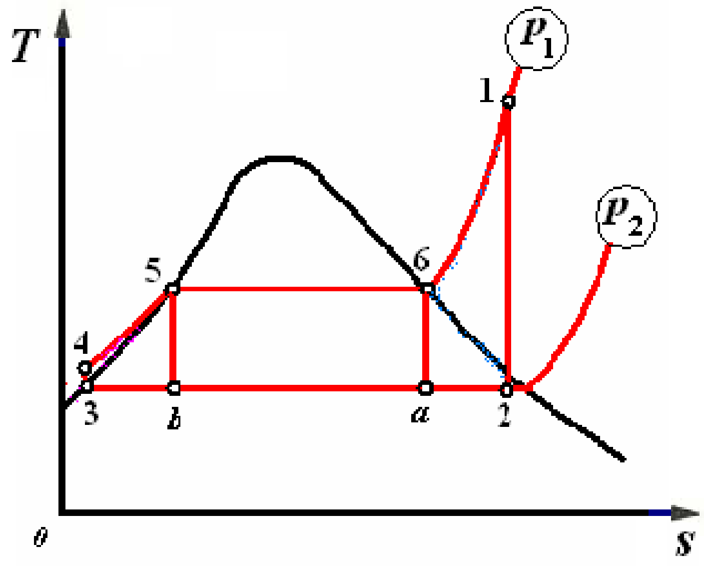
3）朗肯循环的热效率

$$\eta_t = \frac{w_{net}}{q_1} = 1 - \frac{q_2}{q_1}$$

$$w_{net} = w_{t,T} - w_{t,P}$$

$$w_{t,T} = h_1 - h_2 \overset{?}{=} c_p\left(T_1 - T_2\right)$$

$$w_{t,P} = h_4 - h_3$$



$$w_{net} = \left(h_1 - h_2\right) - \left(h_4 - h_3\right)$$

$$q_2 = h_2 - h_3 \overset{?}{=} c_p\left(T_2 - T_3\right)$$

$$\overset{?}{=} T_s\left(s_3 - s_2\right)$$

$$q_1 = h_1 - h_4 \qquad \eta_t = \frac{w_{net}}{q_1} = 1 - \frac{q_2}{q_1} = \frac{\left(h_1 - h_2\right) - \left(h_4 - h_3\right)}{h_1 - h_4}$$

$$w_{t,P} << w_{t,T} \quad \Rightarrow \quad w_{net} \approx w_{t,T}$$

若忽略水泵功，同时近似取$h_4 \approx h_3$，则

$$\eta_t = \frac{h_1 - h_2}{h_1 - h_3} = \frac{h_1 - h_2}{h_1 - h_{2'}}$$

4）耗汽率(steam rate)及耗汽量

理想耗汽率(ideal steam rate) d_0

—装置每输出单位功量所消耗的蒸汽量

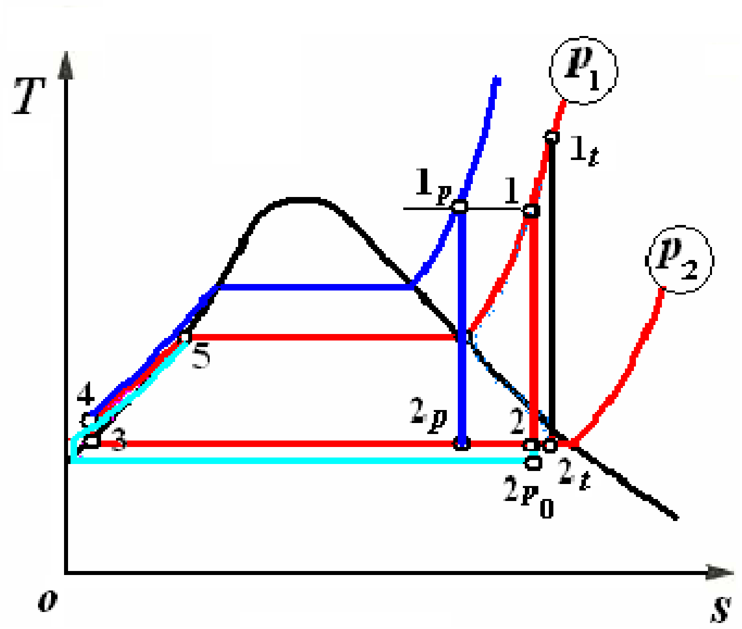
$$d_0 = \frac{1}{h_1 - h_2} \qquad \left[\mathrm{kg/J, 工程上用 kg/\left(kW \cdot h\right)}\right]$$

耗汽量

$$D_0 = d_0 P_0 \qquad -- P_0 \text{ 功率, W}$$

三、初参数对朗肯循环热效率的影响

1. 初温t_1



$$\bar{T}_1 \uparrow \quad \bar{T}_2\text{不变} \quad \Rightarrow \quad \eta_t \uparrow$$

或 循环$1_t2_t3561_t$

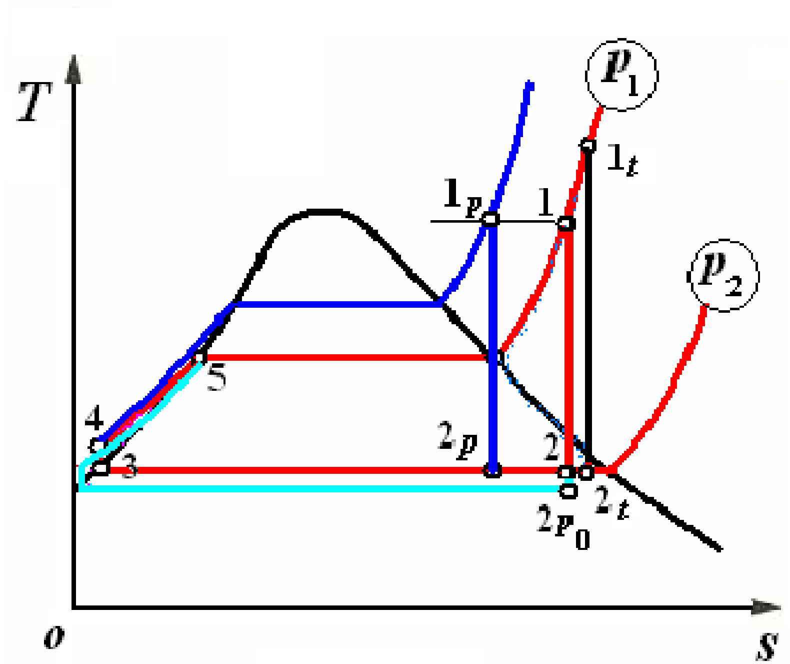
=循环123561+循环11_t2_t21

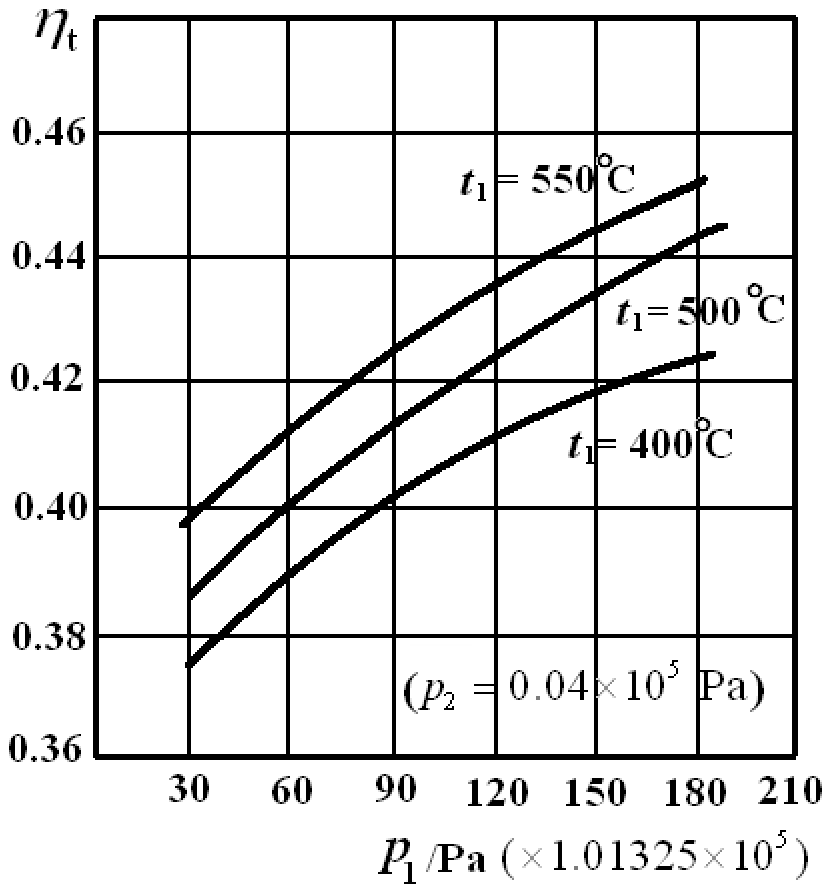
$$\eta_{t11_t2_t21} > \eta_{t123561}$$

$$\eta_t \uparrow$$

2. 初压力 p_1

$\overline{T}_1 \uparrow, \overline{T}_2$不变 $\Rightarrow$ $\eta_t \uparrow$ 但 x_2下降且 p太高造成强度问题

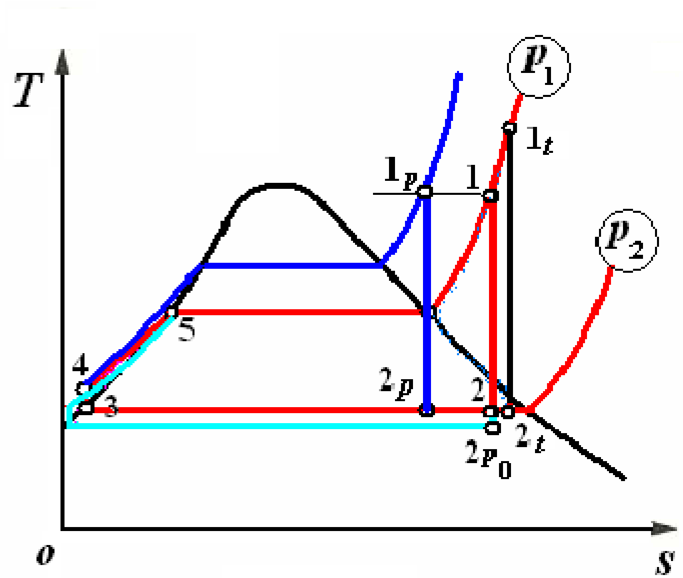


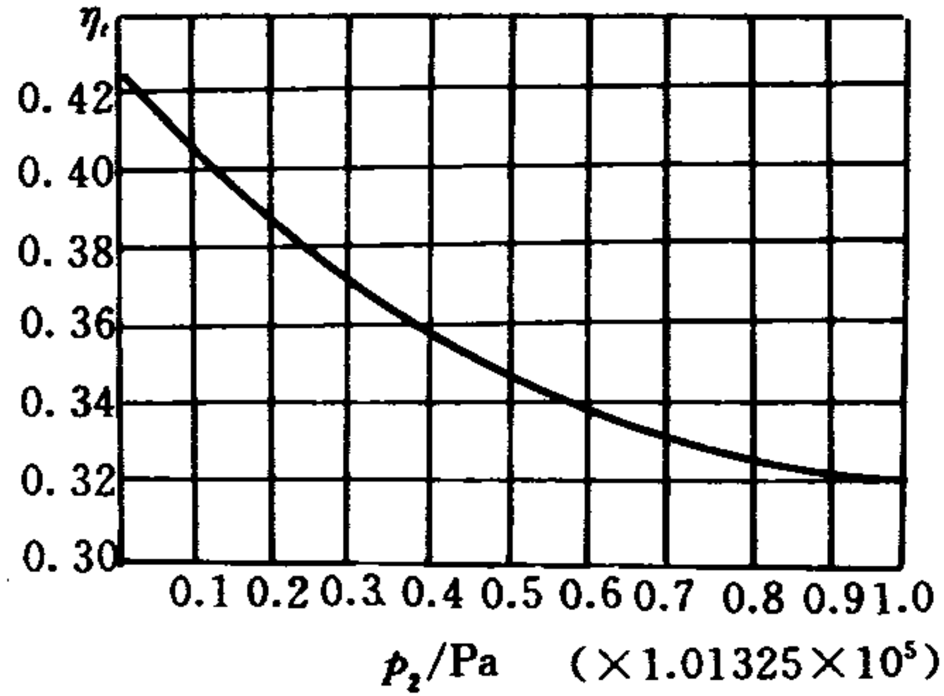


3. 背压 p_2

$\overline{T}_1$不变$\uparrow$,$\overline{T}_2\downarrow \Rightarrow \eta_t \uparrow$ 但受制于环境温度，不能任意降低 $\left(p_2 = 6\text{kPa}, t_s = 36.17^\circ\text{C}; p_2 = 4\text{kPa}, t_s = 28.95^\circ\text{C}\right)$

同时，x_2下降 。



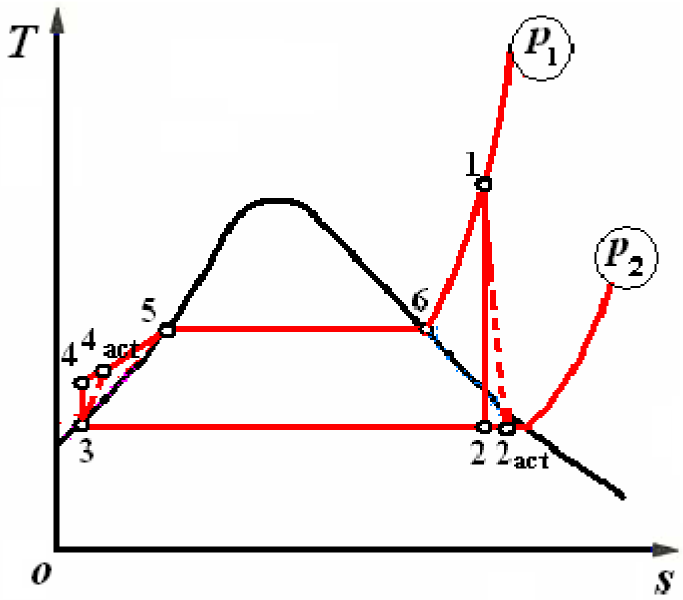


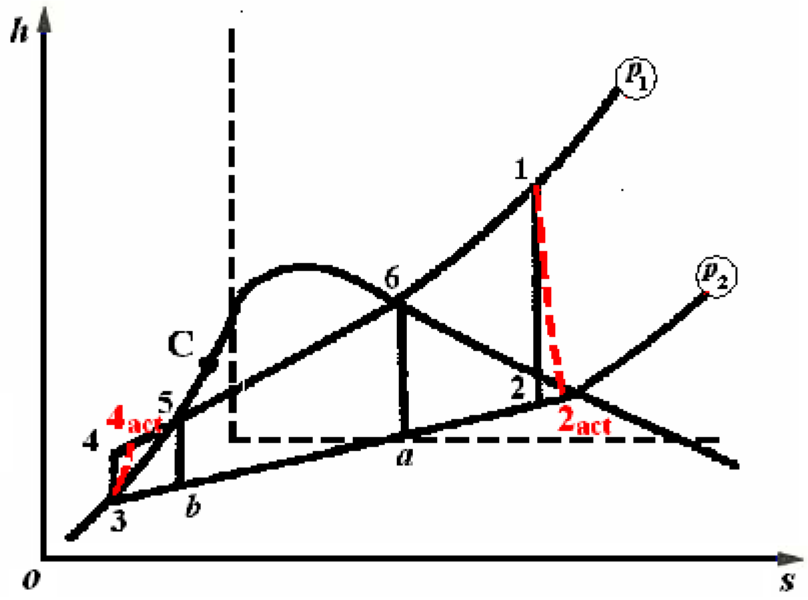
讨论：

我国幅员辽阔，四季温差大，对蒸汽发电机组有什么影响？

四、有摩阻的实际朗肯循环

1. *T*-*s*图及*h*-*s*图





忽略水泵功：

$$q_1 = h_1 - h_3 \quad \text{不变}$$

$$q_2 = h_{2\text{act}} - h_{2'} \quad \uparrow$$

$$\eta_t \downarrow$$

2. 不可逆性衡量

a）汽轮机内部相对效率$\boldsymbol{\eta_T}$（简称汽机效率）

$$\eta_{\mathrm{T}}=\frac{w_{\mathrm{t,Tact}}}{w_{\mathrm{t,T}}}=\frac{h_1-h_{2\mathrm{act}}}{h_1-h_2}$$

近代大功率汽轮机$\boldsymbol{\eta_T}$在**0.92**左右

$\boldsymbol{h_{2act}}$的确定方法：

- 运行中，测出 $\boldsymbol{p_2}$ 及 $\boldsymbol{x_2}$，按 $\boldsymbol{h_x = x_2 h'' + (1-x_2)h'}$
- 设计中，选定$\boldsymbol{\eta_T}$按

$$h_{2\mathrm{act}}=h_1-\eta_{\mathrm{T}}\left(h_1-h_2\right)$$
$$=h_2+\left(1-\eta_{\mathrm{T}}\right)\left(h_1-h_2\right)$$

（$\boldsymbol{h_1 - h_2}$—理想绝热焓降（**ideal enthalpy drop; isentropic enthalpy drop**）） b）装置内部热效率（**internal thermal efficiency**）

忽略水泵功：

$$\eta_{\mathrm{i}} = \frac{w_{\mathrm{net,act}}}{q_1} = \frac{w_{\mathrm{t,Tact}}}{q_1} = \frac{h_1 - h_{2\mathrm{act}}}{h_1 - h_{2'}} = \frac{\eta_{\mathrm{T}}(h_1 - h_2)}{h_1 - h_{2'}} = \eta_{\mathrm{T}}\eta_{\mathrm{t}}$$

c）装置有效热效率$\boldsymbol{\eta_{\mathrm{e}}}$　　　考虑机械损失

$$\eta_{\mathrm{e}} = \frac{P_{\mathrm{e}}}{q_1} = \eta_{\mathrm{T}}\eta_{\mathrm{m}}\eta_{\mathrm{t}}$$

$\boldsymbol{P_{\mathrm{e}}}$—有效轴功率　$\boldsymbol{\eta_{\mathrm{m}}}$—机械效率

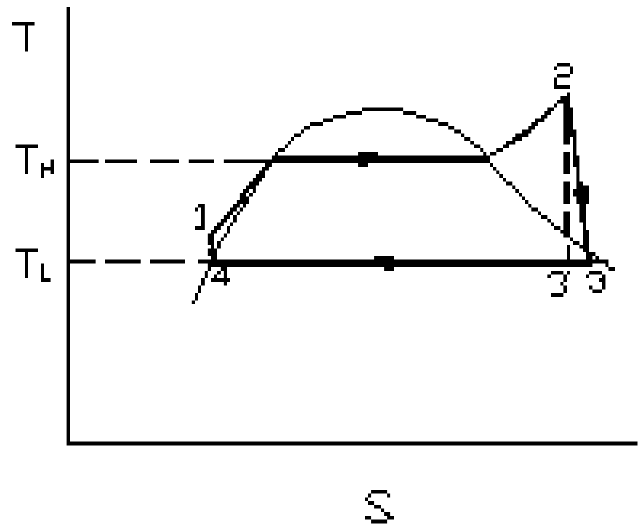
3.实际内部耗汽率$\boldsymbol{d_{\mathrm{i}}}$和耗汽量$\boldsymbol{D_{\mathrm{i}}}$

$$d_{\mathrm{i}} = \frac{1}{h_1 - h_{2\mathrm{act}}} = \frac{h_1 - h_2}{h_1 - h_{2\mathrm{act}}}\frac{1}{h_1 - h_2} = \frac{d_0}{\eta_{\mathrm{T}}}$$

$$D_{\mathrm{i}} = d_{\mathrm{i}}P_{\mathrm{i}}$$

实际内部功率

例：过热蒸汽(8.6MPa, 500℃)经透平, 压力降至0.01MPa, 再经冷凝器冷却至饱和水后进入锅炉, a) 若流体在透平和泵内视为等熵过程, 则求 η_T=? b) 若 $\eta_{s,tur}=\eta_{s,pump}$=0.75, 则 η=? c) 若 $w_{s,tur}$=8000kW, 则 m=?, Q_L=?



解: 由过热蒸汽表可查得:

P(MPa)	*H*(kJ/kg)	*S*(kJ/kg·K)
8	3398.3	6.724
10	3373.7	6.5966

a) 在汽轮机中:

$$h_2 = 3398.3 + \frac{3373.7 - 3398.3}{10000 - 8000} \times (8600 - 8000) = 3390.92\,\text{kJ/kg}$$

$$s_2 = 6.724 + \frac{6.5966 - 6.724}{10000 - 8000} \times (8600 - 8000) = 6.6858\,\text{kJ/(kg} \cdot \text{K)}$$

$$s_{3'} = s_2 = 6.6858\,\text{kJ/(kg} \cdot \text{K)}$$

乏汽处于两相区，由饱和蒸汽表可知:

$$s_{sL}=0.6493,\ s_{sG}=8.1502,\ h_{sL}=191.83,\ h_{sG}=2584.7,\ T_L=318.96\,\mathrm{K}$$

$$s_{3'}=s_g x+s_l(1-x)=8.1502x+0.6493(1-x)=6.6858 \quad x=0.8048$$

于是有:

$$h_{3'}=h_g x+h_l(1-x)=2584.7\times0.8048+191.83(1-0.8048)=2117.7\,\mathrm{kJ/kg}$$

$$W_{s(R),tur}=h_{3'}-h_2=2117.7-3390.92=-1273.3\,\mathrm{kJ/kg}$$

在冷凝器中, 工质为**0.01MPa**的饱和水, 可知: h_4=191.83 kJ/kg

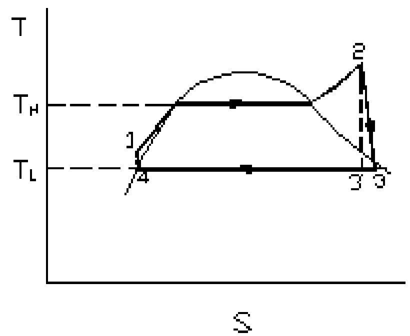
$$q_L=h_4-h_{3'}=191.83-2117.7=-1925.87\,\mathrm{kJ/kg}$$

在泵中, 工质由**0.01MPa**的饱和水压缩至**8.6MPa**的饱和水, **V=0.001 m^3/kg**

$$W_{s(R),pump}=\int_{p_4}^{p_1}V\mathrm{d}p=0.001\times(8.6-0.01)=8.59\ \mathrm{kJ/kg}$$

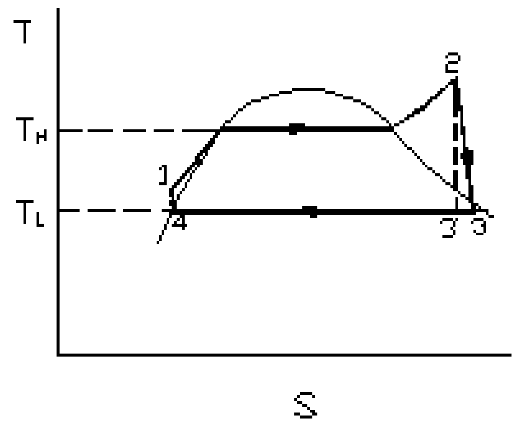
$$q=0,\ W_{s(R),pump}=\Delta h=h_1-h_4$$

$$h_1=h_4+W_{s(R),pump}=191.83+8.59=200.42\ \mathrm{kJ/kg}$$



在锅炉中, 有: $W_s = 0$

$$q_H = \Delta h = h_2 - h_1 = 3390.92 - 200.42 = 3190.5\ \mathrm{kJ/kg}$$



净轴功为:

$$W_{net} = W_{s(R),tur} + W_{s(R),pump} = -1273.3 + 8.59 = -1264.71\, kJ/kg$$

由热力学第一定律可知:

$$W_{net} = q_H + q_L = 3190.5 - 1925.87 = 1264.63\, kJ/kg$$

朗肯循环的热效率为:

$$\eta_T = \left|\frac{W_{s,net}}{q_H}\right| = \frac{1264.63}{3190.5} = 0.3964 \qquad \left(\eta_c = 1 - \frac{T_L}{T_H} = 1 - \frac{318.96}{773.15} = 0.5875\right)$$

b) 若$\eta_{s,tur}= \eta_{s,pump}=0.75$, 求$\eta$

$$W_{s,tur} = \eta_s \times W_{s(R),tur} = 0.75 \times (-1273.3) = -954.98\, kJ/kg$$

$$h_3 = W_{s,tur} + h_2 = -954.98 + 3390.92 = 2435.94\, kJ/kg$$

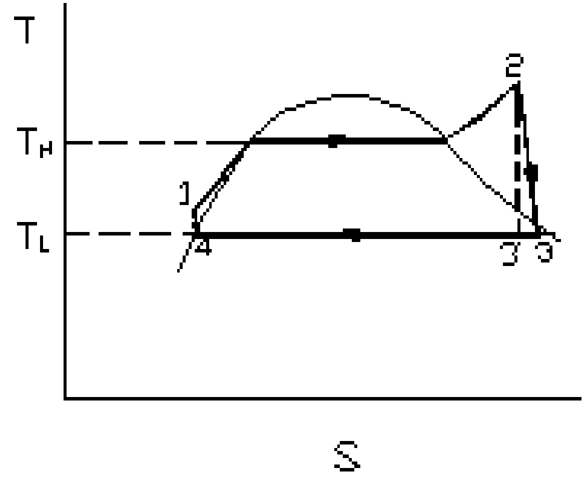
$$q_L = h_4 - h_3 = 191.83 - 2435.94 = -2244.11 kJ/kg$$

$$W_{s,pump} = W_{s(R),pump}/\eta_s = 8.59/0.75 = 11.45\ kJ/kg$$

$$h_1 = h_4 + W_{s,pump} = 191.83 + 11.45 = 203.28\ kJ/kg$$

$$q_H = \Delta h = h_2 - h_1 = 3390.92 - 203.28 = 3187.64 kJ/kg$$

$$\eta_T = \frac{-(W_{s,tur} - W_{s,pump})}{q_H} = \frac{954.98 - 11.45}{3197.64} = 0.2951$$



透平和泵的不可逆性降低了热机循环的热效率.
泵的能量消耗仅占透平做功量的**1%**。

c) 若$w_{s,tur}$=8000kW, 求m和Q_L

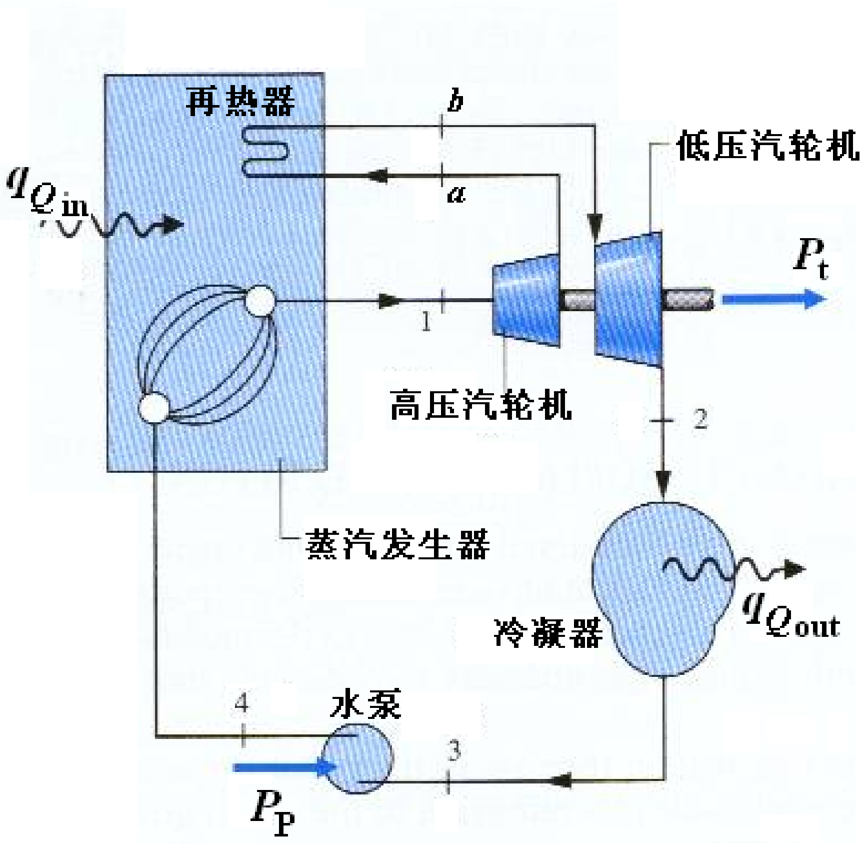
$$W_{s,net} = -(q_H + q_L) = -3187.64 + 2244.11 = -943.53\ kJ/kg$$

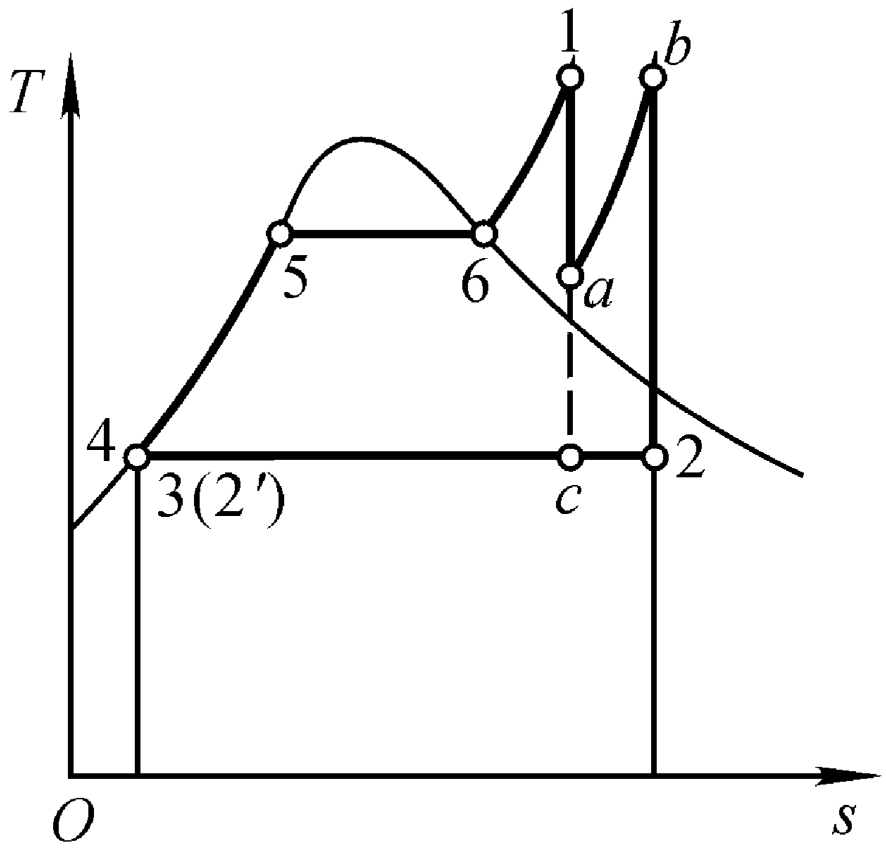
$$m = w_s / W_{s,net} = 80000/943.53 = 84.788\ kg/s$$

$$Q_L = mq_L = 84.788 \times (-2244.11) = -19027.35 kJ/s \approx -19 MW$$

再热循环（reheat cycle）

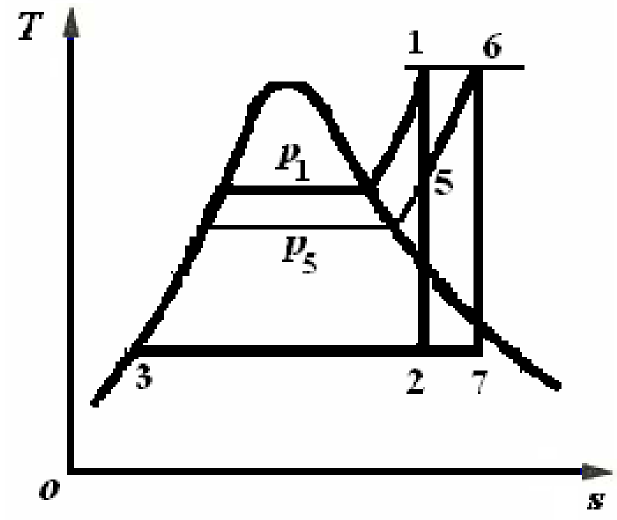
一、设备流程及*T-s*图





二、再热对循环效率的影响

忽略泵功：



$$w_{\text{net}} = h_1 - h_5 + h_6 - h_7$$

$$q_1 = h_1 - h_3 + h_6 - h_5$$

$$\eta_t = \frac{w_{\text{net}}}{q_1} = \frac{h_1 - h_5 + h_6 - h_7}{h_1 - h_3 + h_6 - h_5}$$

$\boldsymbol{\eta}_{\mathbf{t}}$ ⇧ ? ⇩

其他影响：$x_{末}$上升（根本目的）；

d_0下降；

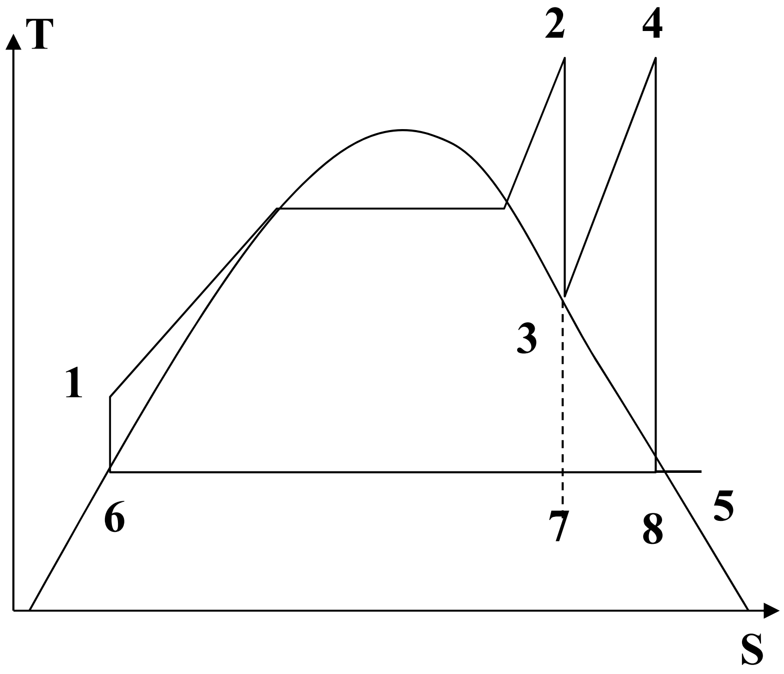
复杂化，投资上升。

例：过热蒸汽(**8.6MPa, 500**℃)经透平变为饱和蒸汽，通入再热器变为**500**℃的过热蒸汽，回到透平膨胀至压力为**10kPa**，经冷凝器变为饱和水后进入锅炉. 透平和泵内的热力过程可视为等熵过程. η_T=?, x=?

解: 利用上述例题的结果, 即：h_2=**3390.9 kJ/kg**, $s_2=s_3$=**6.6858 kJ/(kg.K)**

s	p	h
6.7080	700	2763.5
6.6858	?	?
6.6847	750	2766.4

$$p_3 = 747.64\,kPa,\ h_3 = 2766.26\,kJ/kg$$



➢对于状态点**4:**

$p_4=p_3$=747.64kPa, T_4=500 ℃,

h_4=3481.2kJ/kg, s_4=7.9026 kJ/(kg·K)

➢对于状态点 8: s_8=s_4, p_8=10kPa,

$$s_6 = 0.6493,\ s_5 = 8.1502,\ h_6 = 191.83,\ h_5 = 2584.7,\ T_L = 318.96K$$

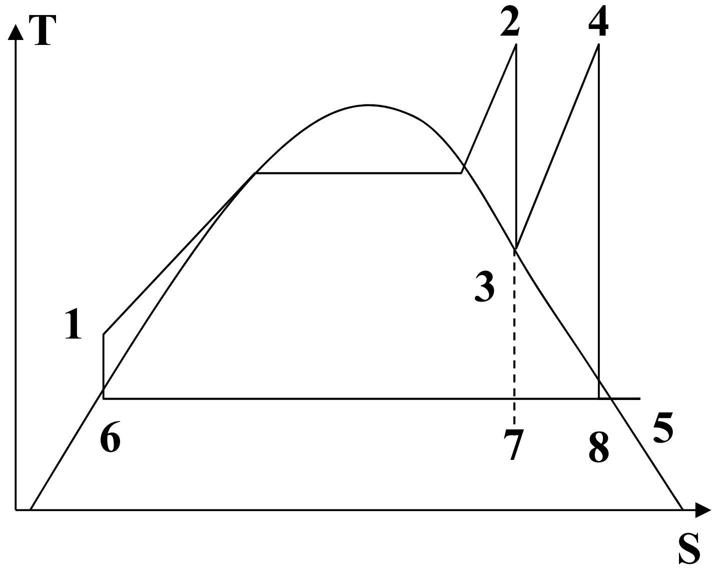
$$s_8 = s_5 x + s_6(1-x) = 8.1502x + 0.6493(1-x) = 7.9026 \qquad x = 0.9670$$

$$h_8 = h_5 x + h_6(1-x) = 2584.7 \times 0.967 + 191.83(1-0.967) = 2505.74\ kJ/kg$$

$$W_{s(R),tur} = h_3 - h_2 + h_8 - h_4$$

$$= 2766.26 - 3390.92 + 2505.74 - 3481.2$$

$$= -1600.12\ kJ/kg$$



$$W_{s(R),pump} = \int_{p_6}^{p_1} V\mathrm{d}p = 0.001 \times (8.6 - 0.01) = 8.59\ \mathrm{kJ/kg}$$

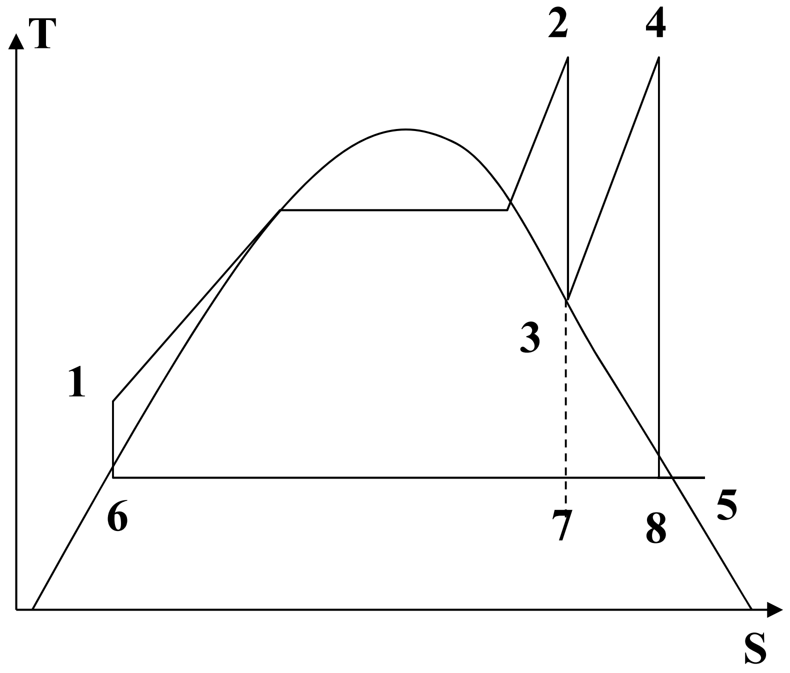
$$h_1 = h_6 + W_{s(R),pump} = 191.83 + 8.59 = 200.42\ kJ/kg$$

$$W_{net} = -1600.12 + 8.59 = -1591.53\ kJ/kg$$

$$q_H = \Delta h = h_2 - h_1 + h_4 - h_3 = 3390.92 - 200.42 + 3481.2 - 2766.26 = 3905.44\ kJ/kg$$

$$\eta_T = \left|\frac{W_{s,net}}{q_H}\right| = \frac{1591.53}{3905.44} = 0.4075$$

再热循环(0.3965 → 0.4075)的热效率增加，乏汽的品质(0.8048 → 0.9670)增加 。

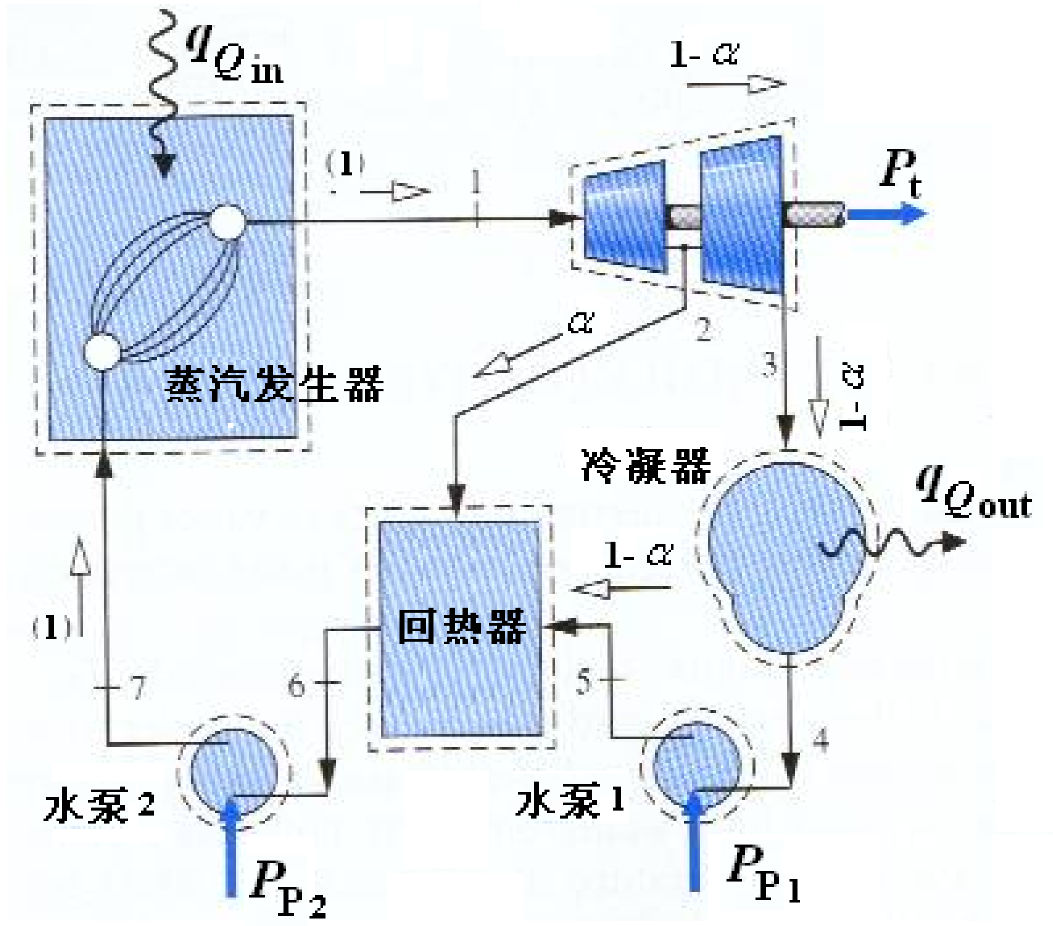


回热循环（regenerative cycle）

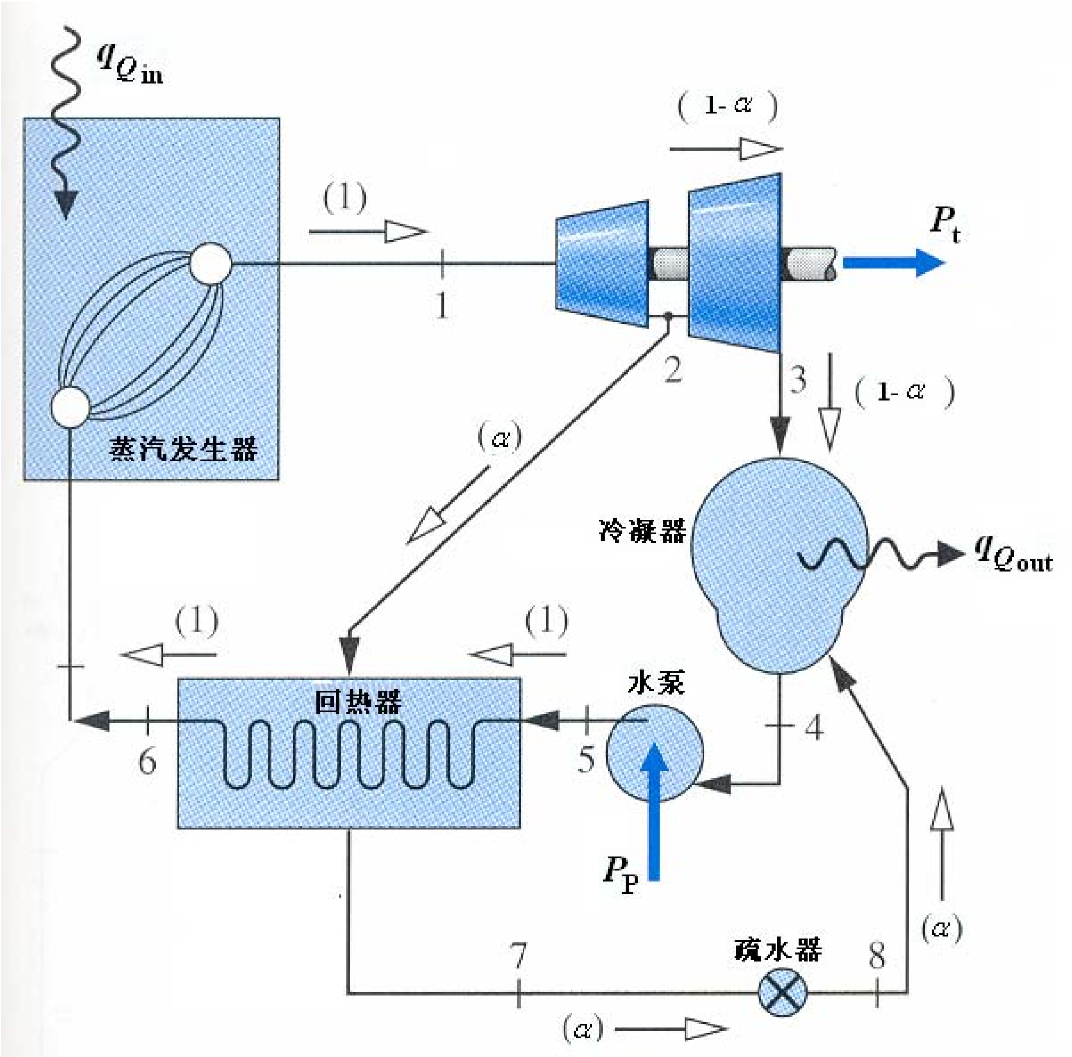
一、抽汽回热循环（regenerative cycle with steam extraction， regenerative cycle with feed-water heater）

回热器两种方式

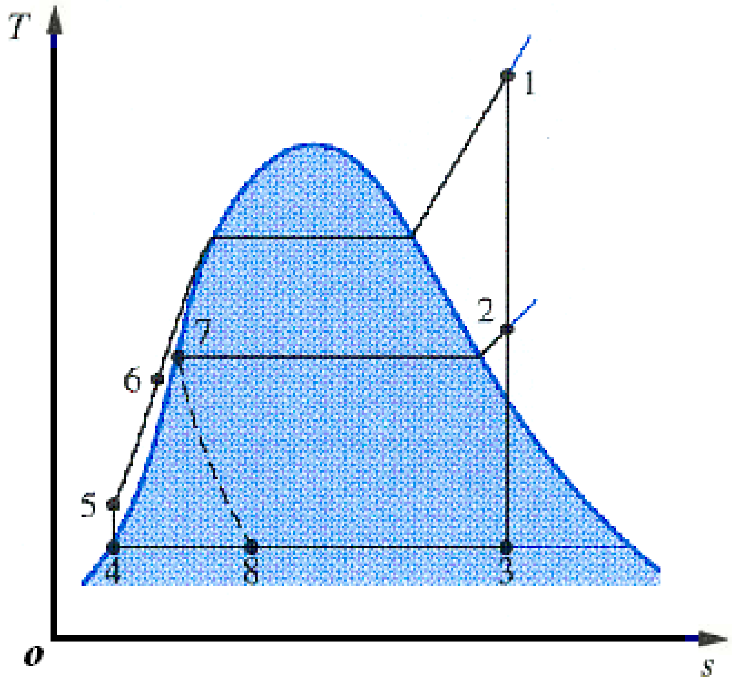
混合式



间壁式



$q_{Q\,in}$
(1)
1
(1-α)
P_t
2
3
(1-α)
(α)
蒸汽发生器
冷凝器
$q_{Q\,out}$
(1)
(1)
回热器
水泵
4
6
5
P_P
7
疏水器
8
(α)
(α)



T
1
2
7
6
5
4
8
3
o
s

二、回热循环计算

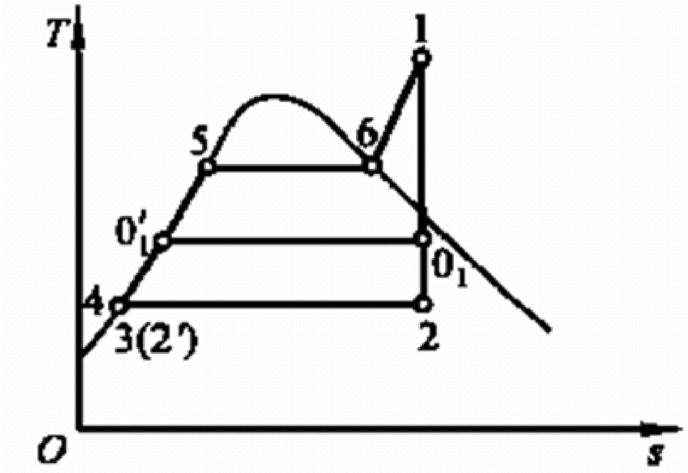
1. 抽汽量

能量方程：

$$(1-\alpha)h_4+\alpha h_{01}-h_{01'}=0$$

忽略泵功 $h_4\approx h_{2'}$

$$\boxed{\alpha=\frac{h_{01'}-h_{2'}}{h_{01}-h_{2'}}}$$



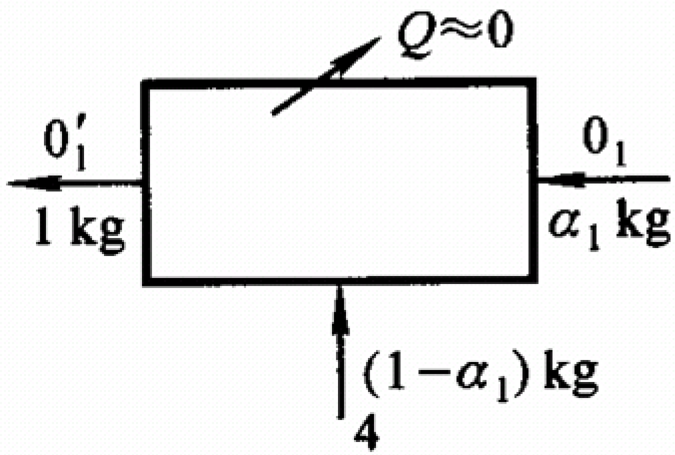
2. 回热器(regenerator)*R*

熵方程：

$$(1-\alpha)s_{2'}+\alpha s_{01}-s_{01'}+S_f+S_g$$

$$=\Delta s_{CV}(=0)$$

$$S_g=s_{01'}-\alpha s_{01}-(1-\alpha)s_{2'}$$



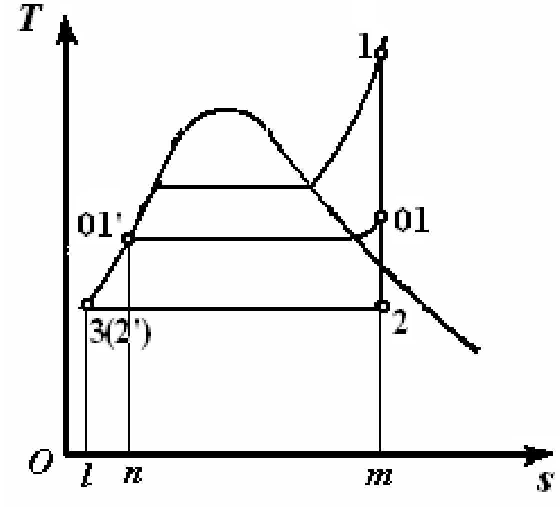
3. 循环热效率

$$w_{\text{net}} = (h_1 - h_{01}) + (1-\alpha)(h_{01} - h_2)$$

$$w_{\text{net}} = (1-\alpha)(h_1 - h_2) + \alpha(h_1 - h_{01})$$

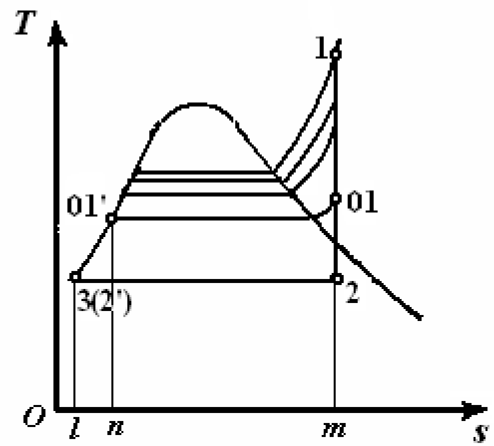
$$q_1 = h_1 - h_{01'}$$

$$q_2 = (1-\alpha)(h_2 - h_{2'})$$



$$\Rightarrow \quad \eta_t = \frac{w_{\text{net}}}{q_1} = \frac{(h_1 - h_{01}) + (1-\alpha)(h_{01} - h_2)}{h_1 - h_{01'}}$$

$$\eta_t = 1 - \frac{q_2}{q_1} = 1 - \frac{(1-\alpha)(h_2 - h_{2'})}{h_1 - h_{01'}}$$

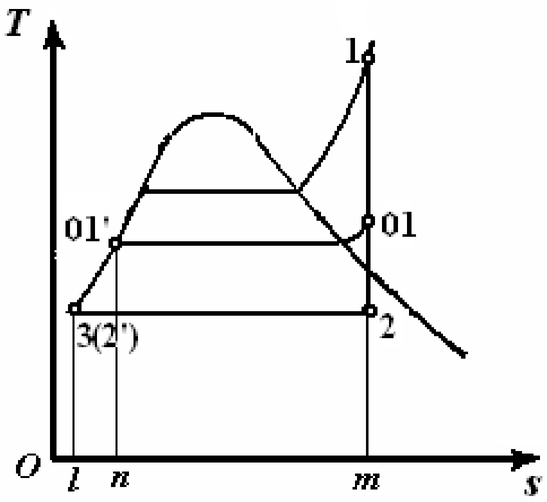


讨论：

1）抽汽回热η_t上升；

2）抽汽级数越多η_t越高，若级数趋向无穷，$\eta_t = 1$？

思考：**1**）抽汽回热循环

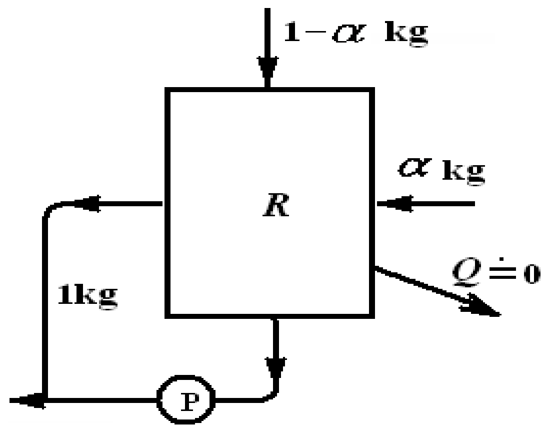


$$\eta_t = 1 - \frac{\overline{T}_{放}}{\overline{T}_{吸}}?$$

其中 $\overline{T}_{吸} = \dfrac{h_1 - h_{01'}}{s_1 - s_{01'}}$ $\qquad \overline{T}_{放} = \dfrac{h_2 - h_{2'}}{s_2 - s_{2'}}$

否 $\eta_t = 1 - \dfrac{Q_2}{Q_1} = 1 - \dfrac{\overline{T_{放}}\Delta S_2}{\overline{T_{吸}}\Delta S_1} = 1 - \dfrac{\overline{T}_{放}(1-\alpha)(s_2 - s_{2'})}{\overline{T}_{吸}(s_1 - s_{01'})} \neq \dfrac{\overline{T}_{放}}{\overline{T}_{吸}}$

2）回热器是间壁式，$\boldsymbol{\alpha}$怎么求？



3）回热器中过程不可逆，为什么循环$\boldsymbol{\eta_t}$上升？

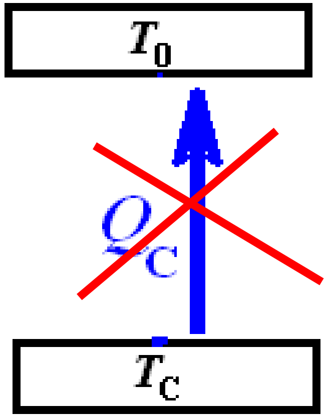
8.3 制冷循环

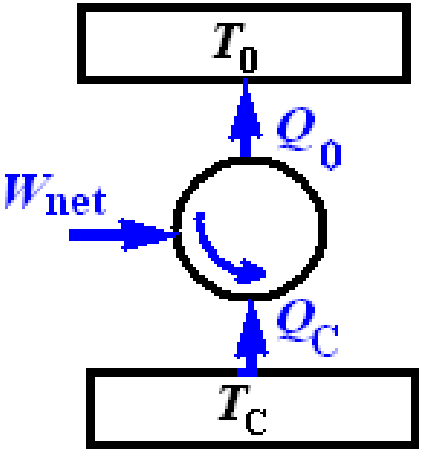
制冷循环概述

一、逆向循环的补偿条件

制冷循环
热泵循环
(heat-pump cycle)

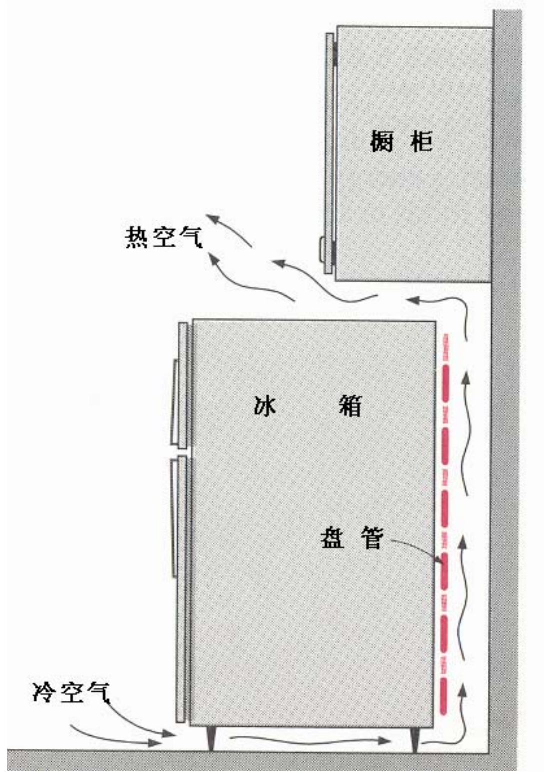
逆向循环
(reverse cycle)





$$\Delta S_{iso} = \Delta S_0 + \Delta S_c < 0$$

$$\Delta S_{iso} = \Delta S_0 + \Delta S_c \geq 0$$



二、经济性指标

$$\varepsilon = \frac{q_c}{q_0 - q_c} \longrightarrow \varepsilon_c = \frac{T_c}{T_0 - T_c}$$

$$\begin{cases} 深冷<1 \\ 普冷>1 \end{cases}$$

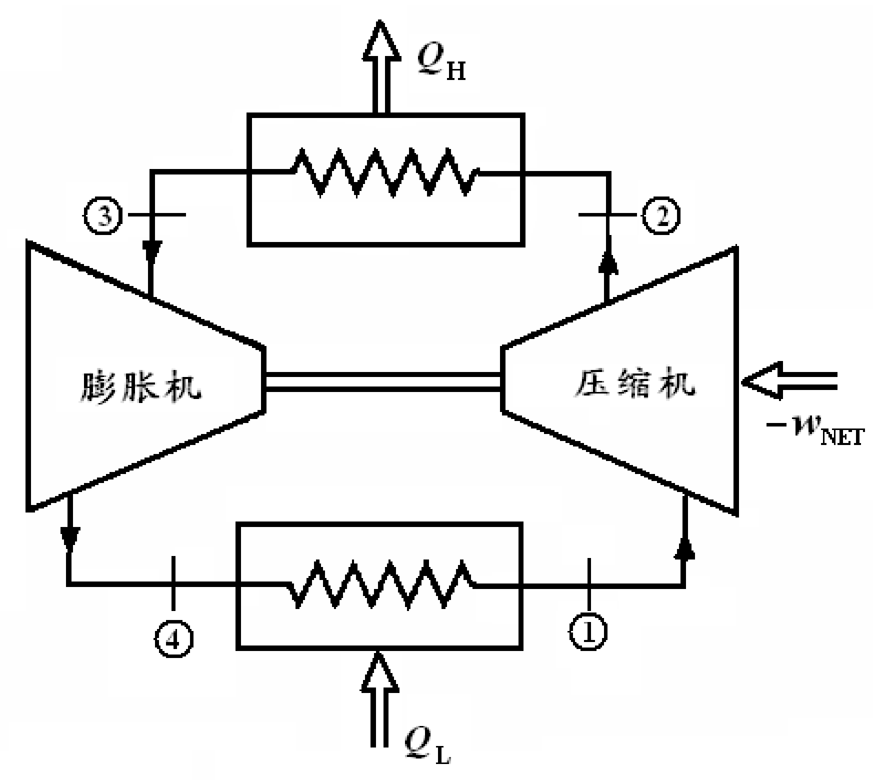
工程上也称**制冷装置工作性能系数COP**。

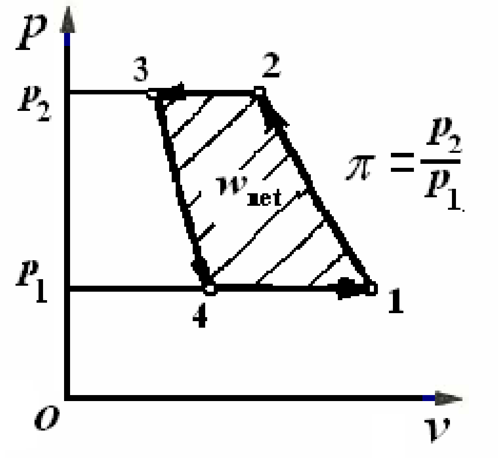
冷吨– **1 000 kg 0º C的饱和水在24 h内冷冻成0 ºC的冰所需的制冷量。**

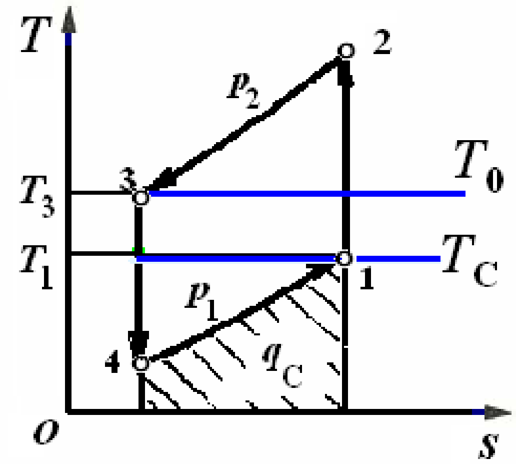
1冷吨=3.86kJ/s；（美国1冷吨=3.517kJ/s ）

压缩气体制冷循环

一、 压缩气体制冷循环（Gas-compression refrigeration cycle）简介

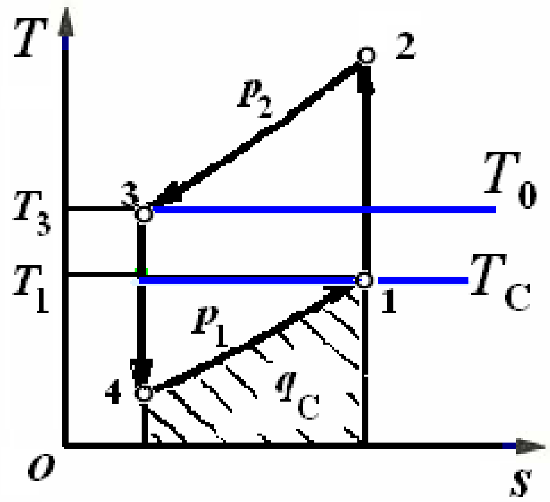






二、制冷系数（the coefficient of performance COP）

$$\varepsilon=\frac{q_C}{w_{net}}=\frac{q_C}{q_1-q_C}$$



$$q_1=h_2-h_3 \qquad q_C=h_1-h_4$$

$$w_{net}=h_2-h_1-(h_3-h_4)=(h_2-h_3)-(h_1-h_4)$$

$$\varepsilon=\frac{q_C}{w_{net}}=\frac{h_1-h_4}{(h_2-h_3)-(h_1-h_4)}=\frac{T_1-T_4}{(T_2-T_3)-(T_1-T_4)}$$

定比热（invariable specific heat capacity）

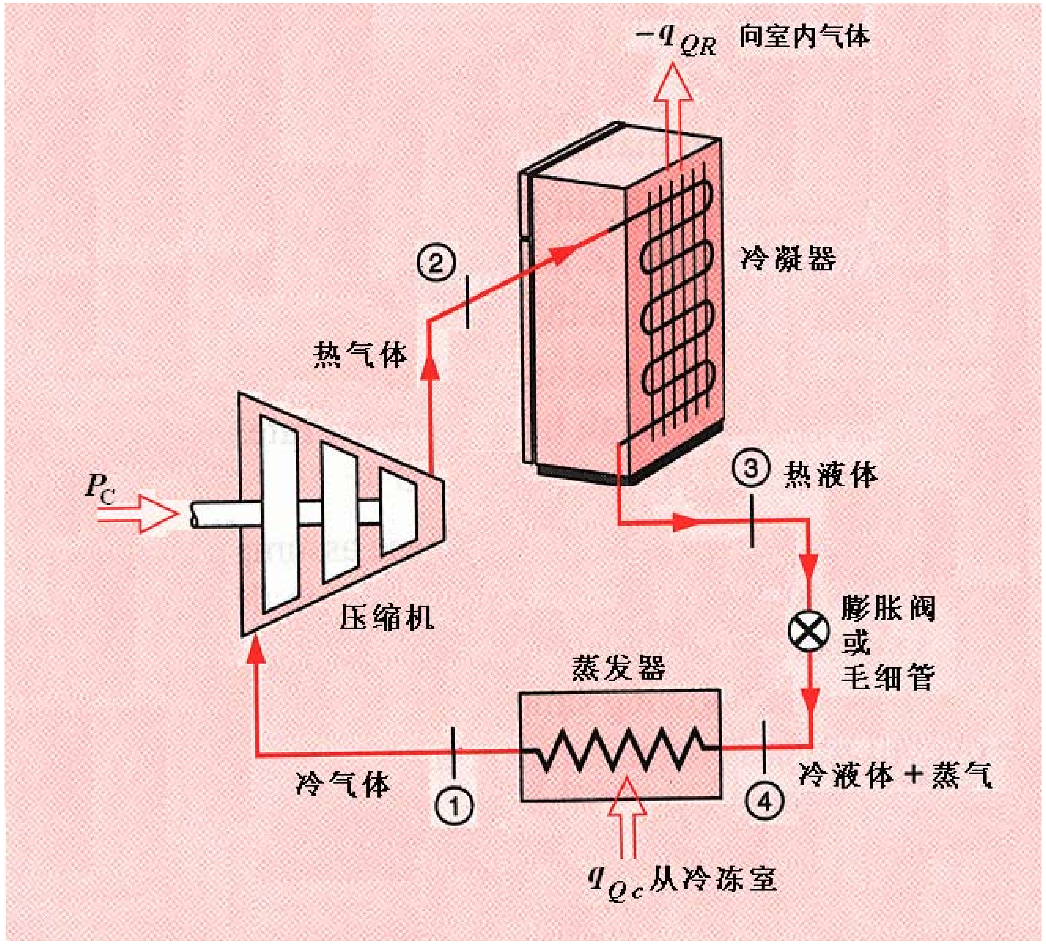
$$=\frac{1}{\pi^{\frac{\kappa-1}{\kappa}}-1}=\frac{T_1}{T_2-T_1}$$

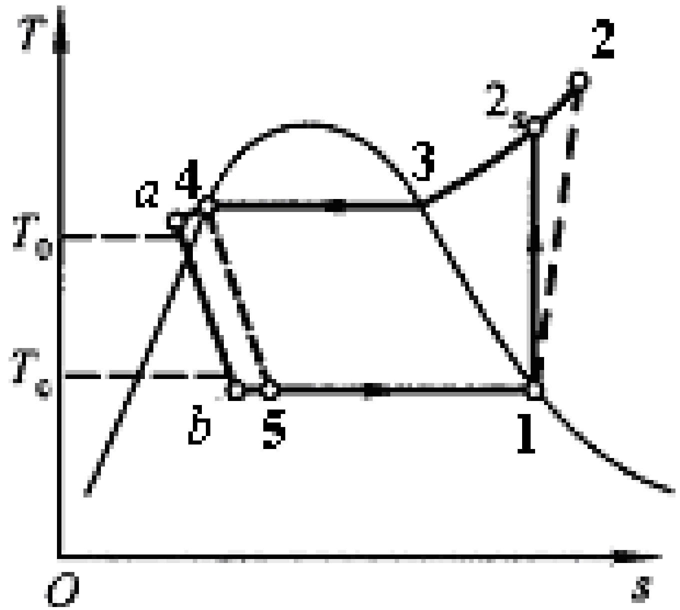
$$T_2=T_1\pi^{\frac{\kappa-1}{\kappa}}$$

$$T_3=T_4\pi^{\frac{\kappa-1}{\kappa}}$$

压缩蒸气制冷循环（The vapor-compression cycle）

一、设备流程及*T*-*s*图



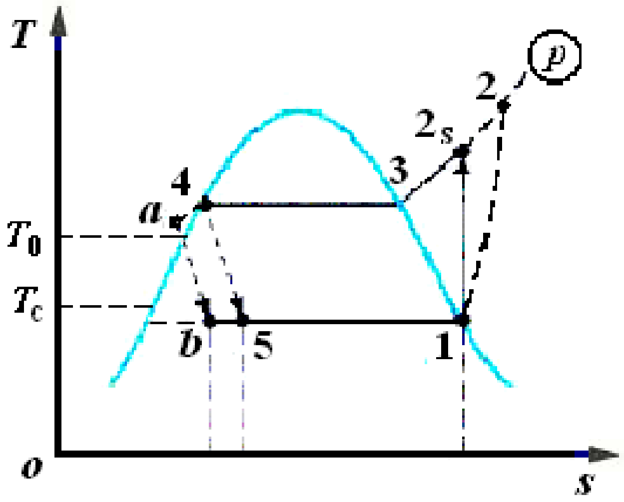


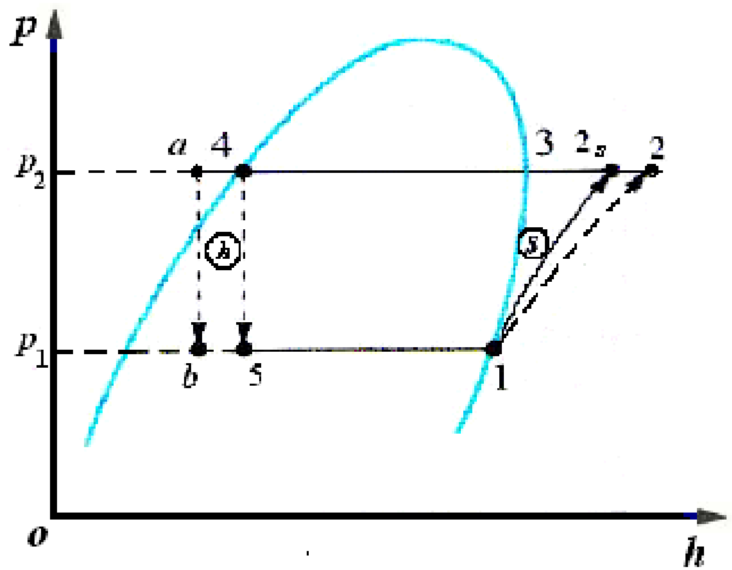
二、制冷系数ε

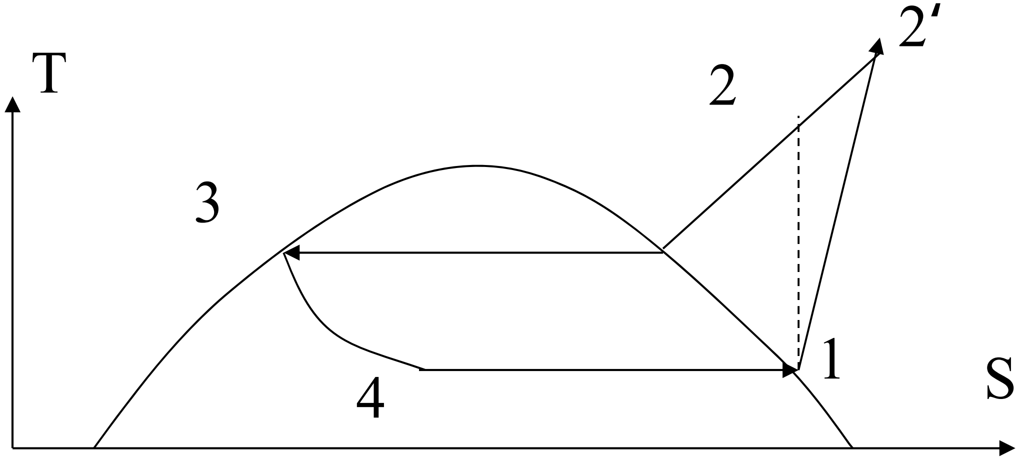
$$
\left.\begin{aligned}
q_C &= h_1 - h_5 = h_1 - h_4 \\
q_1 &= h_2 - h_4 \\
w_{net} &= h_2 - h_1
\end{aligned}\right\}
\varepsilon = \frac{q_C}{w_{net}} = \frac{h_1 - h_4}{h_2 - h_1} \neq \frac{T_1 - T_4}{T_2 - T_1}
$$

三、状态参数确定

1. *T*-*s*图和log*p*-*h*图







- 蒸发器中单位质量工质吸收的热量为：

$$Q_L = \Delta H_{4\to 1} = H_1 - H_4$$

- 工质在冷凝器中释放的热量为：

$$Q_H = \Delta H_{2'\to 3} = H_3 - H_{2'}$$

- 工质在蒸发器出口都变为饱和蒸汽**(即点1)**
- 工质在压缩机出口都变为过热蒸汽**(即点2′)**

✓ 1--2′ 实际压缩(1--2 为可逆压缩)

✓ 2′--3 降温冷凝

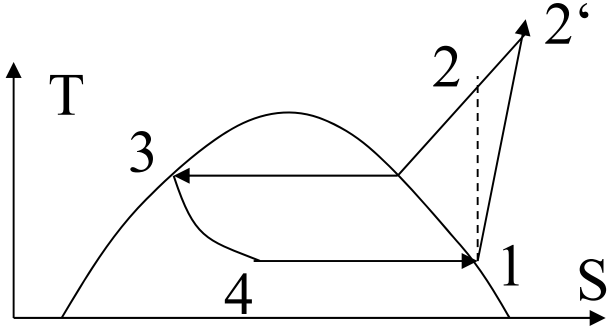
✓ 3 --4 节流（等焓过程）

✓ 4 --1 蒸发

➢压缩机的消耗功：

$$W_S = \Delta H_{1\to 2'} = H_{2'} - H_1$$

$$\text{COP} = \frac{|Q_L|}{|W_S|} = \frac{H_1 - H_4}{H_{2'} - H_1}$$

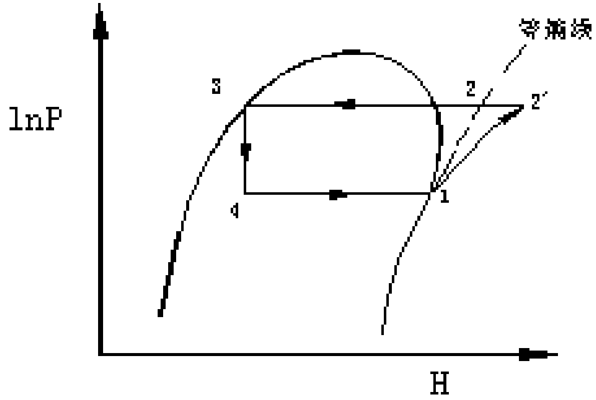


其中,$H_{2'}$是通过等熵效率获得的

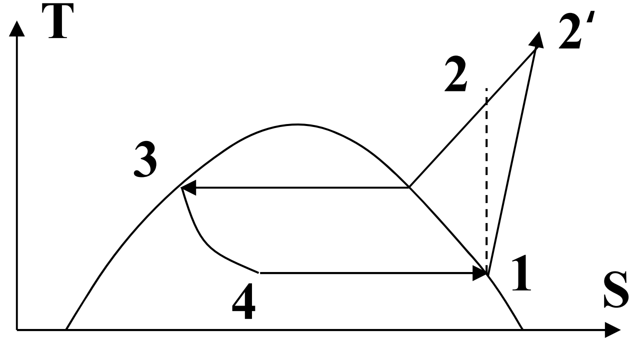
实际制冷循环的COP值随着工质的高低温(T_H &T_L)的变化而不同.

工质的循环速率：$m = \dfrac{Q_L}{H_1 - H_4}$

*p-H*图：适合有关制冷循环的设计及计算



例. 氨制冷机, Q_L=41.8MJ/h, 高温和低温热源为T_H=35℃和T_L=15℃, 传热温差为5℃, 压缩机效率为$\eta_{s,comp}$=0.8, 求COP=?



解：a) $(\mathrm{COP})_c = \dfrac{T_L}{T_H - T_L} = \dfrac{288}{308-288} = 14.4$

b) 对于非等熵过程的实际循环:

$T_H^{'} = 35+5 = 40^\circ C,\ T_L^{'} = 15-5 = 10^\circ C$

由NH_3的T-S图可得 :

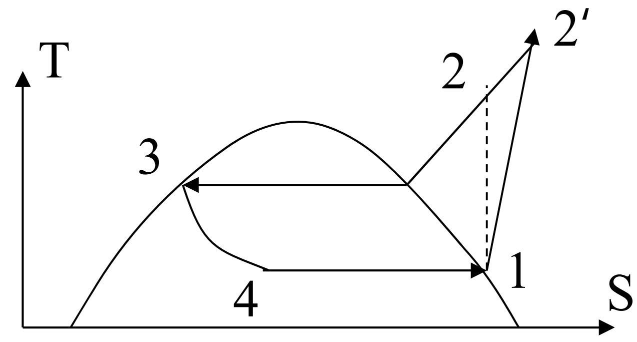
$H_1 = 1452\mathrm{kJ}\cdot kg^{-1} \qquad H_2 = 1573\mathrm{kJ}\cdot kg^{-1} \qquad H_3 = H_4 = 368.2\mathrm{kJ}\cdot kg^{-1}$

$$m = \frac{Q_L}{H_1 - H_4} = \frac{41800}{1452-368.2} = 38.57\,kg/h = 1.0714\times10^{-2}\,kg\cdot s^{-1}$$

$$W_S = m(H_2 - H_1) = 1.0714\times10^{-2}(1573-1452) = 1.296\,kW$$

$$Q_H = \dot{m}(H_3 - H_2) = 1.0714\times10^{-2}(368.2-1573) = -12.9kJ\cdot s^{-1}$$

$$\mathrm{COP}_R = \frac{H_1 - H_4}{H_2 - H_1} = \frac{1452 - 368.2}{1573 - 1452} = 8.957$$



c) 效率为η_s=0.8时的不可逆压缩过程中：

$$\eta_s = \frac{H_2 - H_1}{H_{2'} - H_1} \quad 0.80 = \frac{1573 - 1452}{H_{2'} - 1452} \quad H_{2'} = 1603 kJ \cdot kg^{-1}$$

$$m = \frac{Q_L}{H_1 - H_4} = \frac{41800}{1452 - 368.2} = 38.57 kg/h = 1.0714 \times 10^{-2} kg \cdot s^{-1}$$

$$W_S = m(H_{2'} - H_1) = 1.0714 \times 10^{-2}(1603 - 1452) = 1.62 kW$$

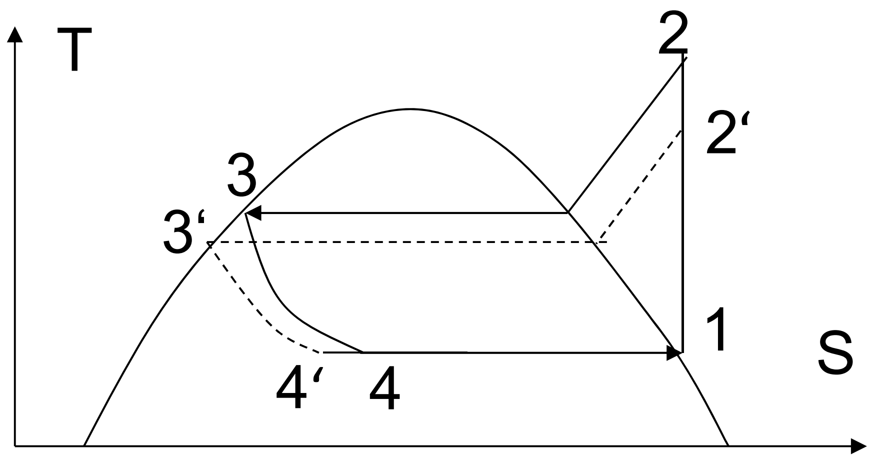
$$Q_H = m(H_3 - H_{2'}) = 1.0714 \times 10^{-2}(368.2 - 1603) = -13.23 kJ \cdot s^{-1}$$

$$\mathrm{COP} = \frac{H_1 - H_4}{H_{2'} - H_1} = \frac{1452 - 368.2}{1603 - 1452} = 7.18$$

很明显，压缩机的不可逆性会增加功的耗散，故降低COP值.

- 制冷循环的改进

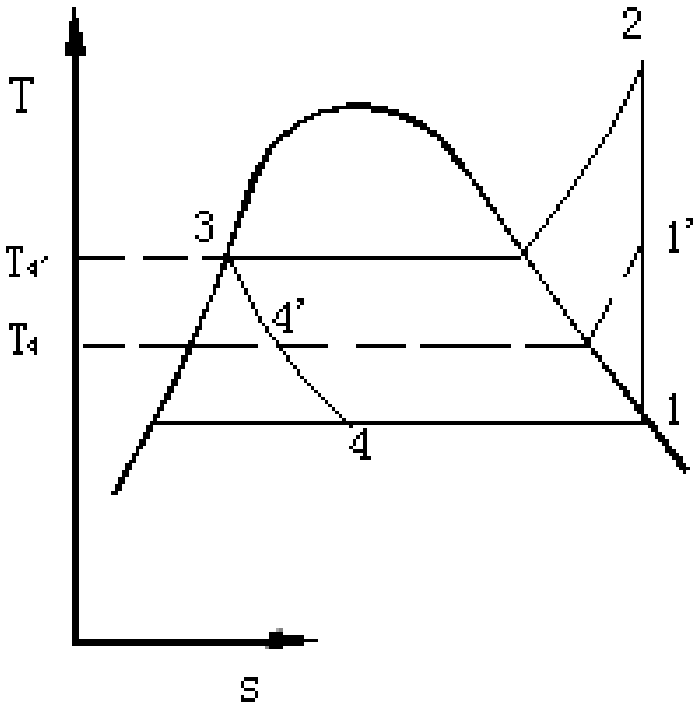
$T_c\downarrow$, COP $\uparrow$;



受环境的限制

$$W_{s,comp} = H_{2'} - H_1,\ Q_L = H_1 - H_{4'}$$

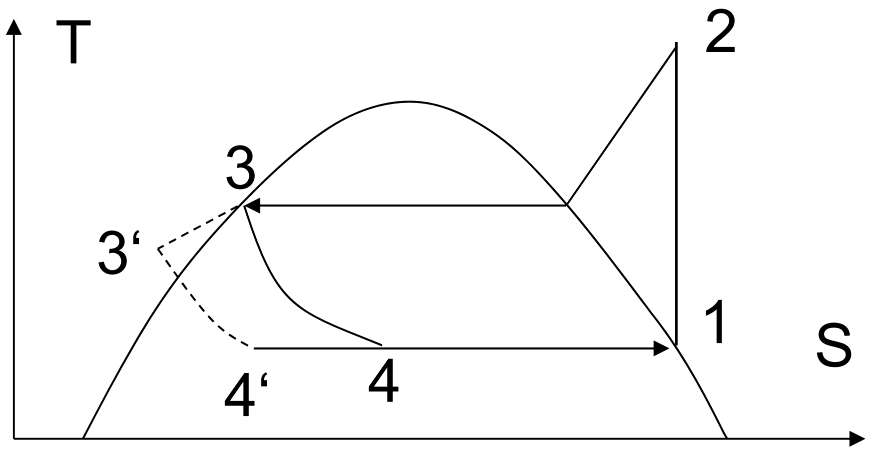
$T_e \uparrow$, COP $\uparrow$;



受设计目的限制

$$W_{s,comp} = H_2 - H_{1'},\ Q_L = H_{1'} - H_{4'}$$

过冷度的影响



受环境的限制

制冷剂(Refrigerants)性质

一、制冷剂热力性质

1. 对应制冷装置工作温度的饱和压力适中；

2. 汽化潜热大；

3. 临界温度应高于环境温度；

4. 蒸汽比体积小，导热系数大；

5. 蒸发压力不低于环境压力，三相点低于制冷循环下限温度。

6. 上、下界限线（在***T-s***图）陡峭，使冷凝更接近定温放热及减少节流引起制冷能力损失。

二、制冷剂其他性质

1.对环境友善；

2.安全无毒；

3.溶油性好，化学稳定性好，等等。

三、蒙特利尔协定书

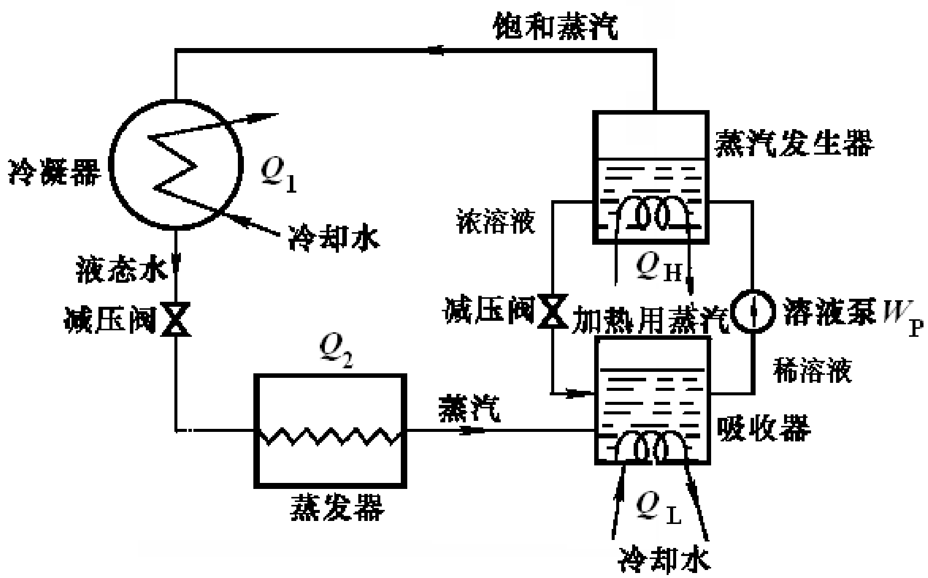
CHCC

HCHC

R134a

其他制冷循环

一、吸收式制冷循环(absorption refrigeration)



$$\mathrm{COP}=\frac{Q_C}{Q_H+W_P}\approx\frac{Q_C}{Q_H}$$

理想条件下

$$w_P=Q_H\eta_t=Q_H\left(1-\frac{T_0}{T_H}\right)$$

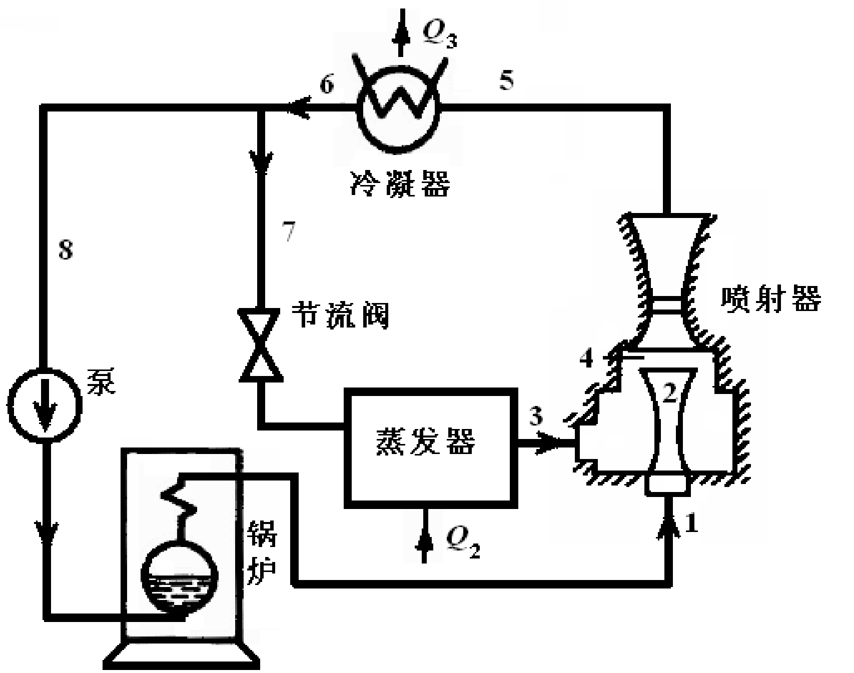
利用此功可获得

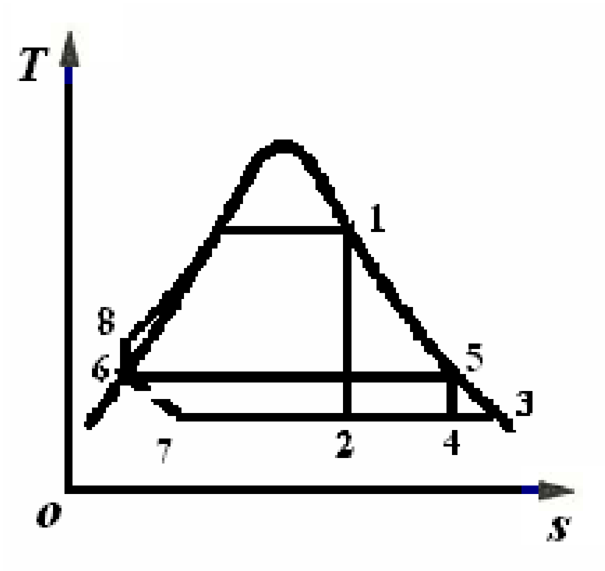
$$Q_{C,\max}=w_P\varepsilon_\kappa$$

$$=Q_H\left(1-\frac{T_0}{T_H}\right)\left(\frac{T_L}{T_0-T_L}\right)$$

$$\mathrm{COP}_{\max}=\frac{Q_{C,\max}}{Q_H}=\frac{T_H-T_0}{T_H}\frac{T_L}{T_0-T_L}$$

二、气流引射式制冷(steam jet refrigeration)





1. 原理及设备流程图

装置工作循环可分成两个循环

制冷蒸汽循环673456

工作蒸汽循环6812456

总循环

每kg制冷量$q_2 = q_{7\text{-}3} = h_3\text{-}h_7$

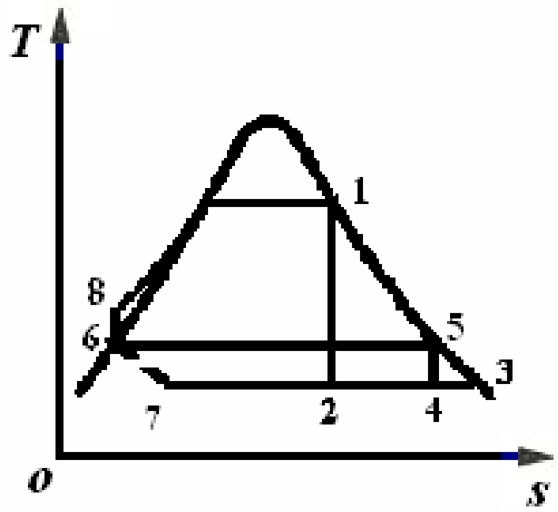
每kg冷凝器放出热量

$q_{冷} = q_{5\text{-}6} = h_6\text{-}h_5$

每kg工作蒸汽吸热量

$q_1 = q_{8\text{-}1} = h_1\text{-}h_8$

2. 能量利用系数



$$\xi = \frac{Q_2}{Q} = \frac{m_1\left(h_3 - h_7\right)}{m_2\left(h_1 - h_8\right)}$$

工作蒸汽及功量最终均以热量形式在冷凝器中向环境散失，构成能质下降以弥补制冷蒸汽的能质提高。

热泵循环(heat pump)

一、简介

二、 供热系数

$$\varepsilon' = \frac{w_{\text{net}} + q_2}{w_{\text{net}}} = 1 + \frac{q_2}{w_{\text{net}}} > 1$$

$$\left.\begin{array}{ll}\text{工业锅炉：} & \eta_{\mathrm{B}} = 0.7 \\ \text{电厂热效率：} & \eta_{\mathrm{t}} = 0.35 \\ \text{热泵供暖系数：} & \varepsilon' = 3\end{array}\right\} \Longrightarrow \left\{\begin{array}{l} Q = Q_a \eta_{\mathrm{B}} = 0.7 Q_a \\ Q = Q_a \eta_{\mathrm{t}} \varepsilon' = 1.05 Q_a \end{array}\right.$$

三、热泵供暖

华北某市热电厂排出水温**30**℃以上，余热量 $3.4\times10^{9}\,\mathrm{kJ/h}$，如以热泵回收，能满足**1**千万**m**²建筑物采暖，一年节煤**100**万吨。

使用限制：

1.ε'与T_R-T_0反比，所以北方ε'比较低。

2.制冷，供暖联合运行工质性质要求苛刻。

3.环境热源土壤，水，空气分别存在λ小、凝固、腐蚀等。

例：热泵, W_s=10kW, T_L=0℃, T_H=90 ℃, Q_{hmax}=?, Q_{lmax}=?

解: 利用卡诺循环获得Q_{hmax}和Q_{lmax}

$$\mathrm{COP}_{C,heat\ pump} = \frac{T_H}{T_H - T_L} = \frac{363}{363-273} = 4.033$$

$$Q_H = W_s.COP_c = 10\times 4.033 = 40.33\,kW$$

$$|Q_L| = |Q_H| - |W_s| = 40.33 - 10 = 30.33\,kW$$

$$\frac{|Q_L|}{|Q_H|} = \frac{30.33}{40.33} = 0.752$$

$$\mathrm{COP}_{C,refrigeration} = \frac{T_L}{T_H - T_L} = \frac{273}{363-273} = 3.033 \quad (\mathrm{COP}_H = \mathrm{COP}_R + 1)$$

$$Q_L = W_s \cdot \mathrm{COP}_c = 10\times 3.033 = 30.33\,kW$$

$$|Q_H| = |Q_L| + |W_s| = 40.33 + 10 = 40.33\,kW$$

Home Works

9.2, 9.10