第九章 气体动力循环

Gas power cycles

9–1 分析动力循环的一般方法

一、分析动力循环的目的

在热力学基本定律的基础上分析循环能量转化的经济性，寻求提高经济性的方向及途径。

二、分析动力循环的一般步骤

1. 实际循环（复杂不可逆） —抽象、简化→ 可逆理论循环

分析可逆循环 ——→ 影响经济性的主要因素和可能改进途径

—指导改善→ 实际循环

2. 分析实际循环与理论循环的偏离程度，找出实际损失的部位、大小、原因及改进办法

三、分析动力循环的方法

1. 第一定律分析法 —— 以第一定律为基础，以能量的数量守恒为立足点。

2. 第二定律分析法 —— 综合第一定律和第二定律从能量的数量和质量分析。

- 熵分析法 —— 熵产 —— 作功能力损失
- 分析法 —— 火用损 —— 火用效率

四、内部热效率η_i(internal thermal efficiency)

——不可逆过程中实际作功量和循环加热量之比

$$\eta_i = \frac{w_{net,act}}{q_1} = \frac{\eta_T w_{net}}{q_1} = \eta_T \eta_t$$

其中

$$\eta_t = \frac{w_{net}}{q_1}$$ 与实际循环相当的内可逆循环的热效率

$$\eta_T = \frac{w_{net,act}}{w_{net}}$$ 相对内部效率(internal engine efficiency) 反映内部摩擦引起的损失

五、空气标准假设(the air-standard hypothesis)

- 气体动力循环中工作流体 ⟶ 理想气体 ⟶ 空气 ⟶ 定比热
- 燃烧和排气过程 ⟶ 吸热和放热过程
- 燃料燃烧造成各部分气体成分及质量改变忽略不计

9–2　活塞式内燃机实际循环的简化

一、活塞式内燃机(internal combustion engine)简介

1.　分类:

按燃料:　煤气机(**gas engine**)
汽油机(**gasoline engine;　petrol engine**)
柴油机(**diesel engine**)

按点火方式:　点燃式(**spark ignition engine**)
压燃式(**compression ignition engine**)

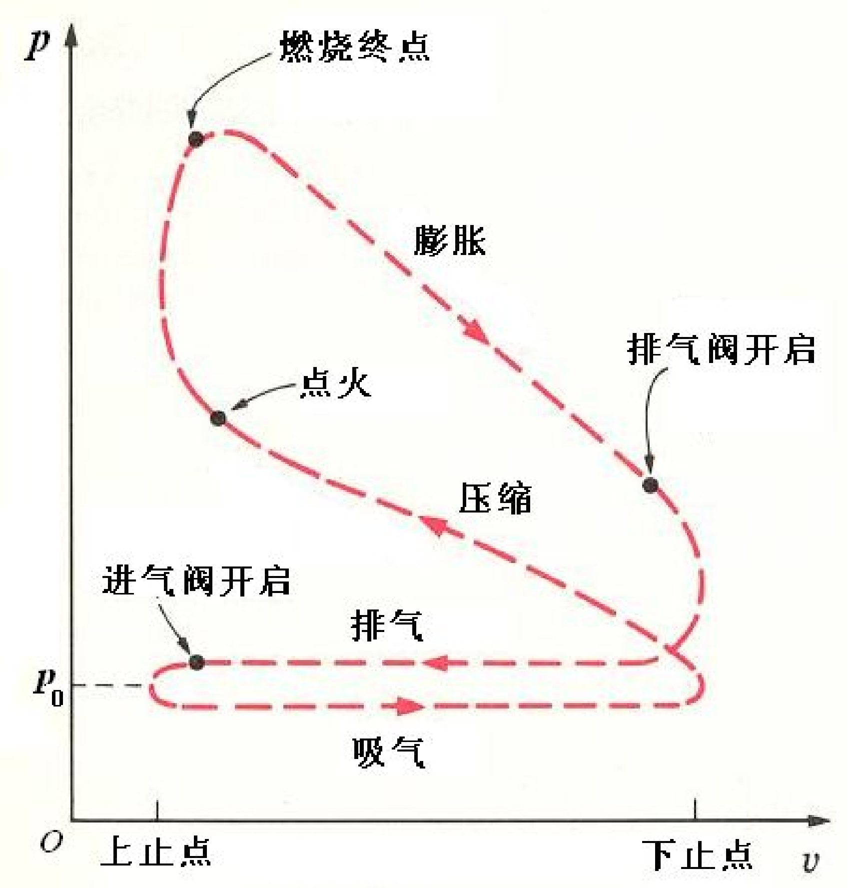
按冲程:　二冲程(**two-stroke**)
四冲程(**four-stroke**)

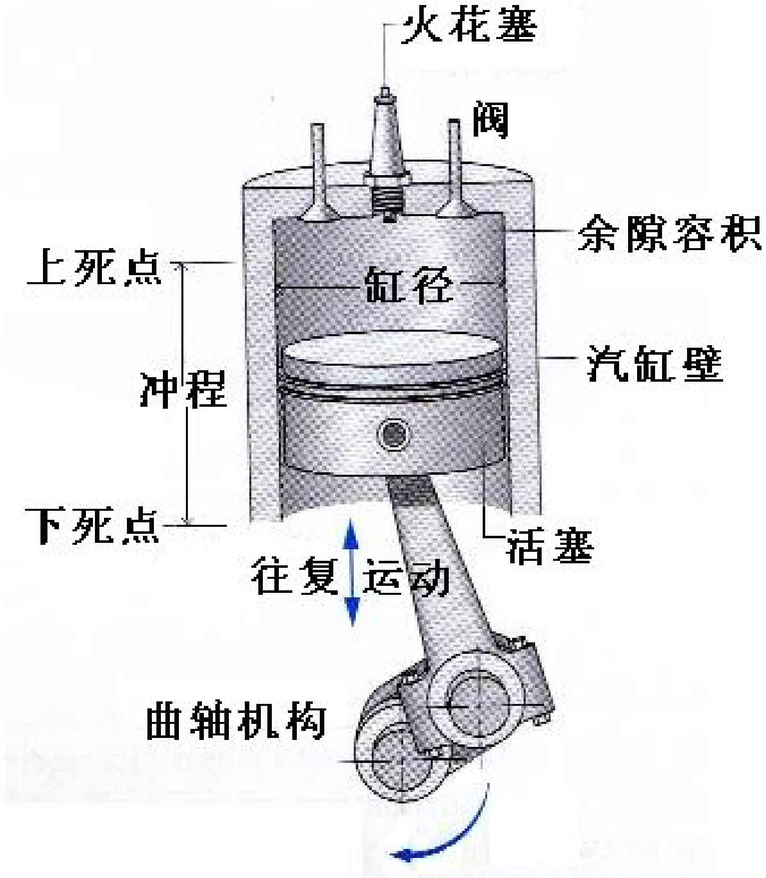
2．活塞式内燃机循环特点

开式循环(open cycle);

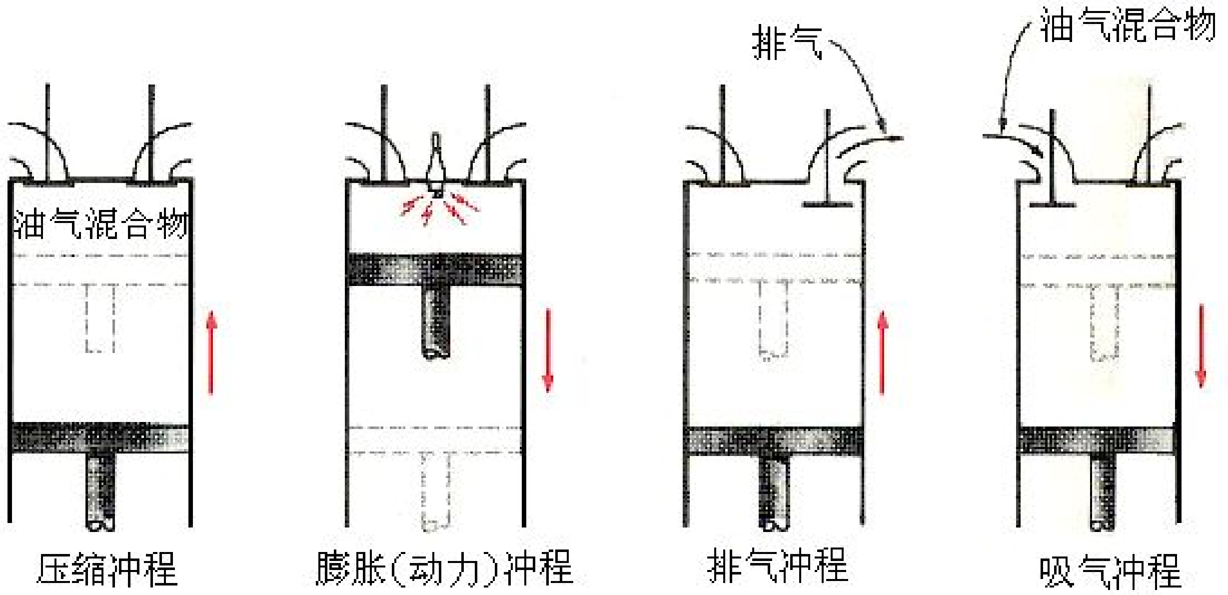
燃烧、传热、排气、膨胀、压缩均为不可逆;

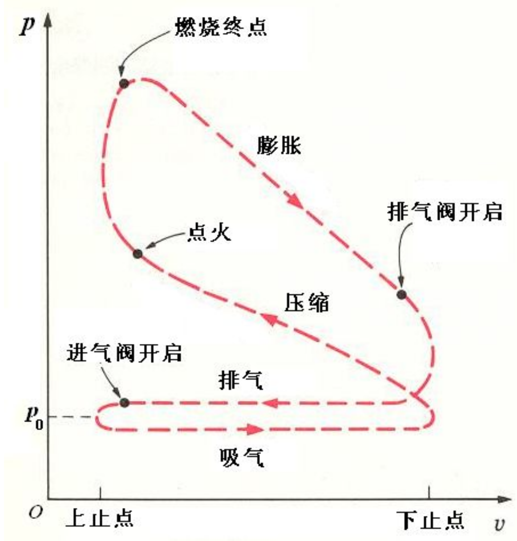
各环节中工质质量、成分稍有变化。

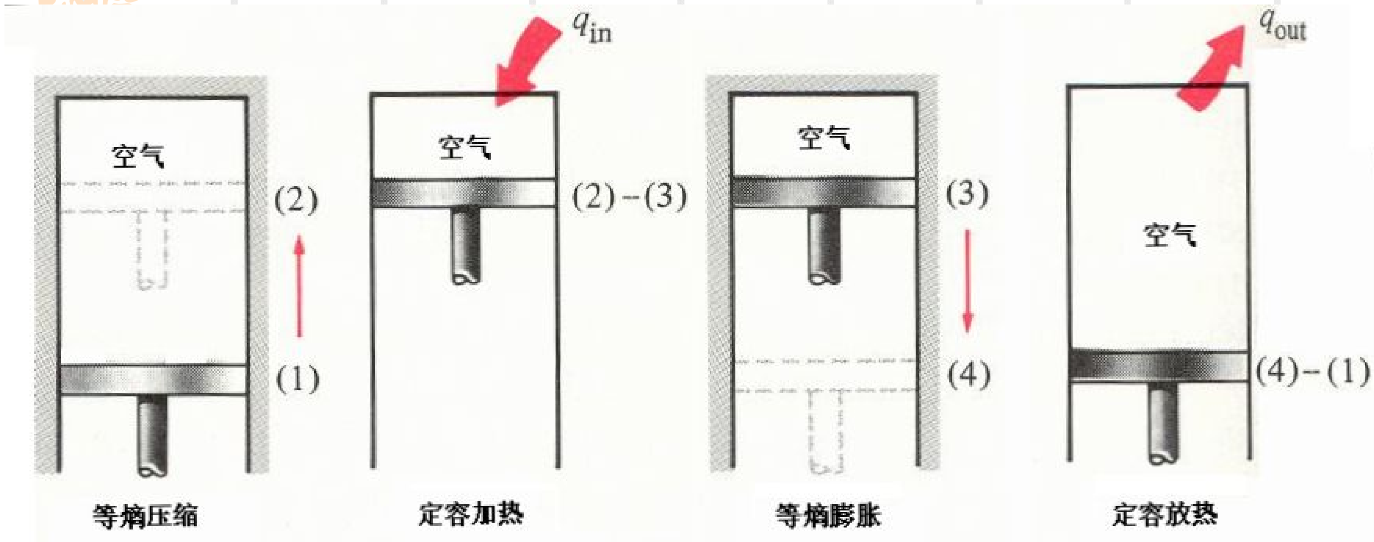




二、活塞式内燃机循环的简化

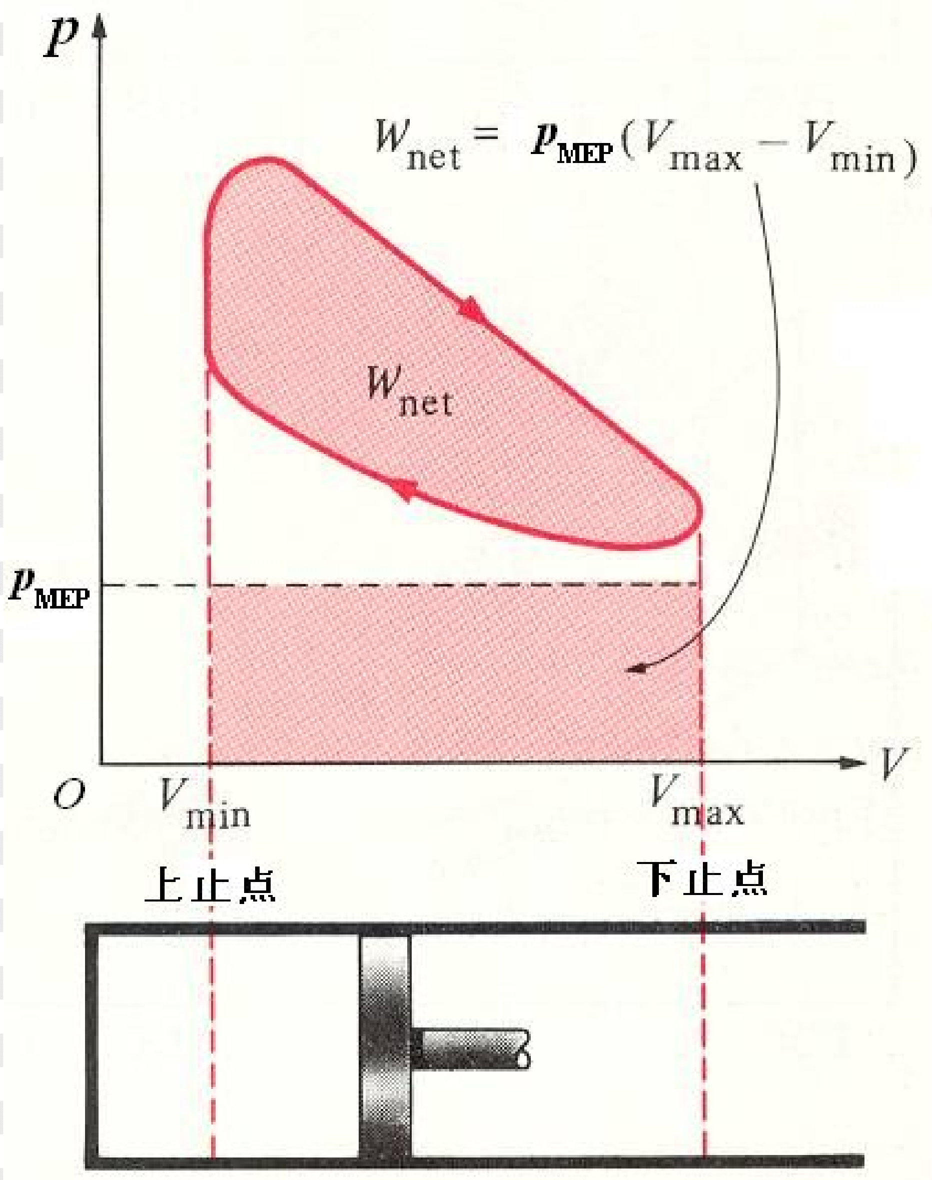






三、平均有效压力(mean effective pressure)

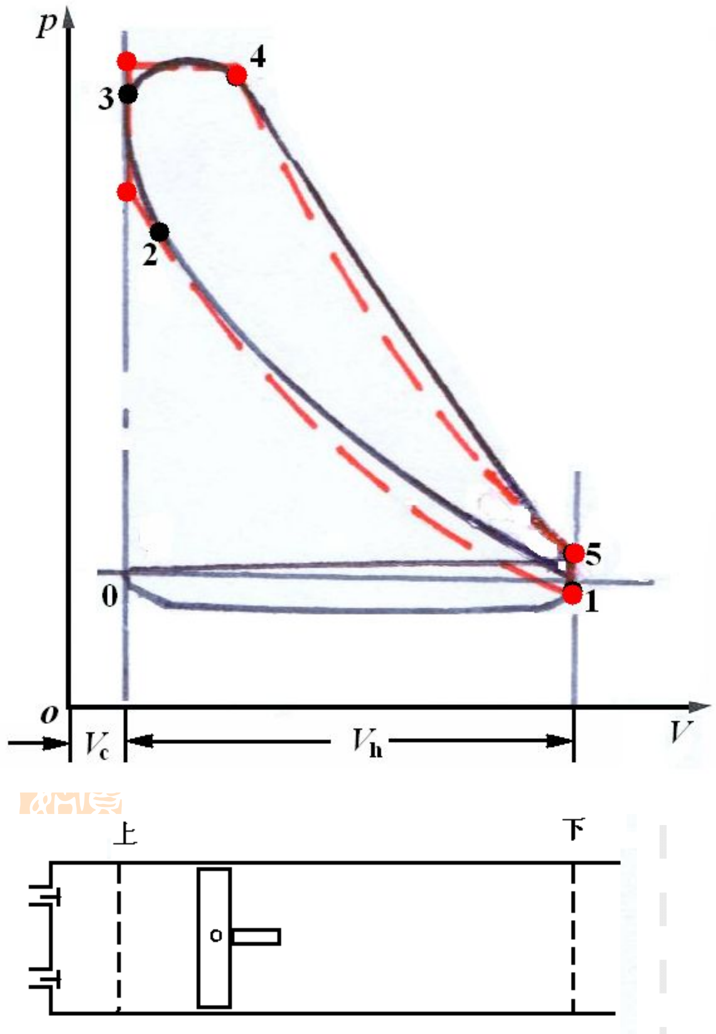
$$p_{\mathrm{MEP}} = \frac{W_{\mathrm{net}}}{V_{\mathrm{h}}}$$



9–3 活塞式内燃机的理想循环

一、混合加热理想循环

（dual combustion cycle）

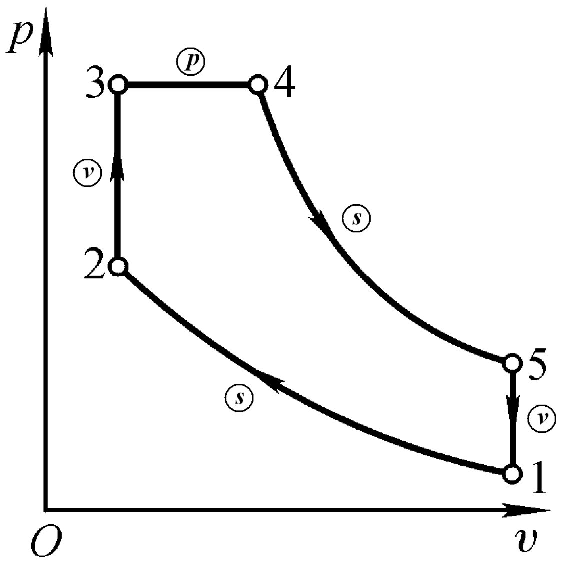


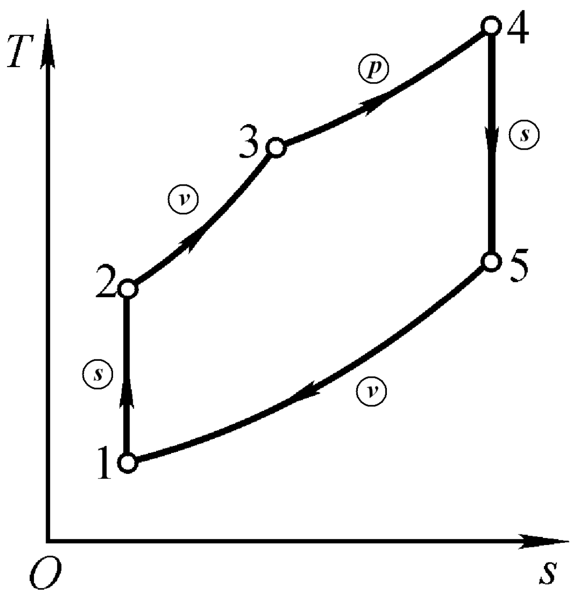
0→1　吸气
1→2　压缩
2→3　喷油、燃烧
3→4　燃烧
4→5　膨胀作功
5→0　排气

简化：引用空气标准假设

- 燃烧→2-3等容吸热+3-4定压吸热
- 排气→5-1等容放热
- 压缩、膨胀→1-2及4-5等熵过程
- 吸、排气线→重合、忽略
- 燃油质量→忽略
- 燃气成分改变→忽略

1. *p-v*图及*T-s*图





1→2 等熵压缩；2→3 等容吸热；
3→4 定压吸热；4→5 等熵膨胀；
5→1 定容放热

特性参数：

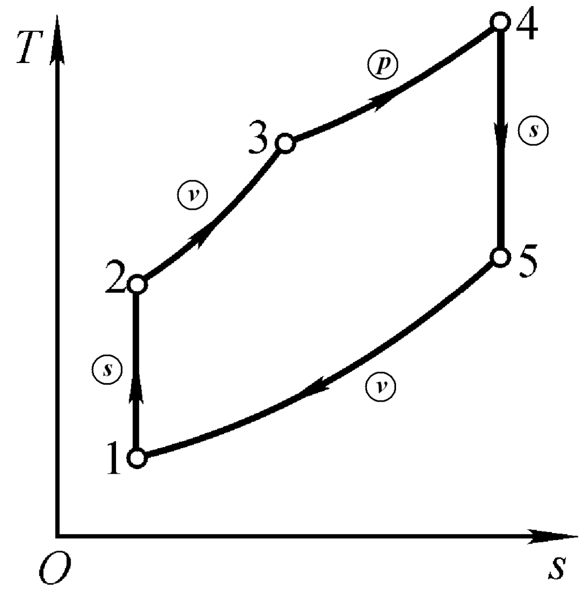
压缩比(compression ratio) $\varepsilon = \dfrac{v_1}{v_2}$

定容增压比(pressure ratio) $\lambda = \dfrac{p_3}{p_2}$

定压预胀比 (cutoff ratio) $\rho = \dfrac{v_4}{v_3}$

2. 循环热效率

$$\eta_t = \frac{w_{net}}{q_1}$$



$$w_{net} = w_{1-2} + w_{2-3} + w_{3-4} + w_{4-5} + w_{5-1}$$
$$= w_{1-2} + w_{3-4} + w_{4-5}$$

$$= \frac{R_g}{\kappa - 1} T_1 \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{\kappa-1}{\kappa}} \right] + p_3 (v_4 - v_3) + \frac{R_g}{\kappa - 1} T_4 \left[1 - \left(\frac{p_5}{p_4} \right)^{\frac{\kappa-1}{\kappa}} \right]$$

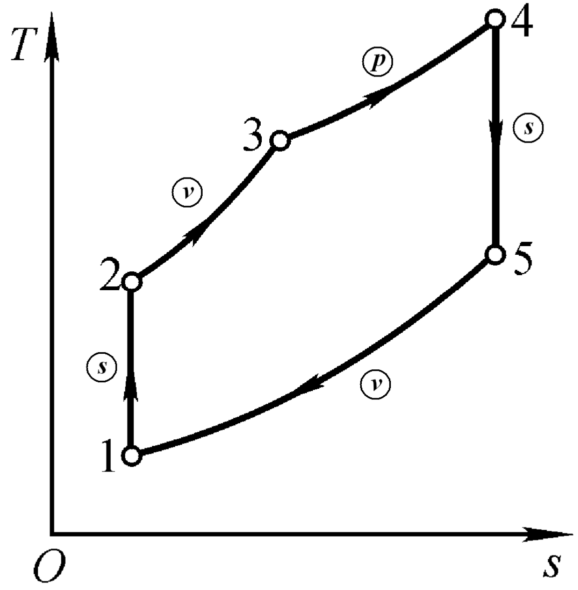
或 $w_{net} = q_{net} = q_1 - q_2$

$$q_1 = q_{2-3} + q_{3-4} = c_V (T_3 - T_2) + c_p (T_4 - T_3)$$

$$q_2 = q_{5-1} = c_V (T_5 - T_1)$$

$$\eta_t = 1 - \frac{q_2}{q_1} = 1 - \frac{T_5 - T_1}{(T_3 - T_2) + \kappa (T_4 - T_3)}$$

利用 ε、λ、ρ 表示 η_t



$1 \rightarrow 2$ $\quad T_2 = T_1 \left(\frac{v_1}{v_2}\right)^{\kappa-1} = T_1 \varepsilon^{\kappa-1}$

$2 \rightarrow 3$ $\quad T_3 = T_2 \frac{p_3}{p_2} = T_1 \lambda \varepsilon^{\kappa-1}$

$3 \rightarrow 4$ $\quad T_4 = T_3 \frac{v_4}{v_3} = T_1 \rho \lambda \varepsilon^{\kappa-1}$

$5 \rightarrow 1$ $\quad T_5 = T_1 \frac{p_5}{p_1}$

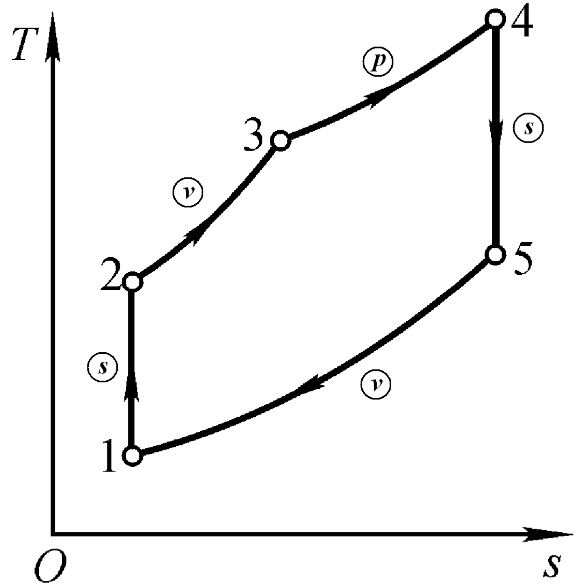
求 $\dfrac{p_5}{p_1}$

$$p_1 v_1^{\kappa} = p_2 v_2^{\kappa}\ ;\quad p_5 v_5^{\kappa} = p_4 v_4^{\kappa}$$

两式相除，考虑到

$$p_4 = p_3 \quad v_1 = v_5 \quad v_2 = v_3$$

$$\frac{p_5}{p_1} = \frac{p_4}{p_2}\left(\frac{v_4}{v_3}\right)^{\kappa} = \frac{p_3}{p_2}\left(\frac{v_4}{v_3}\right)^{\kappa} = \lambda\rho^{\kappa}$$

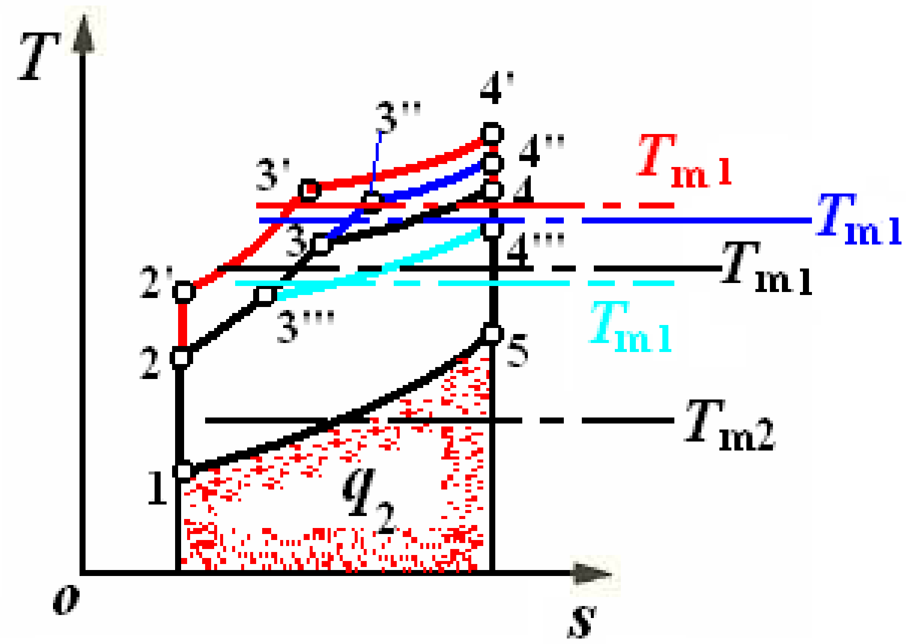


$$T_5 = T_1 \frac{p_5}{p_1} \qquad T_5 = T_1 \lambda \rho^{\kappa}$$

把T_2、T_3、T_4和T_5代入

$$\eta_t = 1 - \frac{T_5 - T_1}{(T_3 - T_2) + \kappa(T_4 - T_3)} \qquad \eta_t = 1 - \frac{\lambda\rho^{\kappa} - 1}{\varepsilon^{\kappa-1}\left[(\lambda - 1) + \kappa\lambda(\rho - 1)\right]}$$

讨论:



a) $\varepsilon\uparrow \quad \eta_t\uparrow$

b) $\lambda\uparrow \quad \eta_t\uparrow$

c) $\rho\uparrow \quad \eta_t\downarrow$

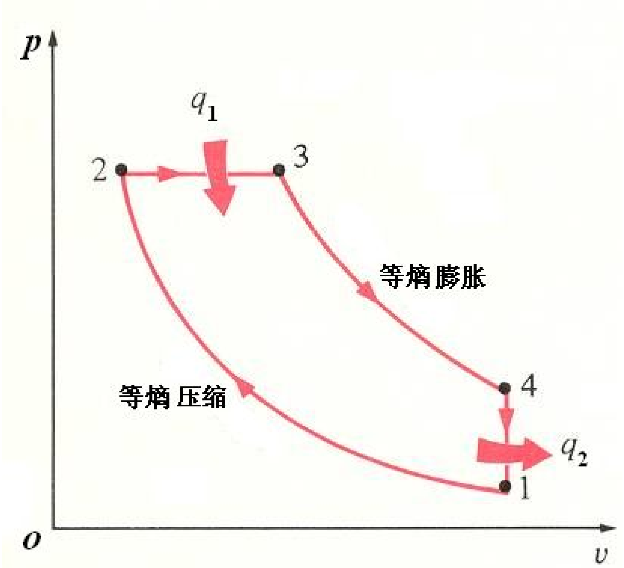
归纳:

a.吸热前压缩气体，提高平均吸热温度是提高热效率的重要措施，是卡诺循环，第二定律对实际循环的指导。

b.利用T-s图分析循环较方便。

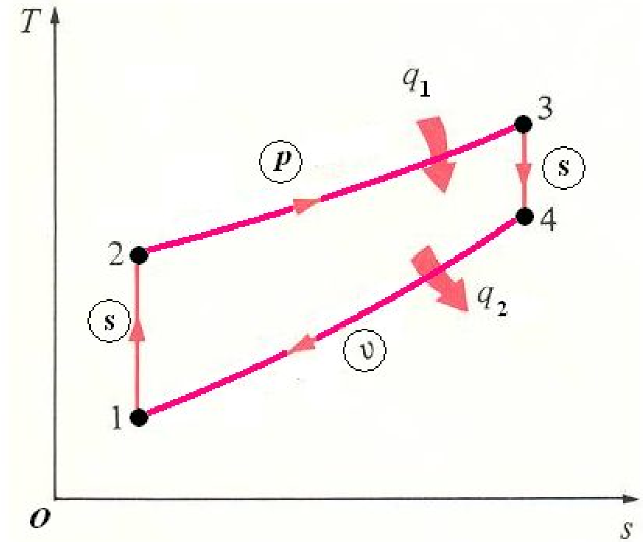
c.同时考虑q_1和q_2或T_{1m}和T_{2m}平均。

二、定压加热理想循环(Diesel cycle)



$$\varepsilon = \frac{v_1}{v_2}$$

$$\rho = \frac{v_3}{v_2}$$



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

$$q_2 = c_V\left(T_4 - T_1\right)$$

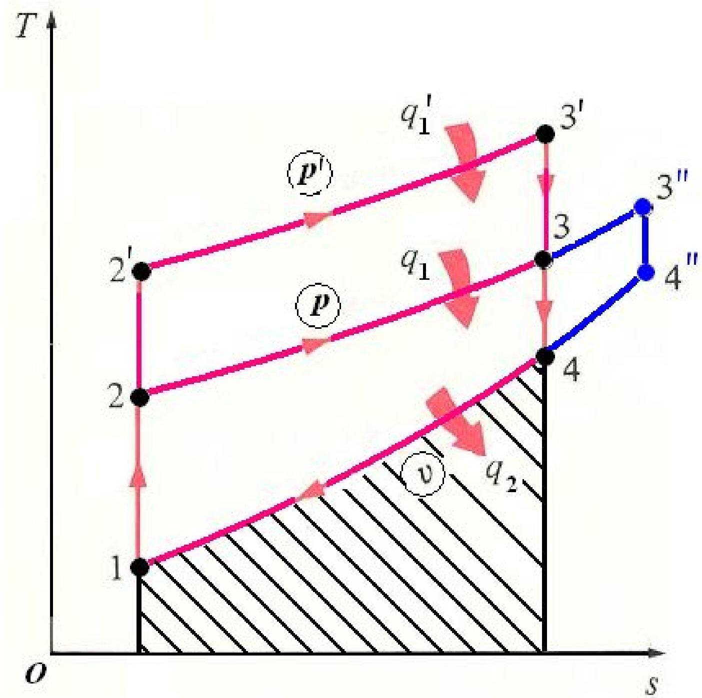
$$q_1 = c_p\left(T_3 - T_2\right)$$

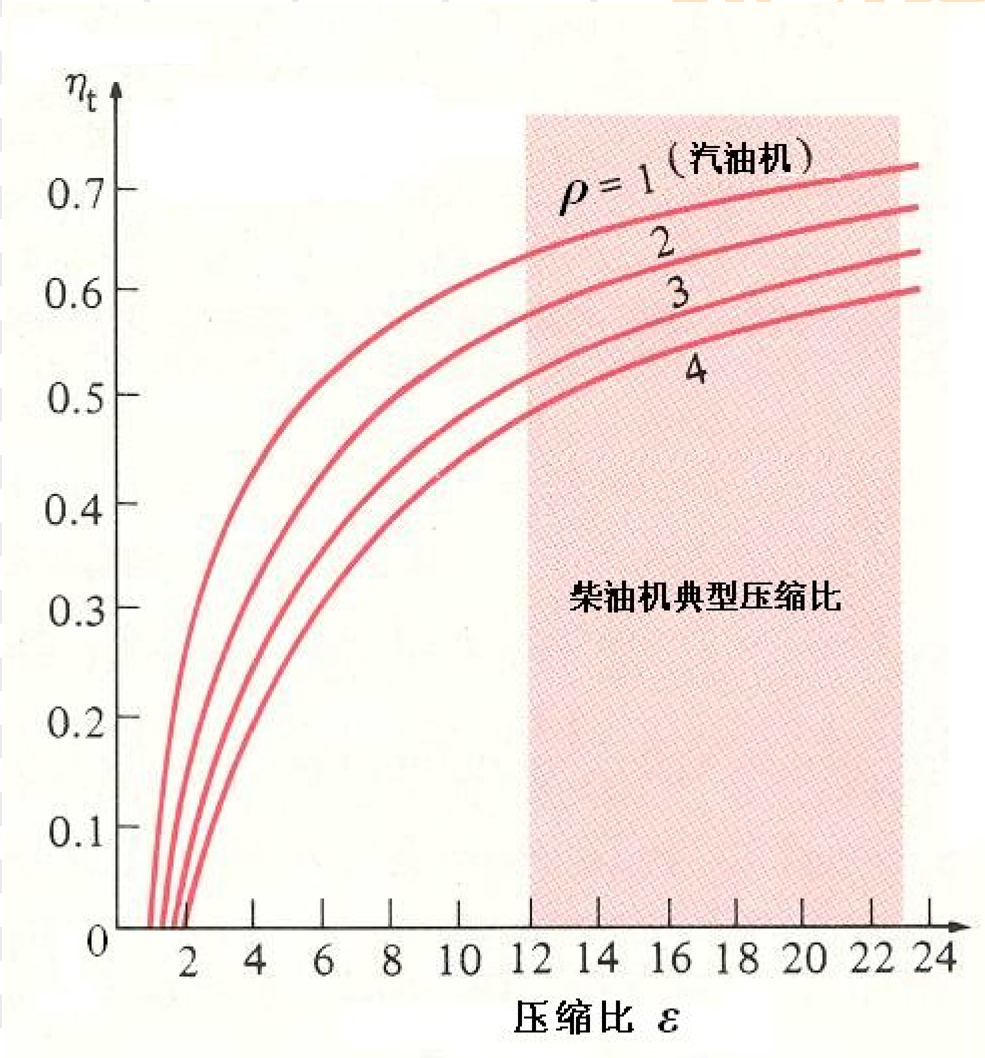
$$\eta_t = 1 - \frac{T_4 - T_1}{\kappa\left(T_3 - T_2\right)}$$

$$\eta_t = 1 - \frac{\lambda\rho^{\kappa} - 1}{\varepsilon^{\kappa-1}\left[\left(\lambda - 1\right) + \kappa\lambda\left(\rho - 1\right)\right]}$$

$$\lambda = 1 \Rightarrow \eta_t = 1 - \frac{\rho^{\kappa} - 1}{\kappa\varepsilon^{\kappa-1}\left(\rho - 1\right)}$$

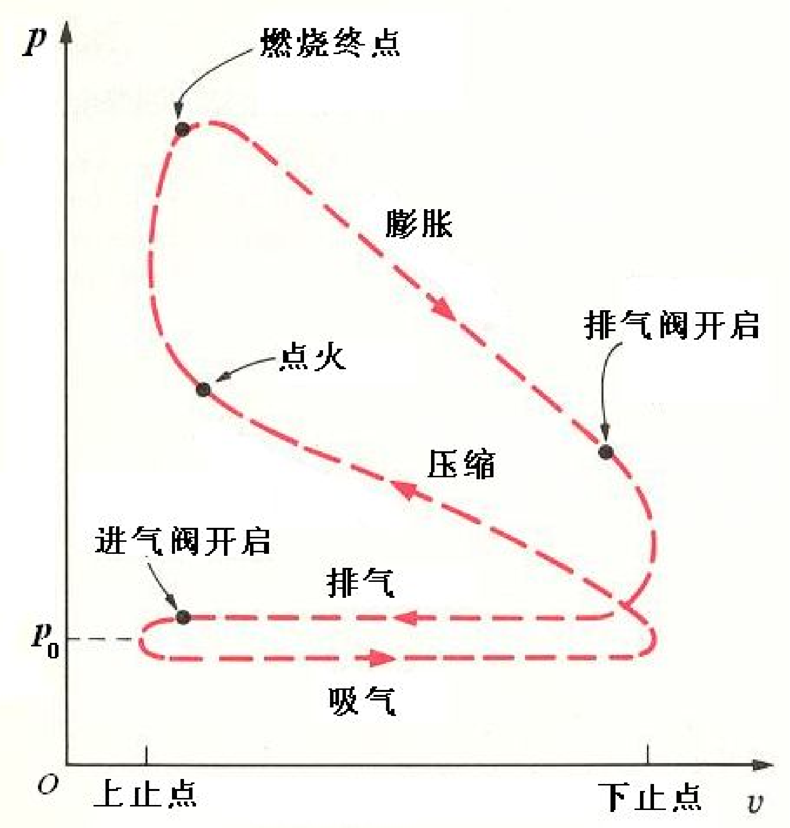
讨论： $a)\ \varepsilon\uparrow\ \ \eta_t\uparrow\ \ w_{net}\uparrow$　　$b)\ \rho\uparrow\ \ \eta_t\downarrow\ \ w_{net}\uparrow$

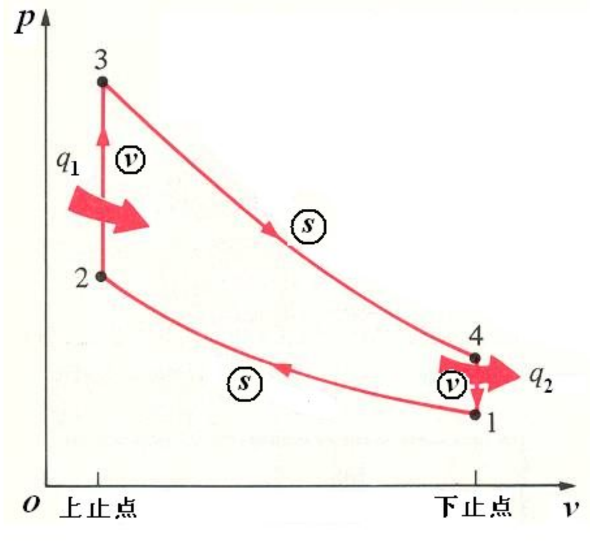


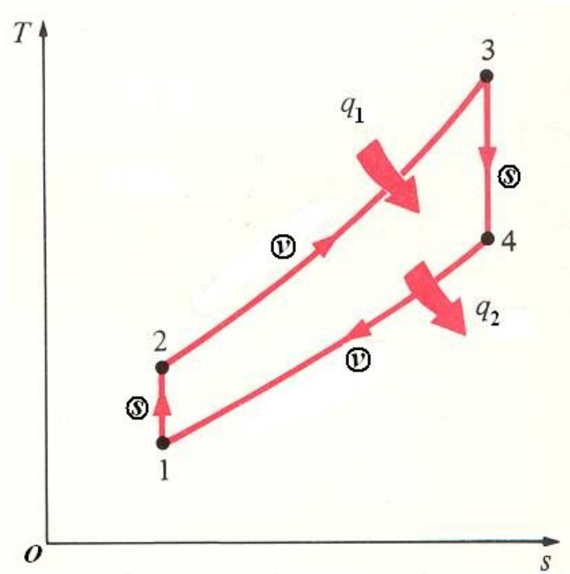


c) 重负荷（$\rho\uparrow$，$q_1\uparrow$）时内部热效率下降，除$\rho\uparrow$外还有因温度上升而使$\kappa\downarrow$，造成热效率下降

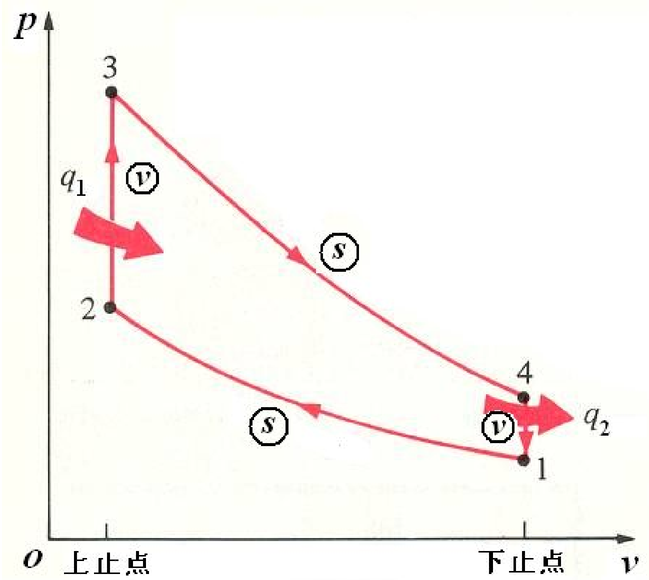
三、定容加热理想循环(Otto cycle)

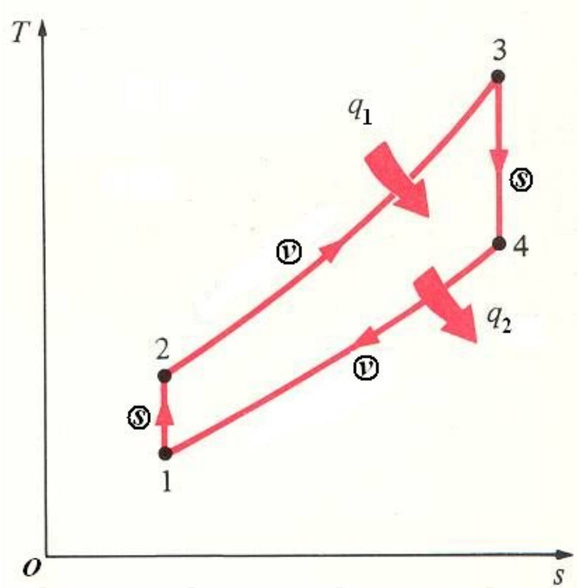






$$\varepsilon = \frac{v_1}{v_2} \qquad \lambda = \frac{p_3}{p_2}$$





$$\varepsilon=\frac{v_1}{v_2}$$

$$\lambda=\frac{p_3}{p_2}$$

$$q_1=c_V\left(T_3-T_2\right)$$

$$\eta_t=1-\frac{q_2}{q_1}=1-\frac{T_4-T_1}{T_3-T_2}$$

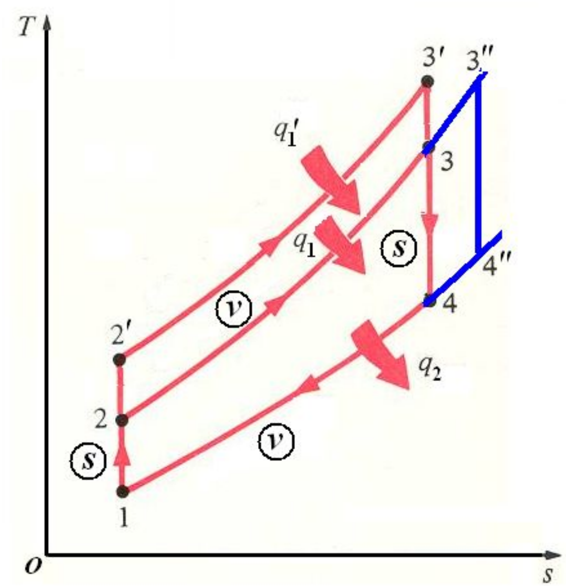
$$q_2=c_V\left(T_4-T_1\right)$$

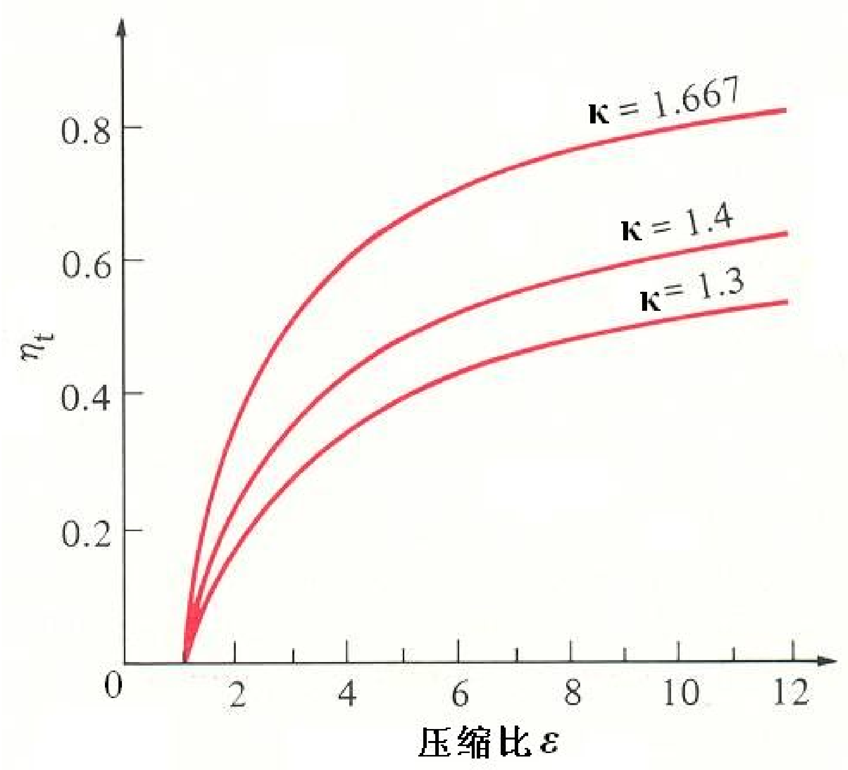
$$\rho=1\Rightarrow\eta_t=1-\frac{\lambda\rho^{\kappa}-1}{\varepsilon^{\kappa-1}\left[\left(\lambda-1\right)+\kappa\lambda\left(\rho-1\right)\right]}=1-\frac{1}{\varepsilon^{\kappa-1}}$$

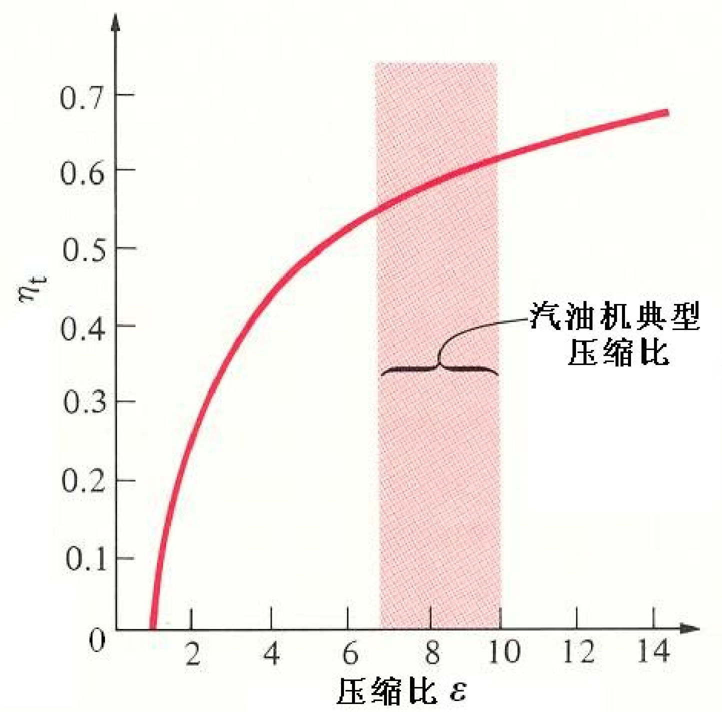
讨论: a) ε ↑ η_t ↑

b) λ↑; η_t不变，但w_{net}↑

c) 重负荷（q_1↑）时内部热效率下降，因温度上升使κ↓，造成热效率下降

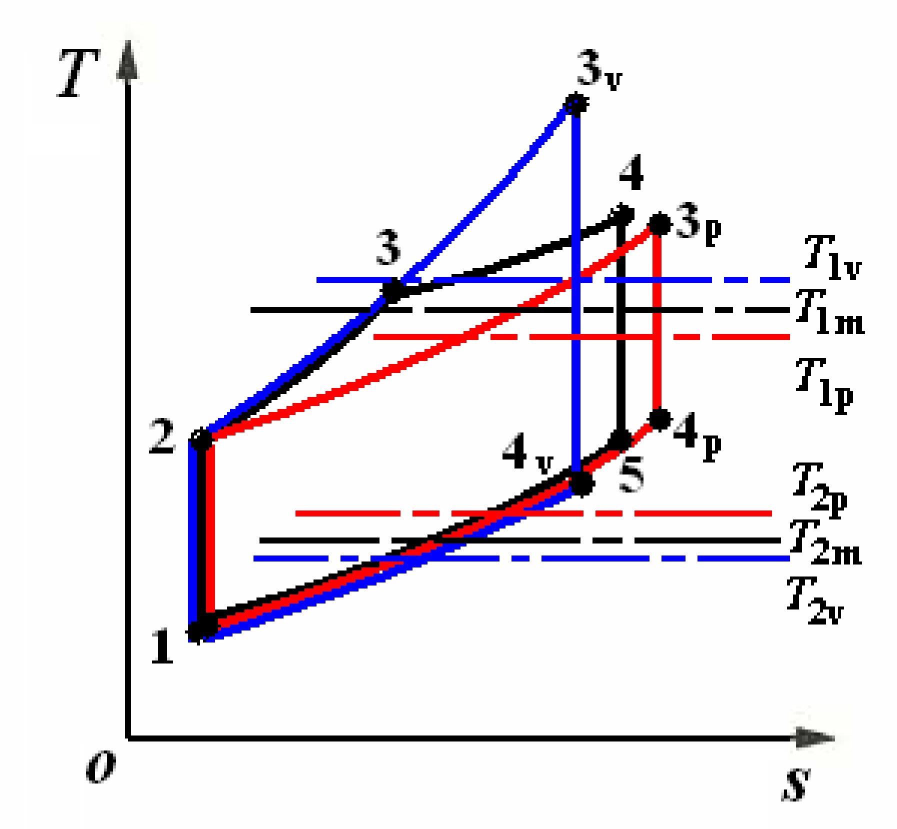






9–4 活塞式内燃机各种理想循环的热力学比较

一、压缩比相同，吸热量相同时的比较



$$q_{1v} = q_{1m} = q_{1p}$$

$$q_{2v} < q_{2m} < q_{2p}$$

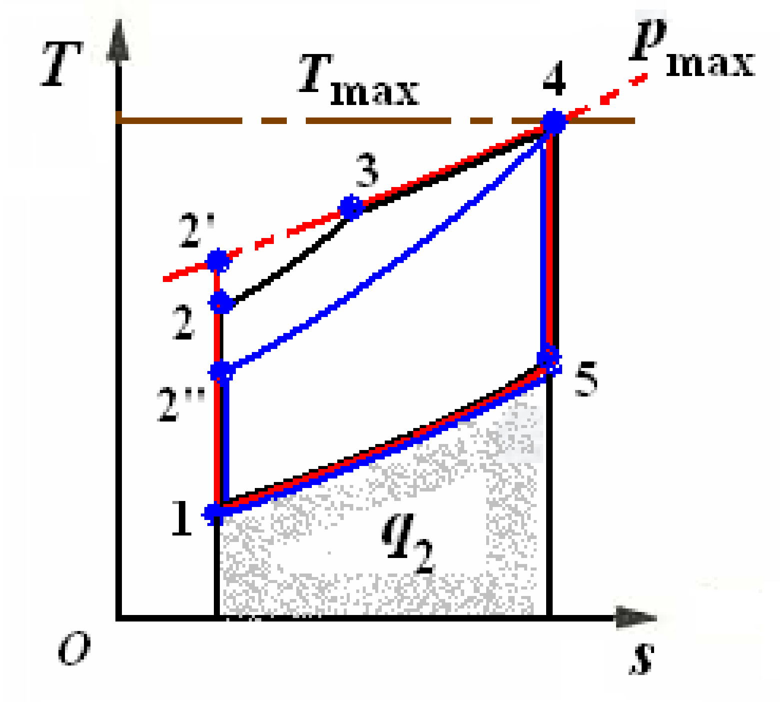
$$\eta_{tv} > \eta_{tm} > \eta_{tp}$$

或

$$\overline{T}_{2v} < \overline{T}_{2m} < \overline{T}_{2p}$$

$$\overline{T}_{1v} > \overline{T}_{1m} > \overline{T}_{1p}$$

二、循环p_{max}、T_{max}相同时的比较



$$q_{2p} = q_{2m} = q_{2v}$$

$$q_{1p} > q_{2m} > q_{2v}$$

$$\eta_{t,p} > \eta_{t,m} > \eta_{t,v}$$

或

$$\overline{T}_{2p} = \overline{T}_{2m} = \overline{T}_{2v}$$

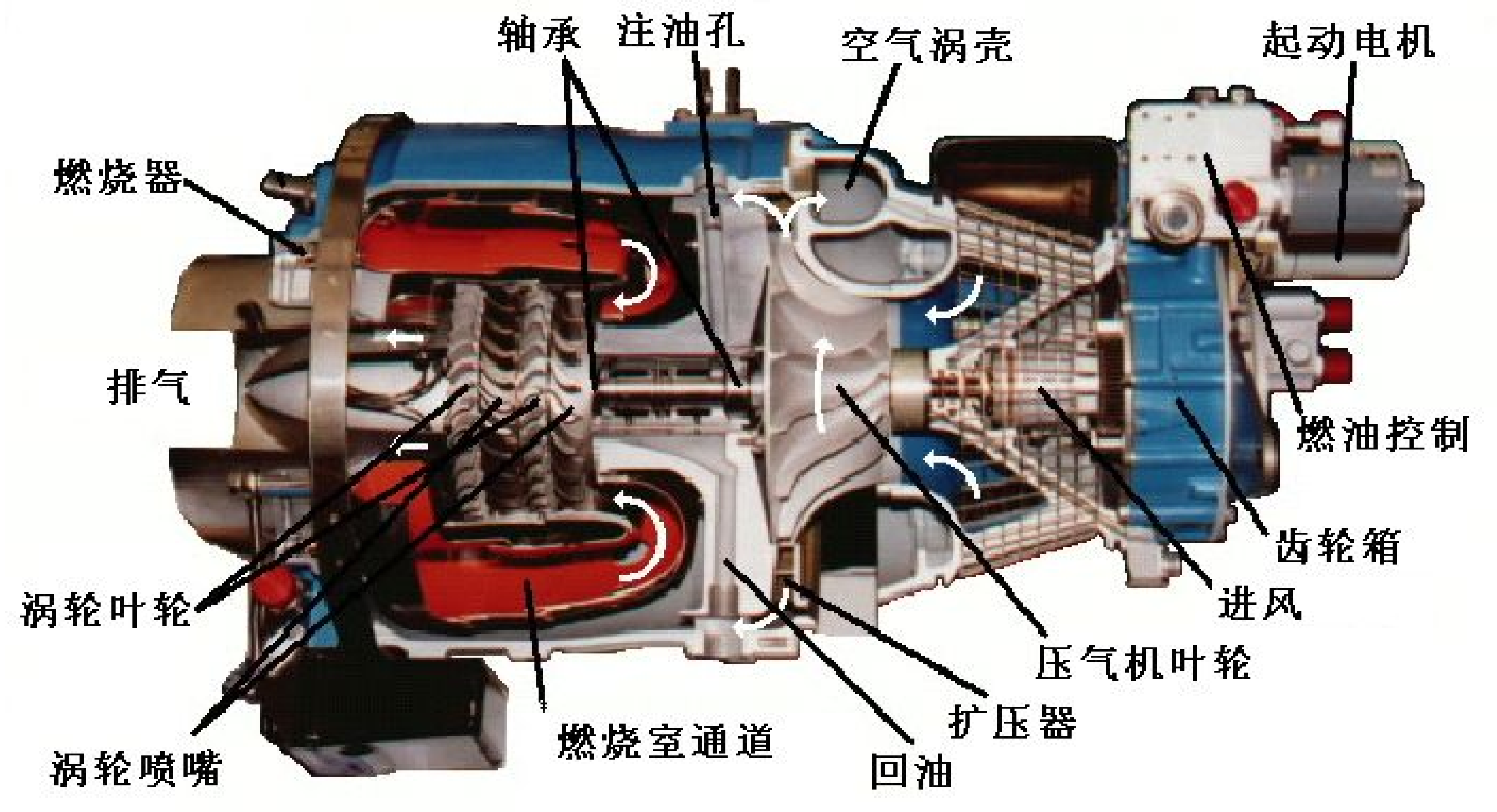
$$\overline{T}_{1p} > \overline{T}_{1m} > \overline{T}_{1v}$$

例A470299

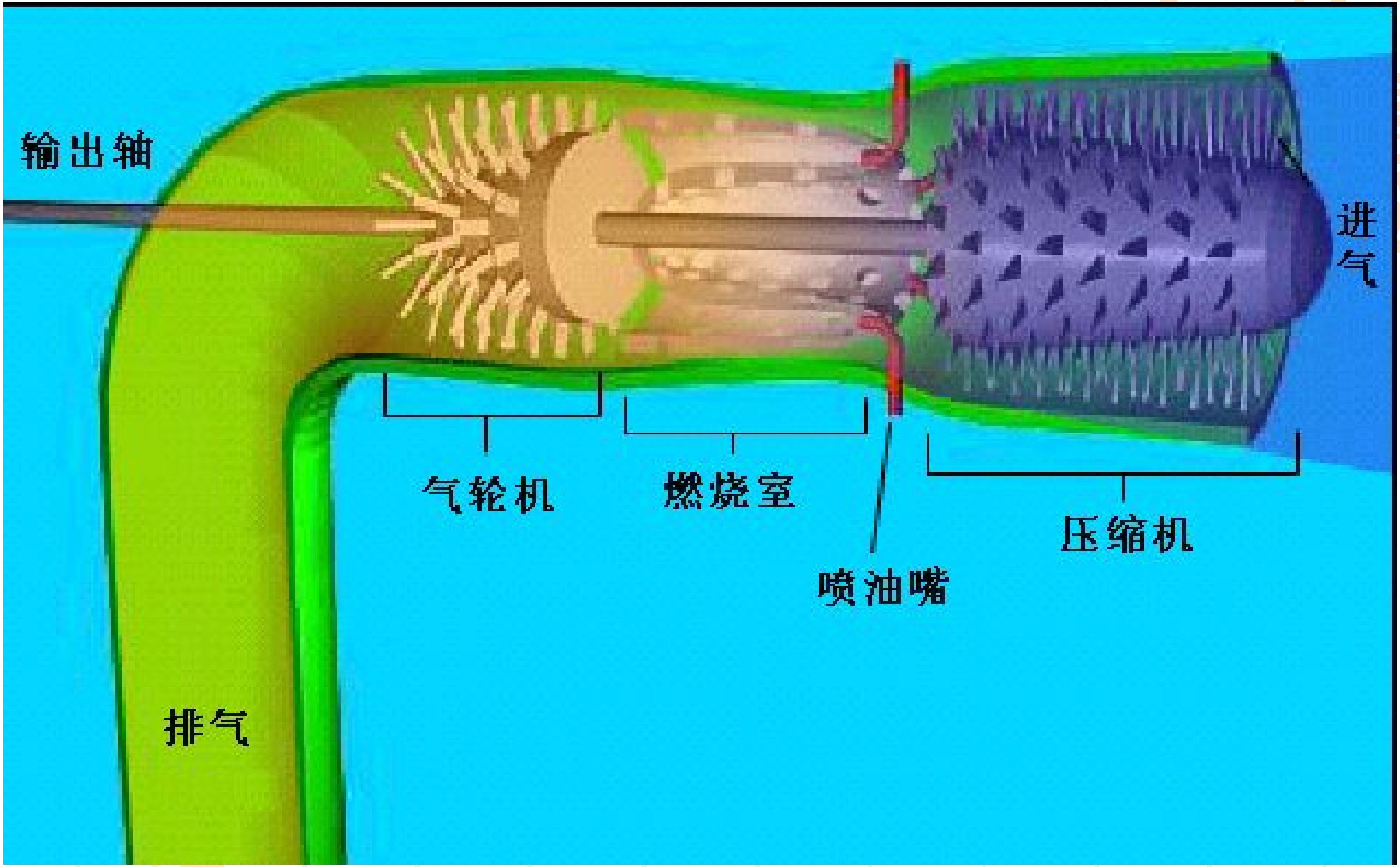
例A447277

9-5 燃气轮机装置循环

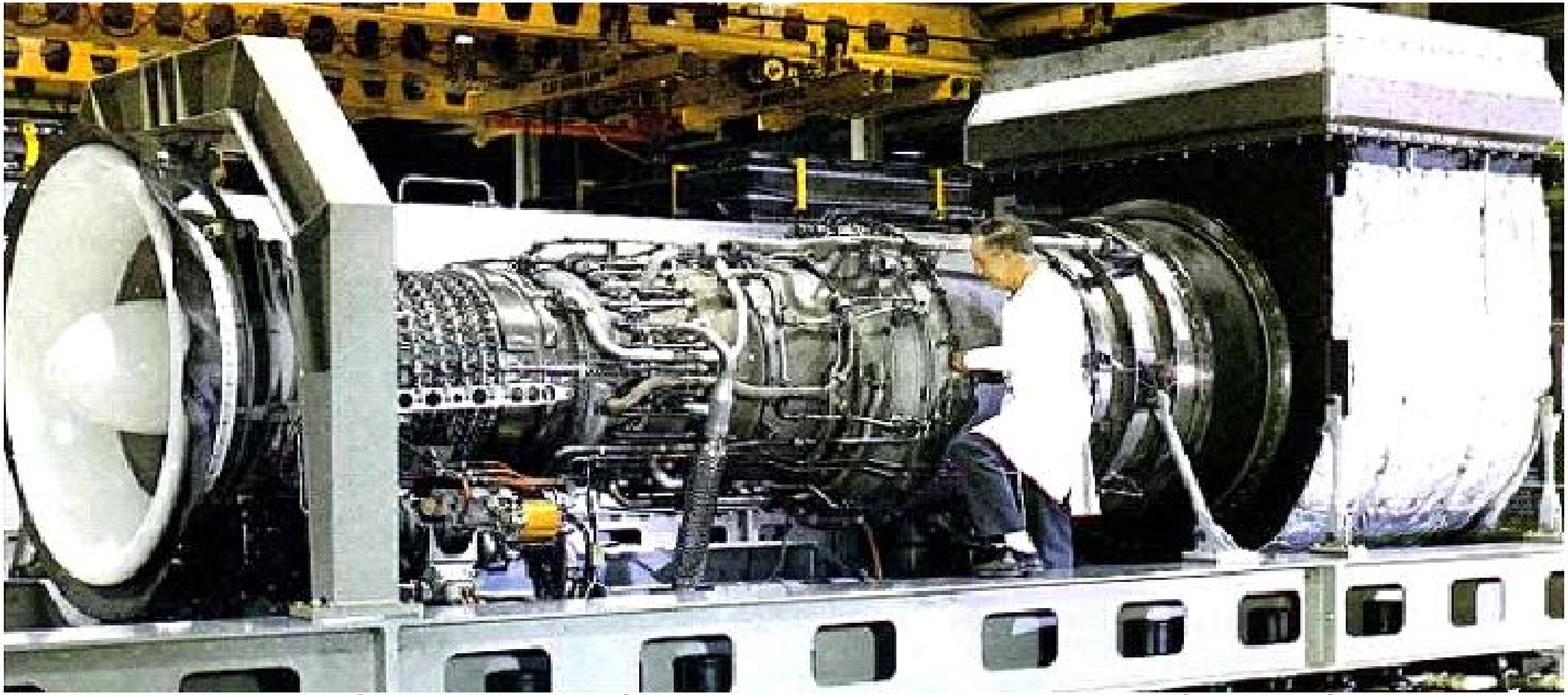
一、燃气轮机(gas turbine)装置简介



小型燃气轮机



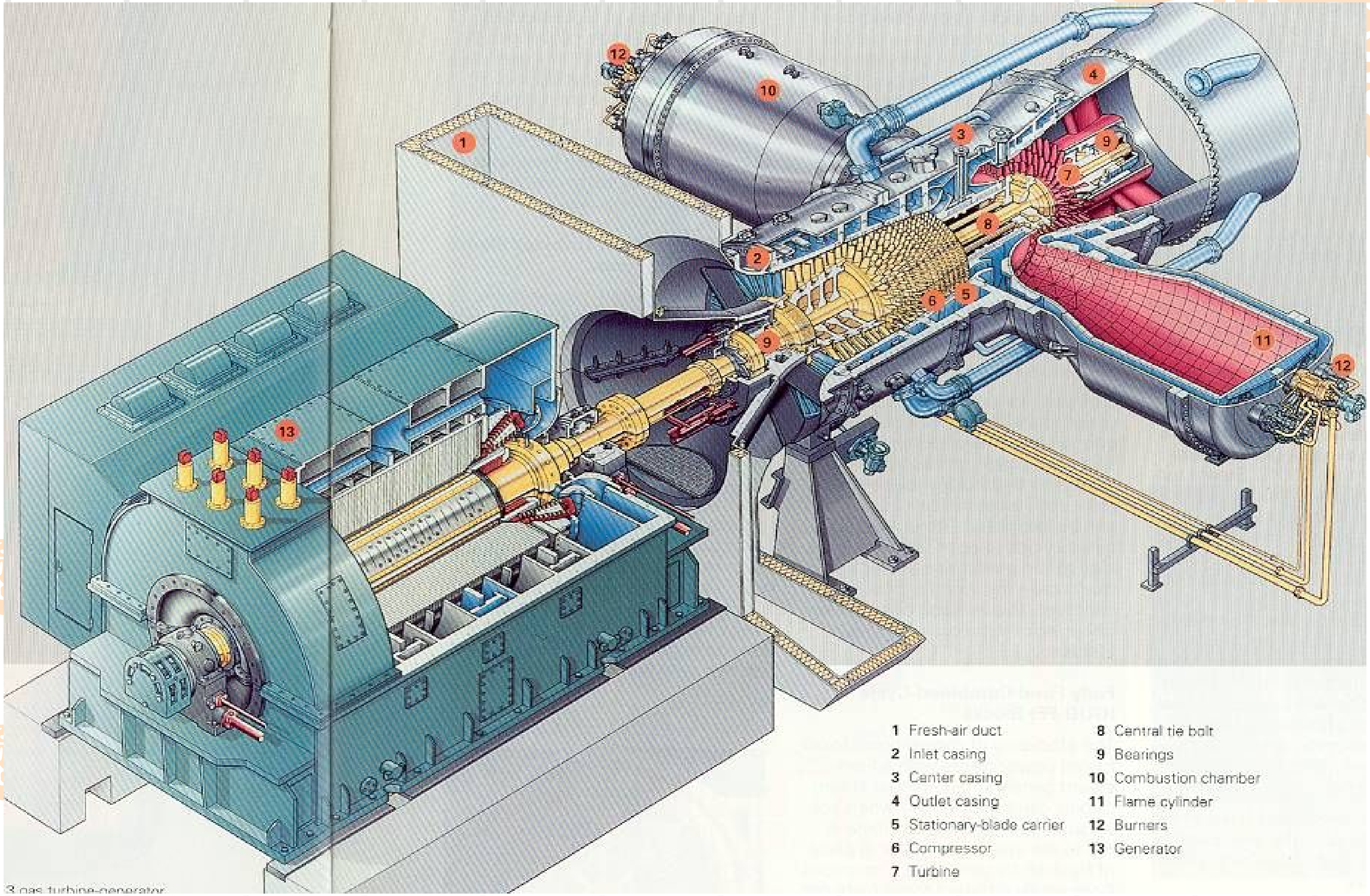
轴流式燃气轮机

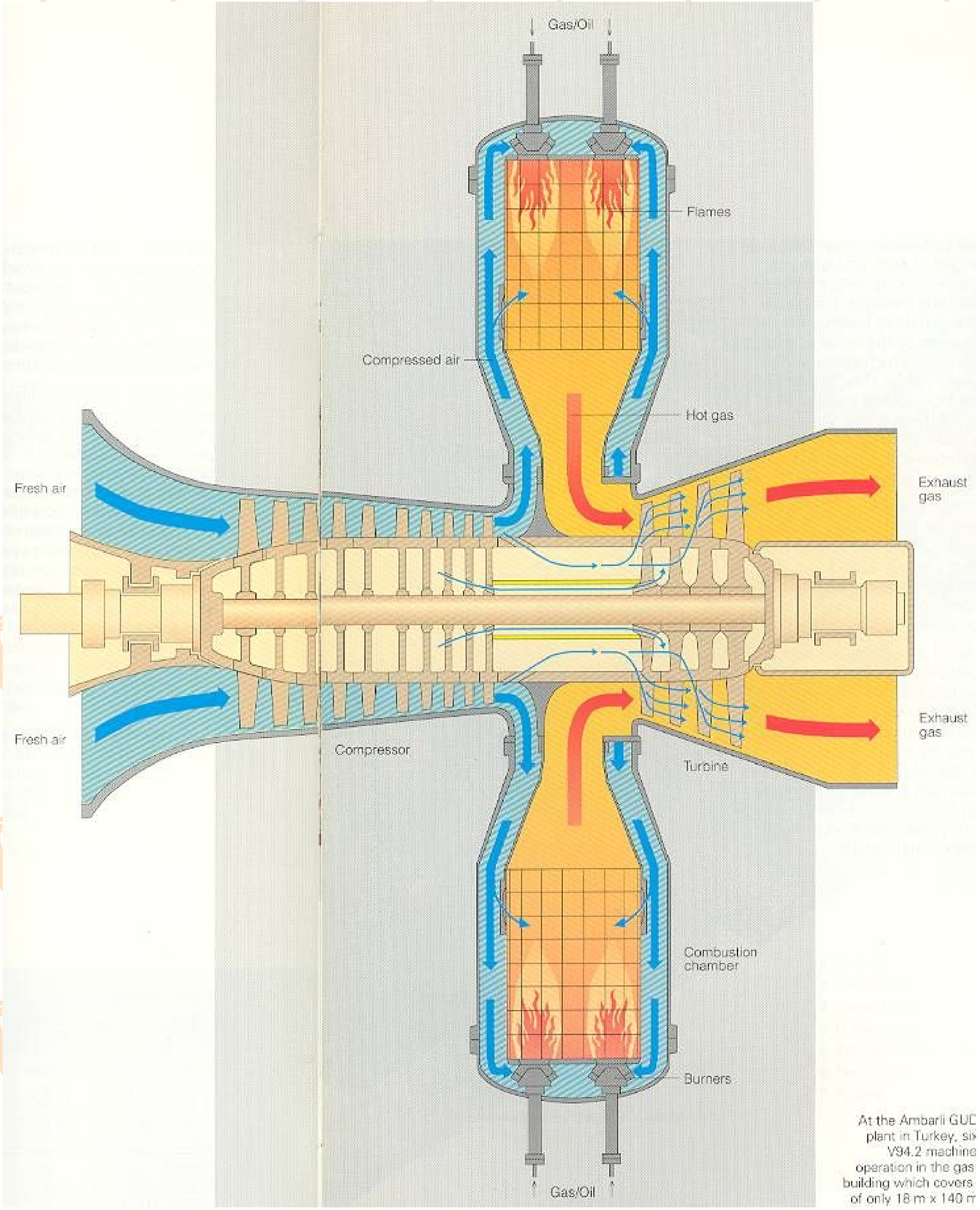


压气机

燃烧室

气轮机


1 Fresh-air duct
2 Inlet casing
3 Center casing
4 Outlet casing
5 Stationary-blade carrier
6 Compressor
7 Turbine
8 Central tie bolt
9 Bearings
10 Combustion chamber
11 Flame cylinder
12 Burners
13 Generator
3 gas turbine-generator

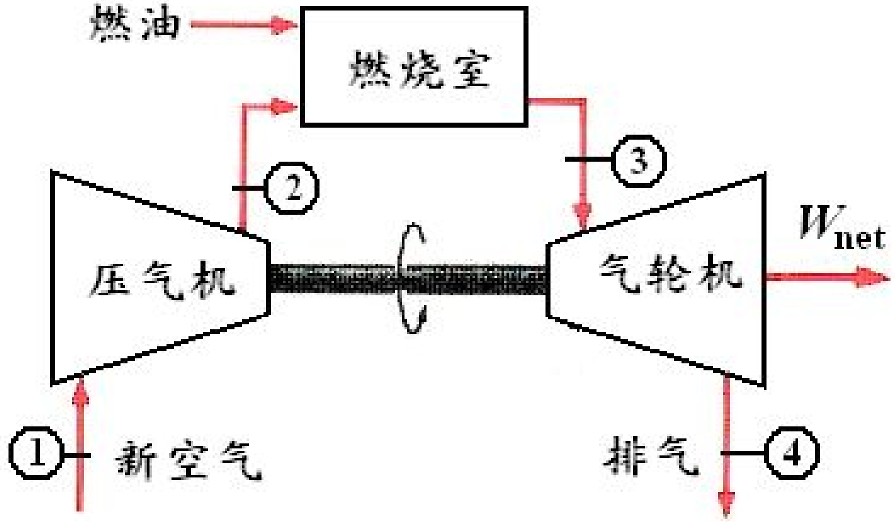

Gas/Oil
Flames
Compressed air
Hot gas
Fresh air
Exhaust gas
Fresh air
Exhaust gas
Compressor
Turbine
Combustion chamber
Burners
Gas/Oil

构成

压气机(compressor)

燃烧室(combustion chamber)

燃气轮机(gas turbine)



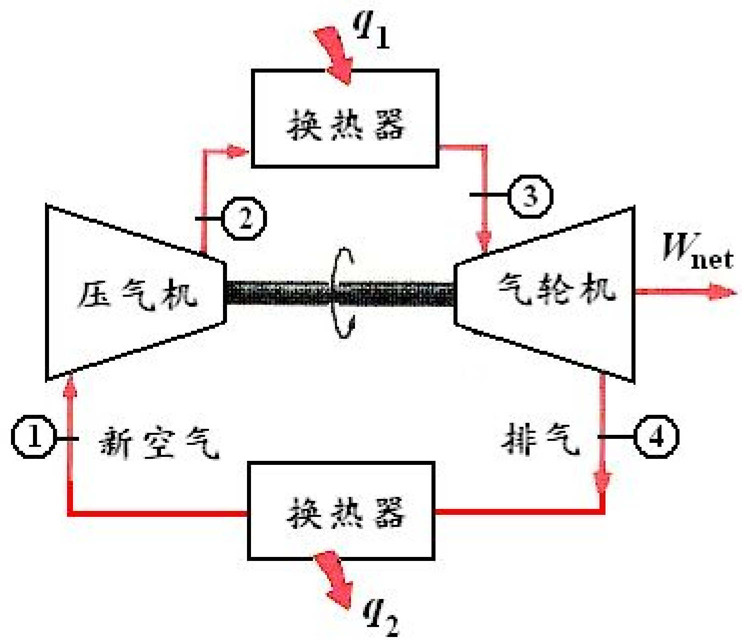
特点

1.开式循环(open cycle)，工质流动;

2.运转平稳，连续输出功;

3.启动快，达满负荷快;

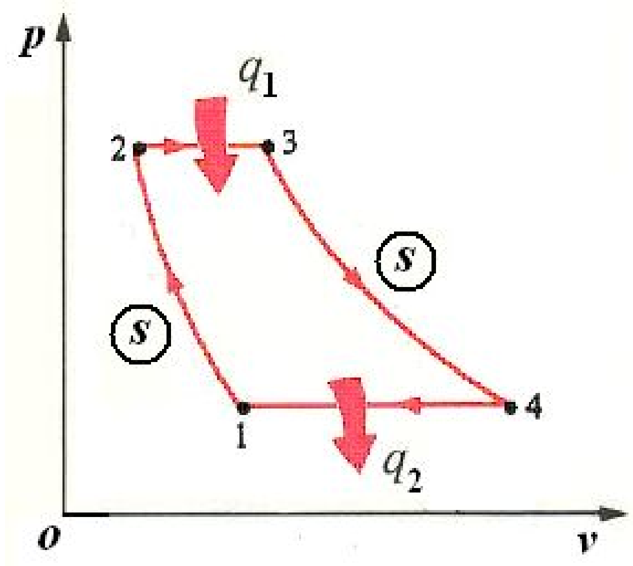
4.压气机消耗了燃气轮机产生功率的绝大部分，但重量功率比(specific weight of engine)仍较大。



用途

飞机、舰船的动力载荷机组，电站峰荷机组(peak-load set) 等。

二、定压加热理想循环（constant-pressure combustion cycle， Brayton cycle）



1-2 等熵压缩（压气机内） $\pi = \frac{p_2}{p_1}$

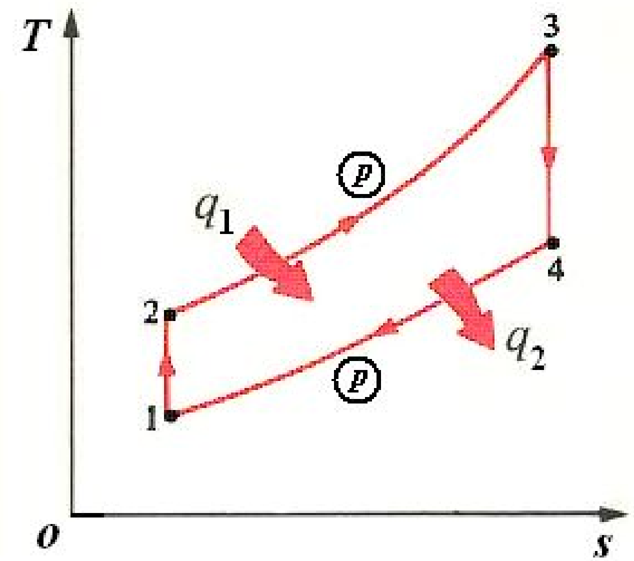
循环增压比（pressure ratio）

2-3 定压吸热（燃烧室内） $\tau = \frac{T_3}{T_2}$

循环增温比（temperature ratio）

3-4 等熵膨胀（燃气轮机内）

4-1 定压放热（排气，假想换热器）



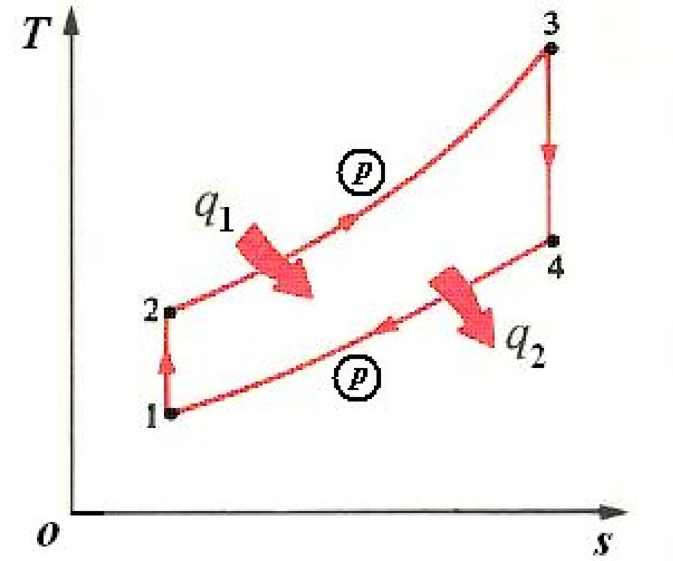
三、定压加热理想循环分析

1.热效率 η_t

$$q_1 = h_3 - h_2 = c_{pm}\Big|_{t_2}^{t_3}(T_3 - T_2) = c_p(T_3 - T_2)$$

$$q_2 = h_4 - h_1 = c_{pm}\Big|_{t_1}^{t_4}(T_4 - T_1) = c_p(T_4 - T_1)$$

$$\eta_t = 1 - \frac{q_2}{q_1} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$



$$\left.\begin{aligned} \because T_4 &= T_3\left(\frac{p_4}{p_3}\right)^{\frac{\kappa-1}{\kappa}} \\ T_1 &= T_2\left(\frac{p_1}{p_2}\right)^{\frac{\kappa-1}{\kappa}} \end{aligned}\right\} \begin{aligned} p_4 &= p_1 \\ p_3 &= p_2 \end{aligned} \Rightarrow \frac{T_4}{T_3} = \frac{T_1}{T_2} \Rightarrow \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2}$$

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

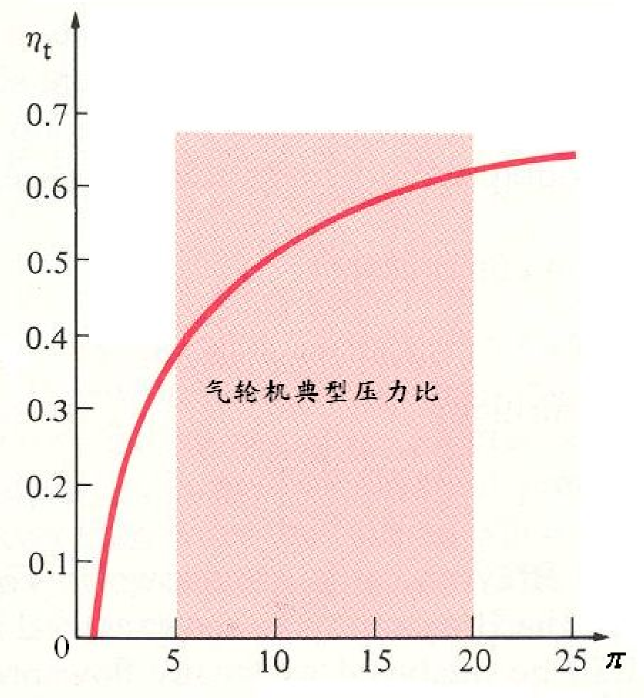
注意：式中T_1、T_2并非指高温热源，低温热源。

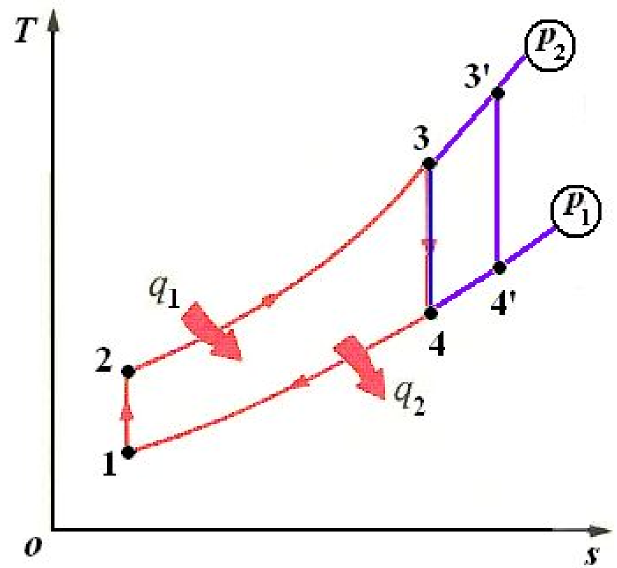
2.分析

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

a) $\pi\uparrow$ $\eta_t\uparrow$ η_t与T_3无关 ？

b) π一定 $q_1\uparrow$ $w_{net}\uparrow$ η_t不变



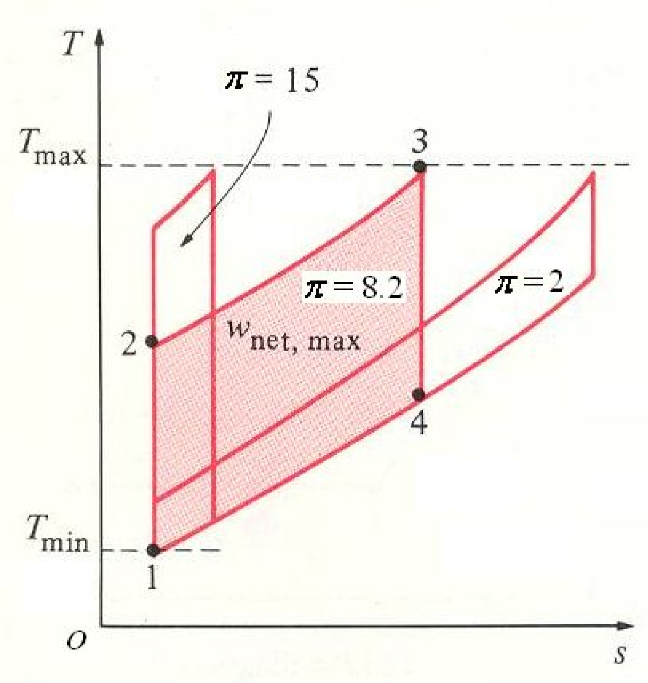


c) τ一定，π取某值$w_{net} \to w_{max}$

$$w_{net} = q_1 - q_2$$

$$= c_p\left[(T_3 - T_2) - (T_4 - T_1)\right]$$

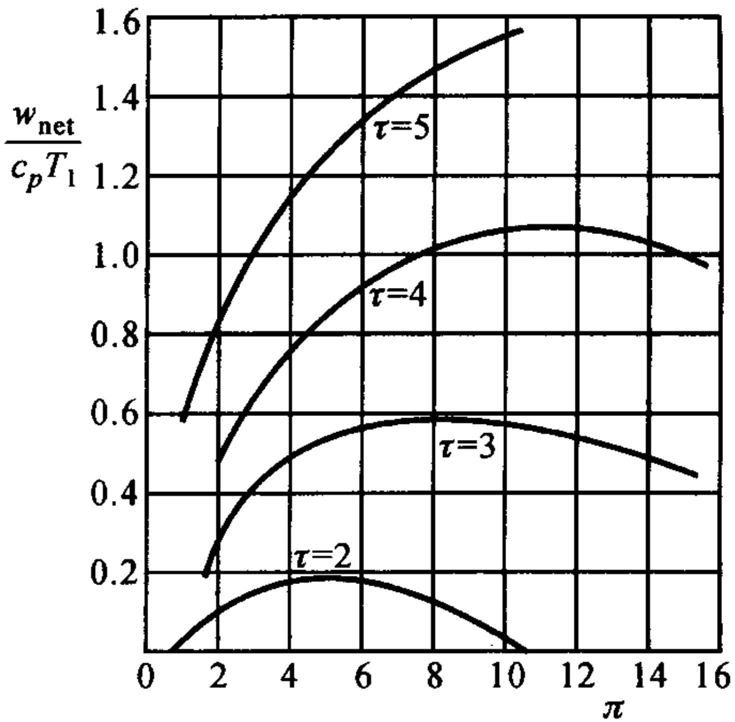
$$= c_p T_1\left[\frac{\tau\left(\pi^{\frac{\kappa-1}{\kappa}} - 1\right)}{\pi^{\frac{\kappa-1}{\kappa}}} - \left(\pi^{\frac{\kappa-1}{\kappa}} - 1\right)\right]$$



$$\frac{\delta w_{net}}{d\pi} = 0 \rightarrow \pi = \tau^{\frac{\kappa}{2(\kappa-1)}} \rightarrow w_{net} \to w_{net,max}$$

d) w_{net}与τ及π的关系

由c)$w_{net}=c_pT_1\left(\pi^{\frac{\kappa-1}{\kappa}}-1\right)\left(\frac{\tau}{\pi^{\frac{\kappa-1}{\kappa}}}-1\right)$



可见:

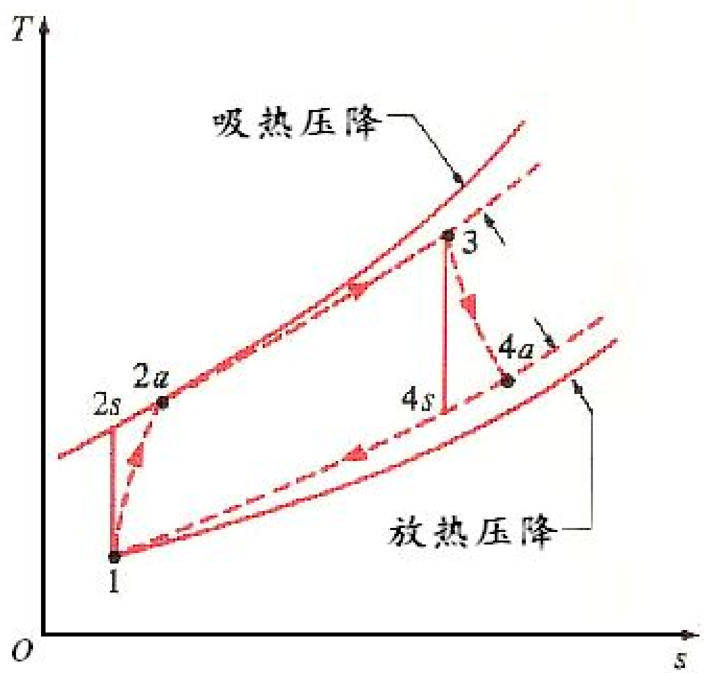
1）对于每一τ，均有π，其$w\rightarrow w_{net,max}$

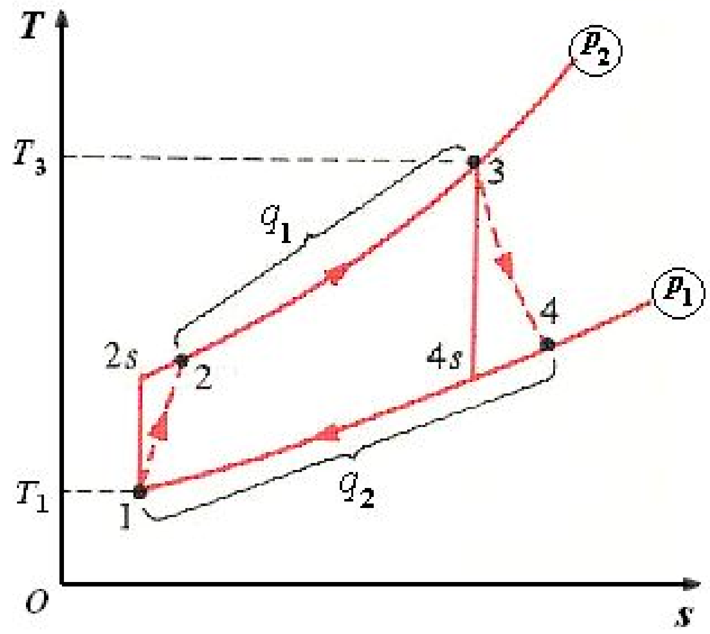
2）τ上升，即T_3上升，使取得$w_{net,max}$的π上升，η_t上升，所以提高T_3能带动$w_{net,max}$及η_t同时升高。

9–6 燃气轮机装置定压加热实际循环

一、定压加热的实际循环

1-2 不可逆绝热压缩;
2-3 定压吸热;
3-4 不可逆绝热膨胀;
4-1 定压放热。





二、压气机绝热效率(adiabatic compressor efficiency)和燃气轮机相对内效率(adiabatic turbine efficiency)

$$\eta_{C,s}=\frac{w_{C,s}}{w'_{C}}=\frac{h_{2_s}-h_1}{h_2-h_1}$$

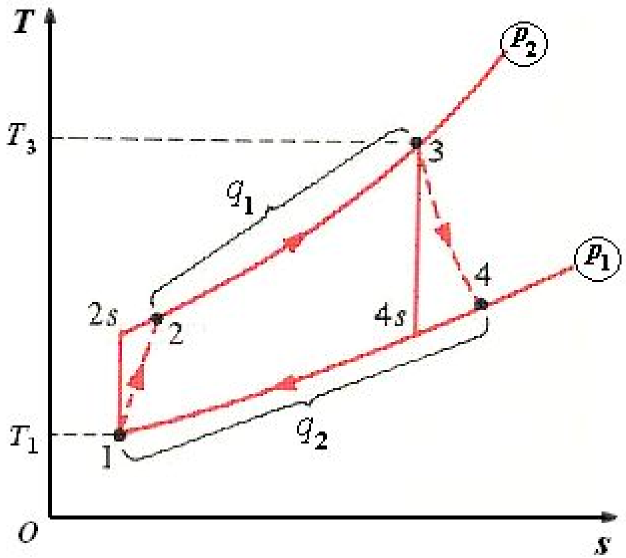
$$w'_{C}=\frac{1}{\eta_{C,s}}\left(h_{2_s}-h_1\right)$$

$$h_2=h_1+\frac{1}{\eta_{C,s}}\left(h_{2_s}-h_1\right)$$

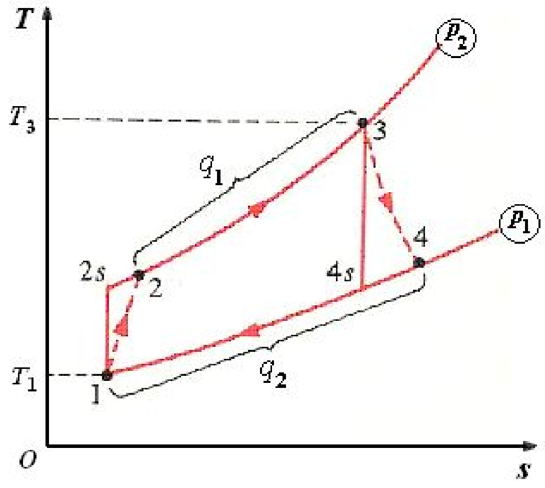
$$\eta_{T}=\frac{w'_{t,T}}{w_{t,T}}=\frac{h_3-h_4}{h_3-h_{4_s}}$$

$$w'_{t,T}=\eta_{T}\left(h_3-h_{4_s}\right)$$

$$h_4=h_3-\eta_{T}\left(h_3-h_{4_s}\right)$$



三、燃气轮机装置的内部热效率 (internal thermal efficiency) η_i



$$\eta_\mathrm{i}=\frac{w'_\mathrm{net}}{q'_1}$$

$$w'_\mathrm{net}=w'_\mathrm{t,T}-w'_\mathrm{C}=\eta_\mathrm{T}\left(h_3-h_{4_\mathrm{s}}\right)-\frac{1}{\eta_\mathrm{Cs}}\left(h_{2_\mathrm{s}}-h_1\right)$$

$$q'_1=h_3-h_2=h_3-h_1-\frac{1}{\eta_\mathrm{Cs}}\left(h_{2_\mathrm{s}}-h_1\right)$$

整理

$$\eta_\mathrm{i}=\frac{\eta_\mathrm{T}\left(h_3-h_{4_\mathrm{s}}\right)-\frac{1}{\eta_\mathrm{Cs}}\left(h_{2_\mathrm{s}}-h_1\right)}{h_3-h_1-\frac{1}{\eta_\mathrm{Cs}}\left(h_{2_\mathrm{s}}-h_1\right)}=\frac{\eta_\mathrm{T}\frac{\tau}{\pi^{\frac{\kappa-1}{\kappa}}}-\frac{1}{\eta_\mathrm{Cs}}}{\frac{\tau-1}{\pi^{\frac{\kappa-1}{\kappa}}-1}-\frac{1}{\eta_\mathrm{Cs}}}$$

$$\eta_i = \frac{\eta_T(h_3 - h_{4_s}) - \frac{1}{\eta_{Cs}}(h_{2_s} - h_1)}{h_3 - h_1 - \frac{1}{\eta_{Cs}}(h_{2_s} - h_1)} = \frac{\eta_T \frac{\tau}{\pi^{\frac{\kappa-1}{\kappa}}} - \frac{1}{\eta_{Cs}}}{\frac{\tau - 1}{\pi^{\frac{\kappa-1}{\kappa}} - 1} - \frac{1}{\eta_{Cs}}}$$

讨论：

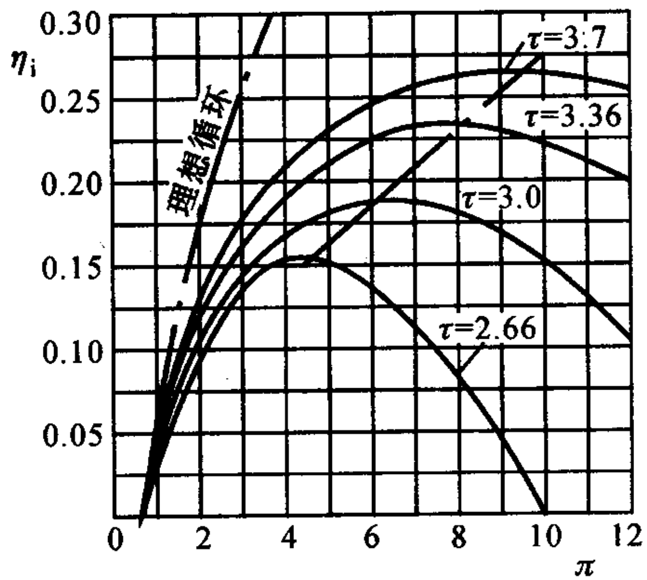
a)除π、τ外η_i还与η_{Cs}、η_T有关

$\eta_T \uparrow \eta_{Cs} \uparrow \Rightarrow \eta_i \uparrow$

目前$\eta_T = 0.85 \sim 0.92$，$\eta_{Cs} = 0.85 \sim 0.90$

b) π一定时，$\tau \uparrow, \eta_i \uparrow$

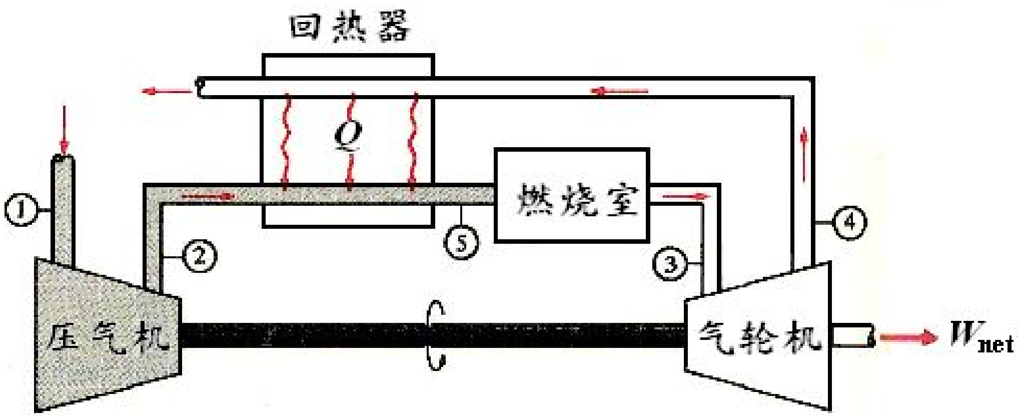
c) $\pi \uparrow, \eta_i \uparrow$但有极值

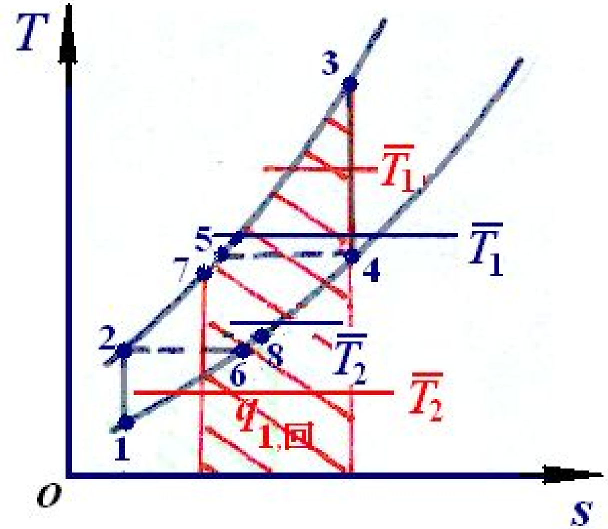


增大τ是提高燃气轮机装置性能（w_{net}，η_i）的方向。

9–7 提高燃气轮机装置热效率的热力学措施

一、回热（regeneration）



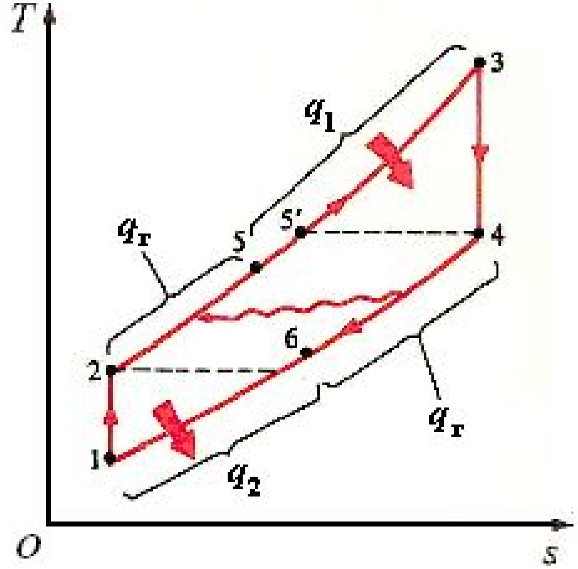


讨论

1) $q_{1回} = c_p(T_3 - T_7)$

$q_{2回} = c_p(T_8 - T_1)$

$$\Rightarrow \eta_{t,回} = 1 - \frac{q_{2回}}{q_{1回}} = 1 - \frac{\overline{T}_{2回}}{\overline{T}_{1回}} > \eta_t$$

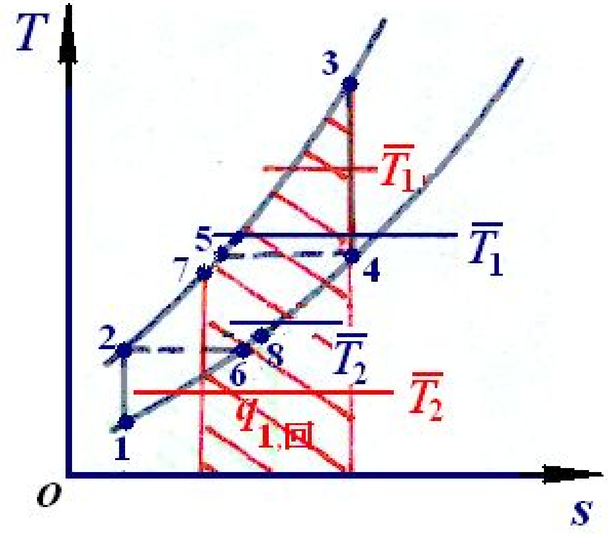


2）极限回热 $q_{1回} = c_p(T_3 - T_5)$ $q_{2回} = c_p(T_6 - T_1)$

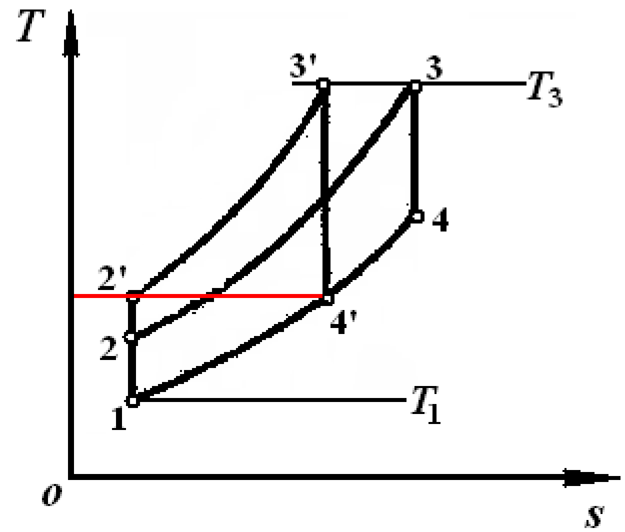
3）回热度(regenerator effectiveness)

$$\sigma = \frac{\text{实际回热利用的热量}}{\text{理论上极限可利用的热量}}$$

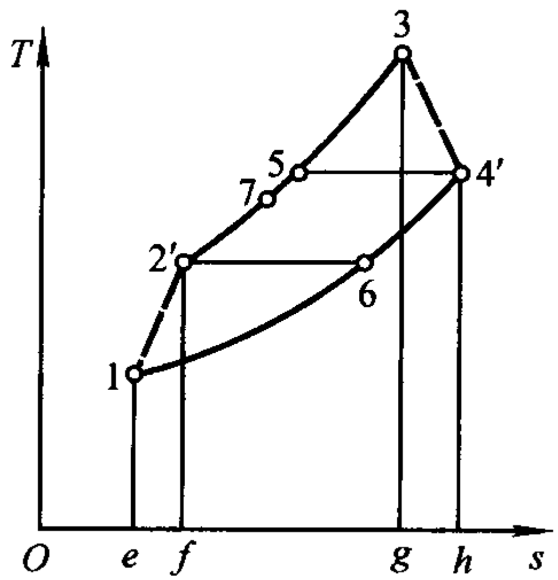
$$= \frac{h_7 - h_2}{h_5 - h_2} = \frac{h_4 - h_8}{h_4 - h_6}$$



注意： π 达一定值，回热不能进行。



4）实际循环的回热



$$\sigma' = \frac{h_7 - h_{2'}}{h_5 - h_{2'}} = \frac{h_7 - h_{2'}}{h_{4'} - h_6}$$

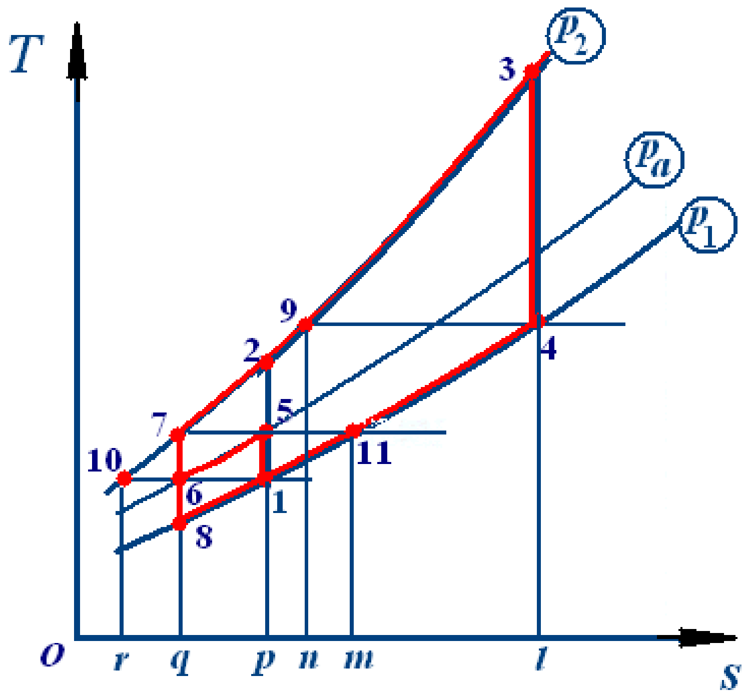
二、回热基础上分级压缩，中间冷却

压气机耗功很大

分级压缩可降低压气机耗功

分级压缩，中间冷却

（**multistage compression，intervening cooling**）



采用分级压缩，中间冷却后 η_t↑？

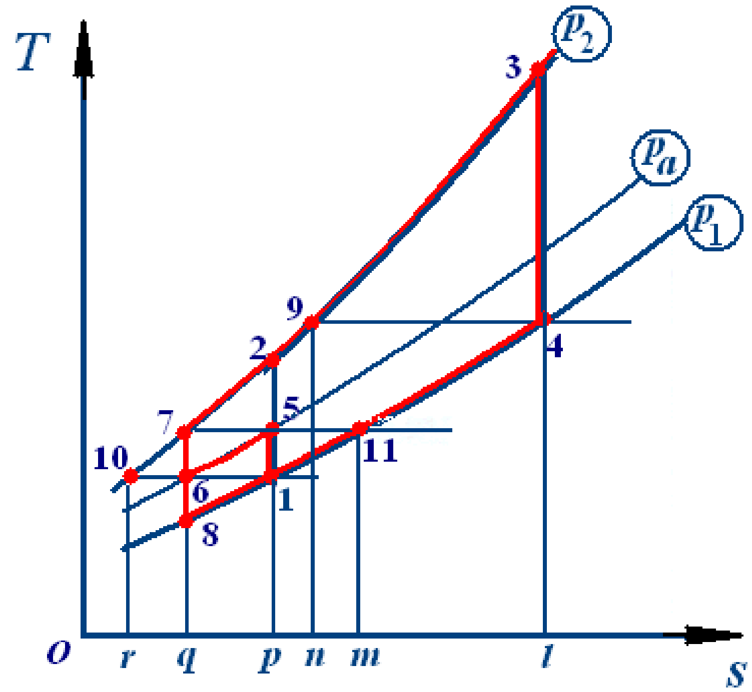
循环12341： $\eta_t = 1 - \dfrac{1}{\pi^{\frac{\kappa-1}{\kappa}}}$

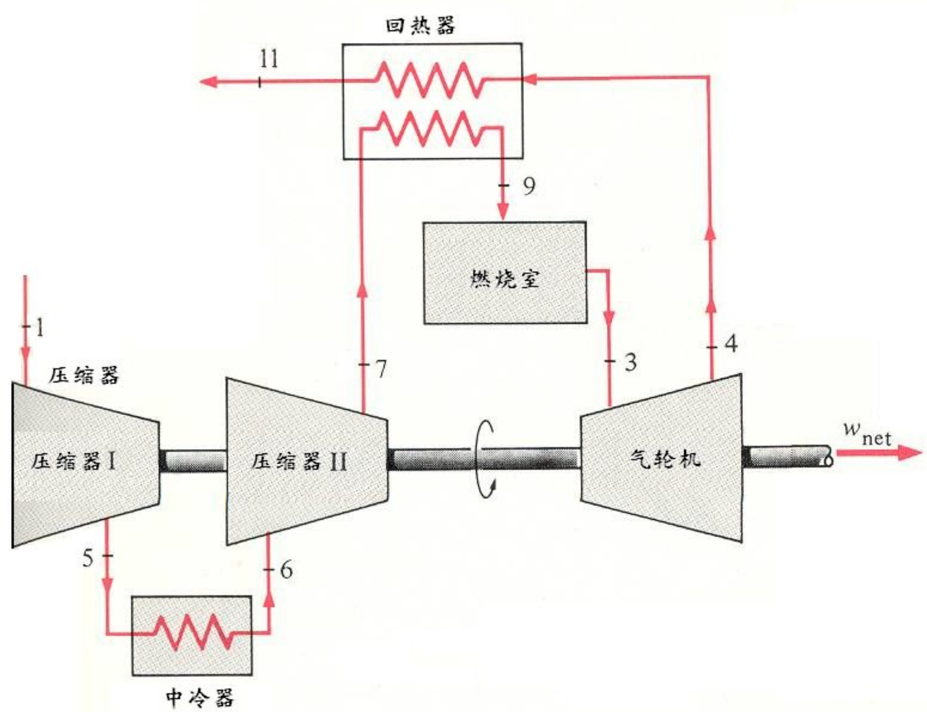
循环1567341： 循环12341 + 循环67256

循环67256： $\eta_t' = 1 - \dfrac{1}{\pi_1^{\frac{\kappa-1}{\kappa}}} < \eta_t$

$$\therefore \eta_{t1567341} < \eta_{t12341}$$

回热基础上分级压缩中间冷却





$$w_{\text{net},1567341} > w_{\text{net},12341}$$

$$q_{1,1567341} = q_{1,12341}$$

$$\therefore \eta_{t,1567341} > \eta_{t,12341}$$

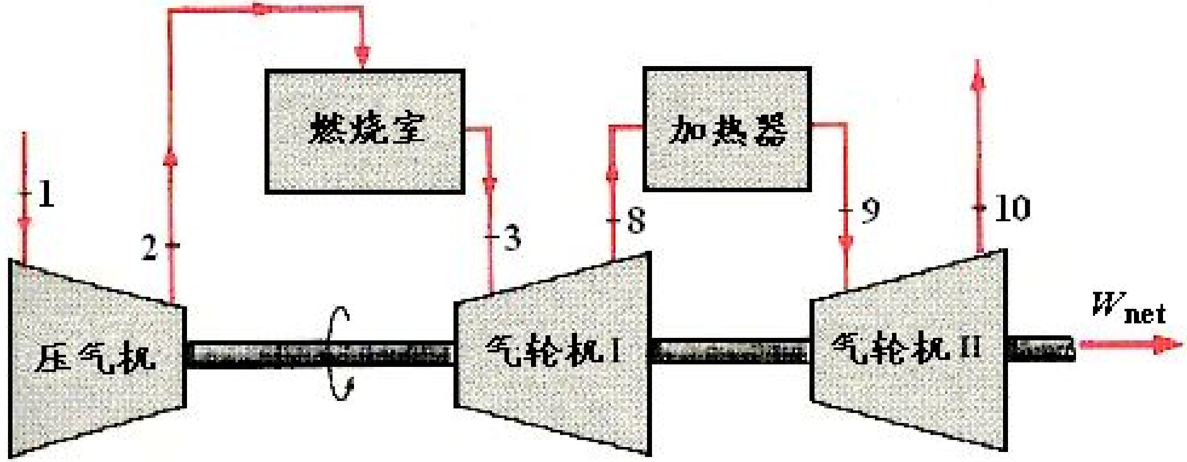
三、回热基础上分级膨胀，中间加热

循环12389101= 循环127101−循环37983

若无回热

$$\left.\begin{array}{l}\eta_{t,12341}=\eta_{t,127101}\\ \eta_{t,2389101}<\eta_{t,127101}\end{array}\right\}$$

$$\eta_{t,2389101}<\eta_{t,12341}$$

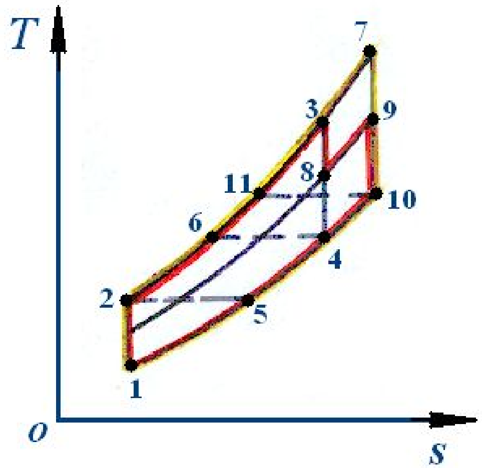


若回热

循环12389101与循环12341

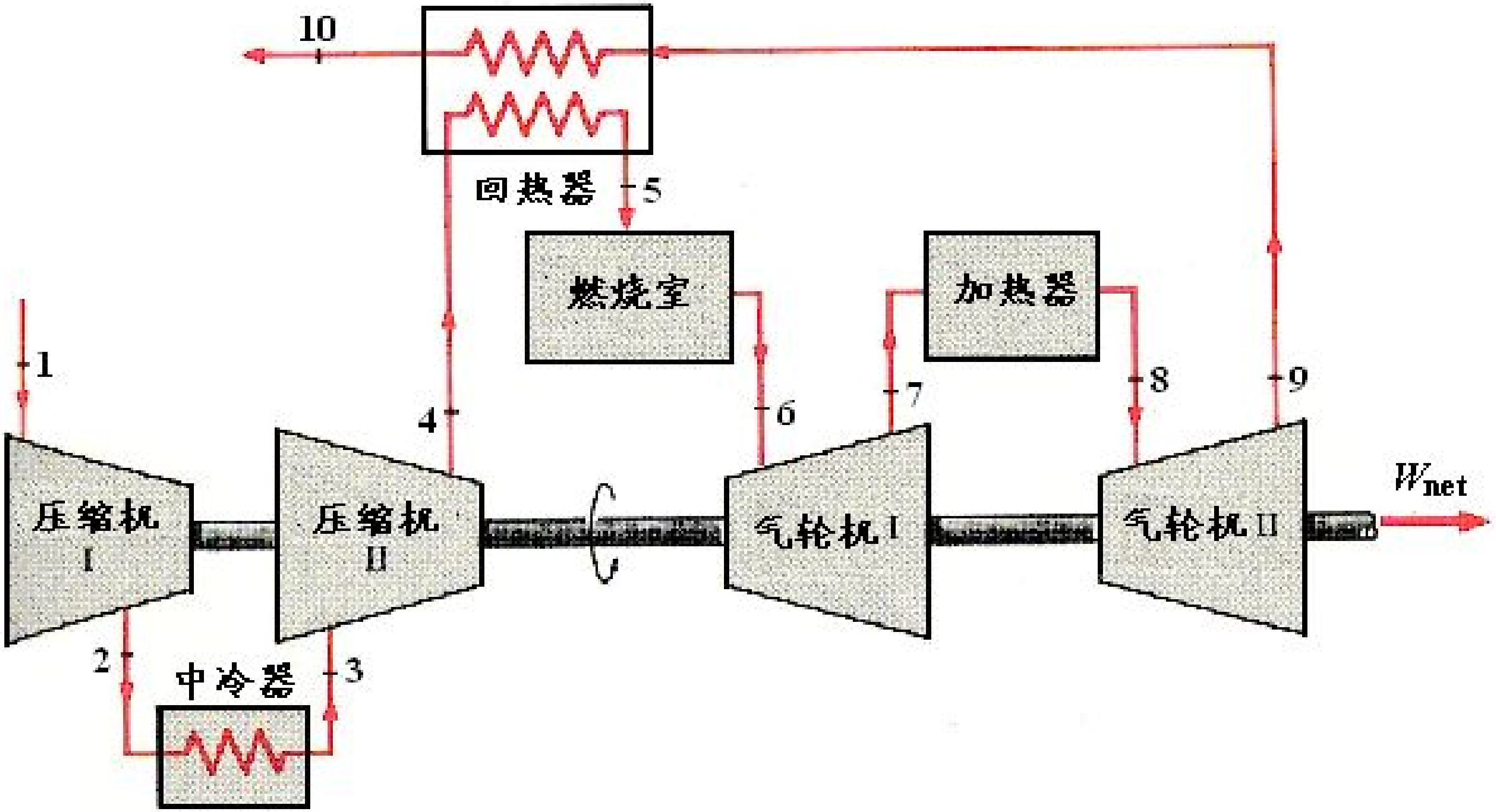
比较T_{1m}上升，T_{2m}下降

$$\eta_{t,12389101}>\eta_{t,12341}$$

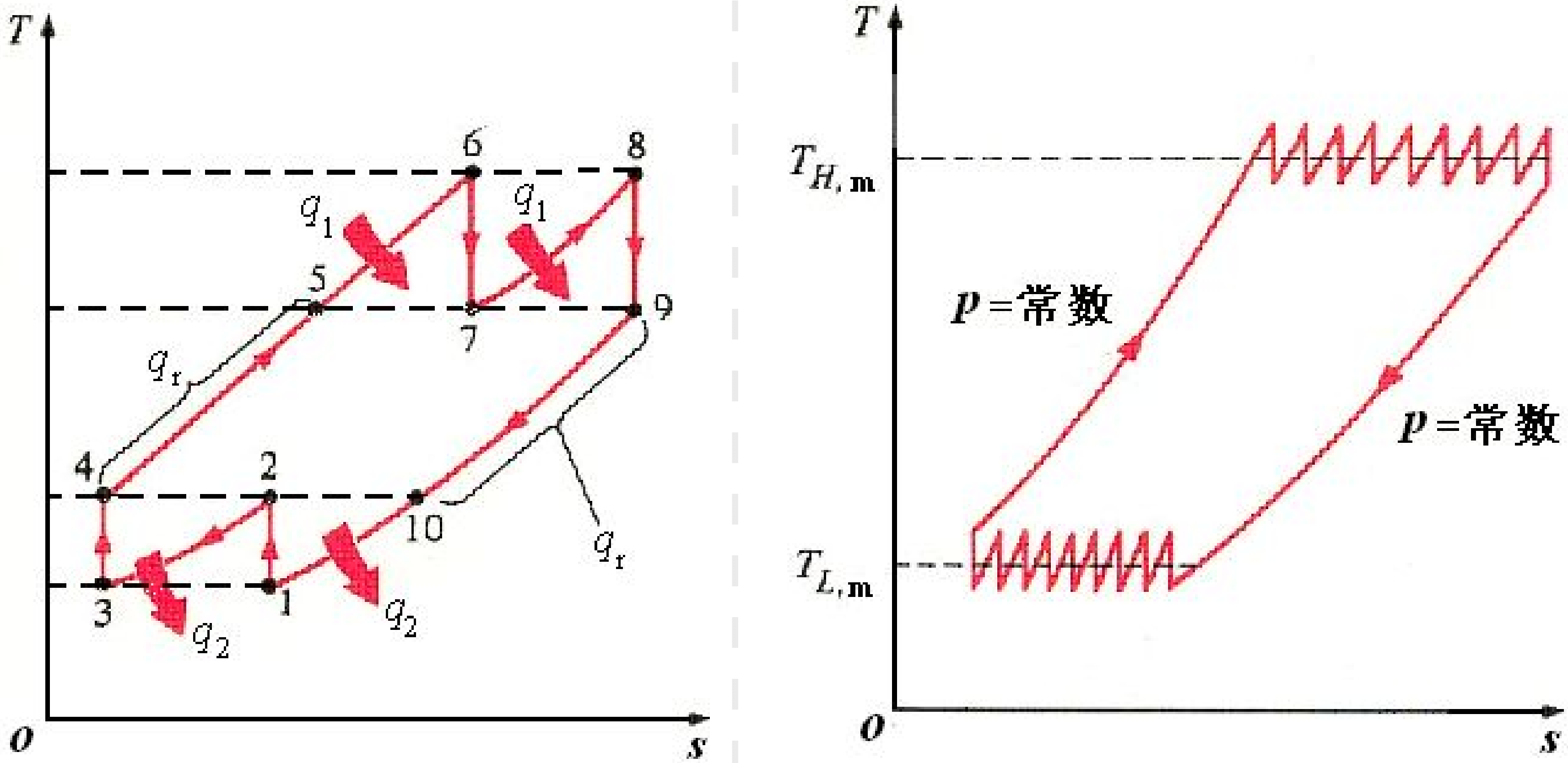


五、回热基础上

分级压缩，中间冷却；分级膨胀，中间加热



当分级压缩中间冷却；分级膨胀中间再热，级数趋向无穷多时，定压加热理想循环趋于概括性卡诺循环。



气体动力循环热效率分析归纳:

基础:

$$\eta_t = \frac{w_{net}}{q_1} = 1 - \frac{q_2}{q_1} \qquad = 1 - \frac{\overline{T_2}}{\overline{T_1}} \qquad = 1 - \frac{T_L}{T_h}$$

方法:

在T–s图上叠加、拆分等;

在T–s图上与同温限卡诺循环比较;

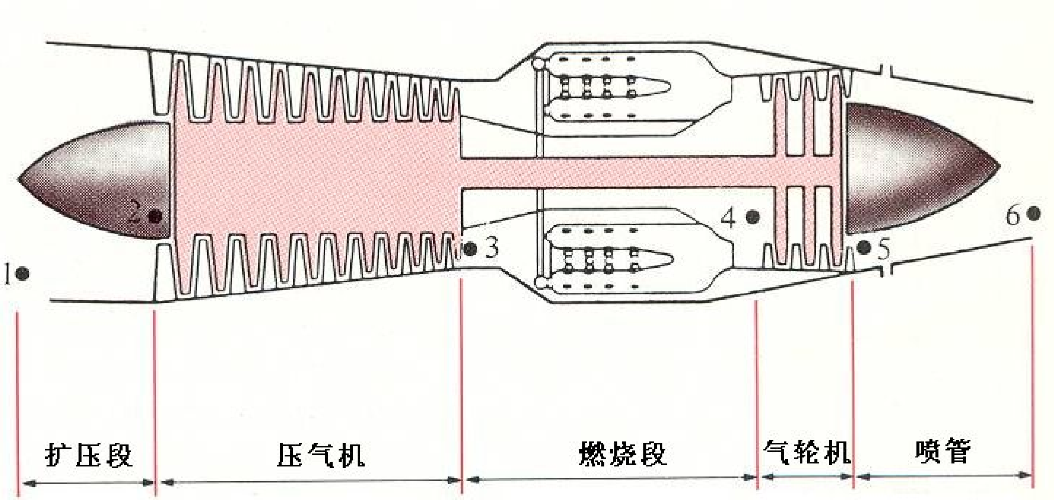
利用 $\eta_t = f(x, y, z \cdots)$的数学特性。

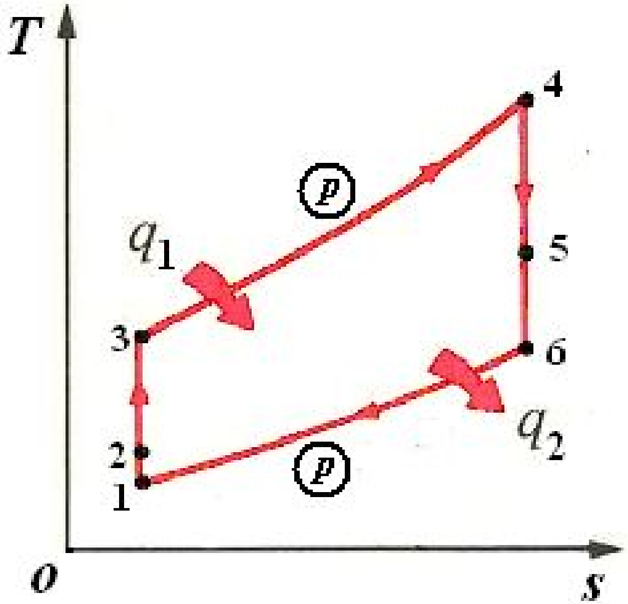
例A474299

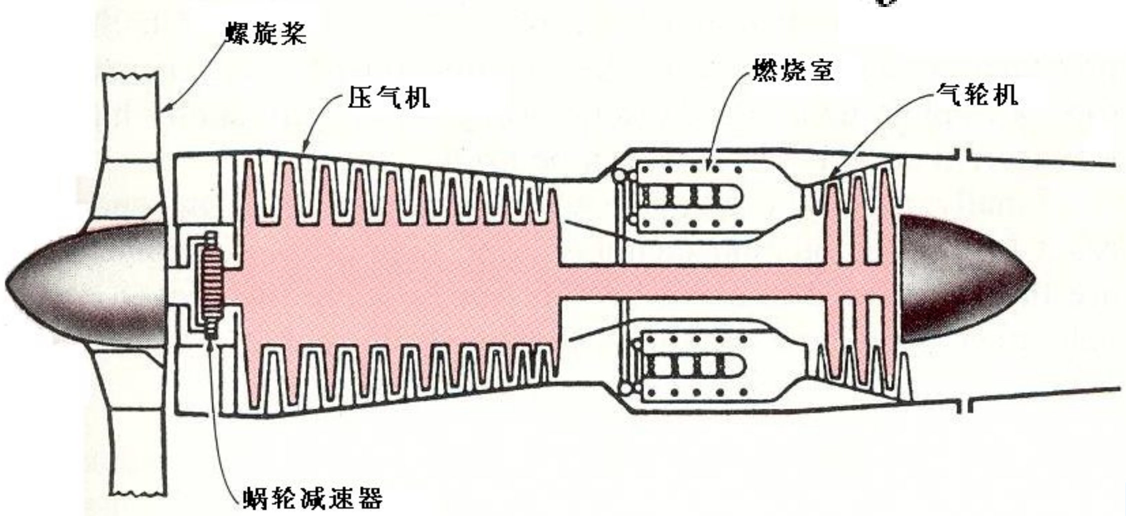
例A470389

9–8 喷气发动机简介

定压燃烧喷气式发动机(jet engine)的理论循环及实际循环与燃气轮机装置定压加热循环相同。







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