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第四章　热力学第一定律

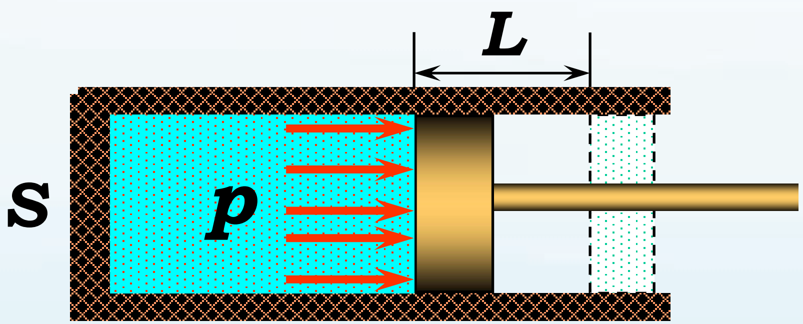
4.1 准静态过程

1°概念：每时每刻系统状态都无限接近平衡态

2°特点：(1) 过程进行缓慢

(2) 每个状态都可用确定的状态参量描述

(3) 可以用平滑的过程曲线来表示



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4.1 准静态过程

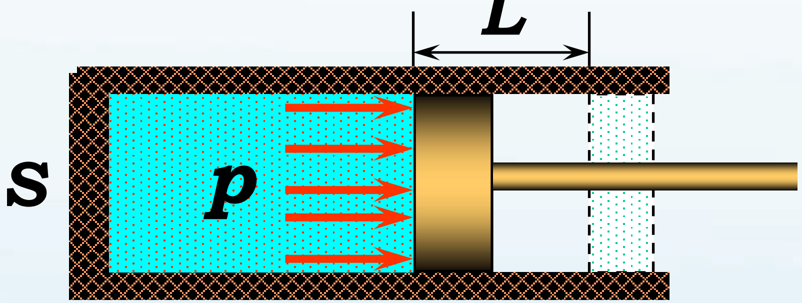
3°判剧

(1) 弛豫时间τ：从原平衡态恢复到新平衡态需时

(2) 准静态过程判剧：τ恒$<t_i$(每步进行的时间)

(3) 示例：内燃机汽缸活塞v=10m/s，p趋匀速率300m/s

$\tau=L/300 < t=L/10$ 是！



不作说明，均为准静态过程！

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4.2 功与热量

1° 广义功概念

(1) 广 义 力: 破坏力学平衡的作用 (机械力 电磁力)

(2) 广义位移: 广义力作用下的状态变化

(3) 广 义 功: 广义力作用下产生广义位移所做的功

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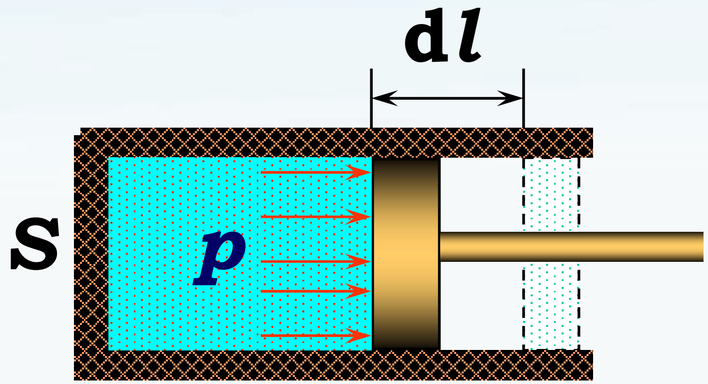
4.2 功与热量

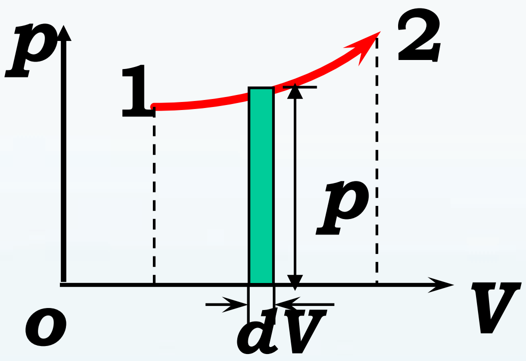
2° 热力学典型的广义功

体积变化功

①数学表达式 $A = \int_{V_1}^{V_2} p\,dV$



$$dA = \vec{F} \cdot d\vec{l} = pSdl = pdV$$



②本质：过程量 度量状态量变化

③功的正负：

系统作功取“+”，否则取“−”

电源功示例-电容器充电

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3° 热量Q

(1) 本质: 是能量, 是过程量, 用来度量状态量变化.

(2) 正负: 系统从外界吸热取“+”, 否则取 “–”

4° 功、热量之比较

(1) 联系: 都是过程量, 是系统内能变化仅有两条途径

(2) 区别: 作功通过物体的宏观位移实现

传热通过分子间微观作用实现

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4.3 热力学第一定律

1° 内能概念

微观视角
- 动能(平转振)[不包括整体运动动能]
- 势能(分子间相互作用)
- ~~电子能量 原子核内能量~~

2° 内能定理

$$\boxed{A_{\text{绝热}} \overset{def}{=} E_2 - E_1}$$

系统从同一个初态变化为同一个末态的所有绝热过程中,外界对系统做功$A_{\text{绝热}}$为恒量

内能特点——态函数 关注其相对值

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3°热力学第一定律（实验总结）

(1) 表述: 系统从外界获取热量, 一部分使系统内能增加,

另一部分使系统对外作功

(2) 数学表达式

有　限过程: $Q=\Delta E+A$

无限小过程: $đQ=dE+đA$

准静态过程: $đQ=dE+pdV$

(3) 本质: 能量守恒定律

能量既不能产生又不能消失,

只能从一个物体传递给另一物体,

或从一种形式转化为另一种形式

4°热力学第一定律的应用

(1) 第一类永动机造不出

$$\begin{cases} Q = 0 \\ \Delta E = 0 \end{cases} \Rightarrow A = Q - \Delta E = 0$$

没有外界提供任何能量，
状态不断变化回到初态，
同时不断对外作功的机器.

(2) 科技发现的试金石

4.4 一定量理想气体对等值过程的应用

1° 摩尔热容

(1) 比热(容) $c \overset{def}{=} dQ/mdT$ 单位质量物体变化1K与外界换热

(2) 热容 $C \overset{def}{=} dQ/dT = cm$ 物体变化1K与外界交换热量

(3) 摩尔热容 $C_{mol} \overset{def}{=} C/(m/M_m) = M_m c$　1mol物体的热容

C_{mol} 与过程有关

(4) 定容摩尔热容 $\boxed{C_V} \overset{def}{=} dQ_V/dT \overset{度量}{=} \boxed{\frac{i}{2}R}$

等容过程C_{mol}　$dQ_V = dE = \frac{i}{2}RdT$

(5) 定压摩尔热容 $\boxed{C_p} \overset{def}{=} dQ_p/dT \overset{度量}{=} \boxed{\frac{i+2}{2}R}$

等压过程C_{mol}　$dQ_p = \frac{i}{2}RdT + RdT$

$\boxed{C_p = C_V + R}$　迈尔公式

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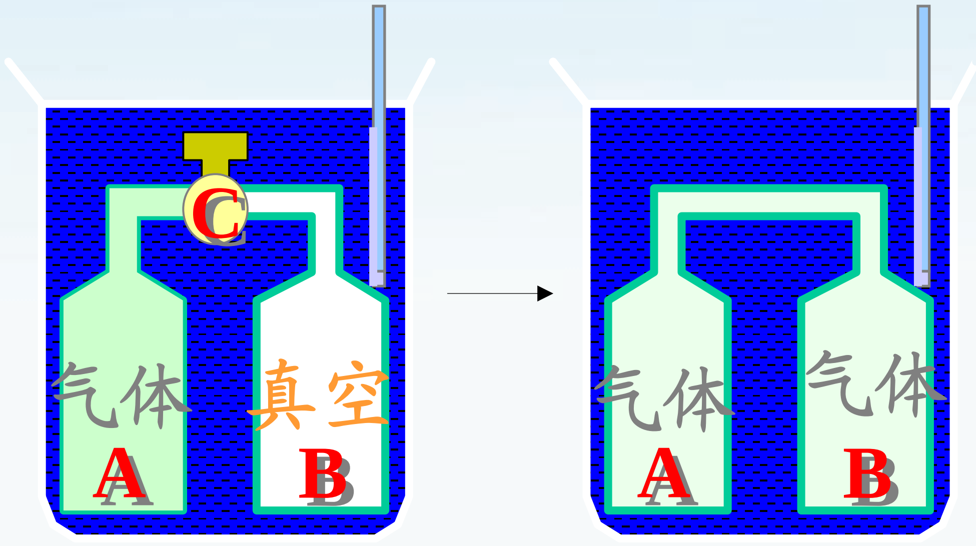
2° 理想气体内能

（1）焦耳实验



（2）焦耳定律

$$\begin{cases} A = 0 \\ Q = 0 \end{cases}$$

打开阀门:气体自由膨胀

实验结果：水温不变!

$$\Rightarrow \Delta E = Q - A = 0$$

$$\left.\begin{aligned} &\Rightarrow E_2(T_2, V_2) = E_1(T_1, V_1) \\ &T_2 = T_1 \end{aligned}\right\}$$

→理想气体内能与体积无关，只是温度的函数

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（3）理想气体的定体热容与内能

$$C_V \overset{def}{=} \frac{d\,E}{\upsilon dT} \quad \Rightarrow \Delta E = \int_{T_1}^{T_2} \upsilon C_V dT$$

（4）理想气体的定压热容与焓

$$\left.\begin{array}{l} C_p \overset{def}{=} \dfrac{d\,Q_p}{\upsilon dT} \\ dQ_p = d(E + pV) \\ H \overset{def}{=} E + pV \end{array}\right\} \Rightarrow \Delta H = \int_{T_1}^{T_2} \upsilon C_p dT$$

3° 一定量理想气体对等值过程的应用

$$dQ = \upsilon C_V dT + p dV$$

(1) 等容过程

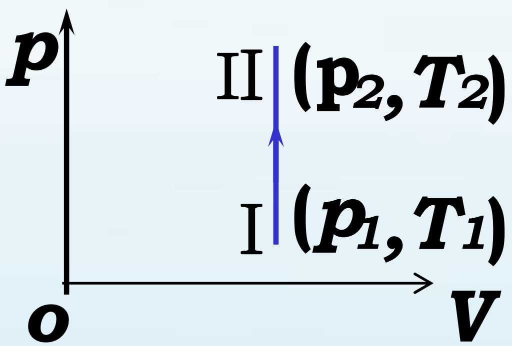
①特征 $V = const.$

②过程方程 $p_1/T_1 = p_2/T_2$

③ $Q, \Delta E, A$

$$\begin{cases} dA = p dV \Rightarrow A = 0 \\ Q_V = \Delta E = \int_{T_1}^{T_2} \upsilon C_V dT \end{cases}$$

④ p-V 图



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(2) 等温过程

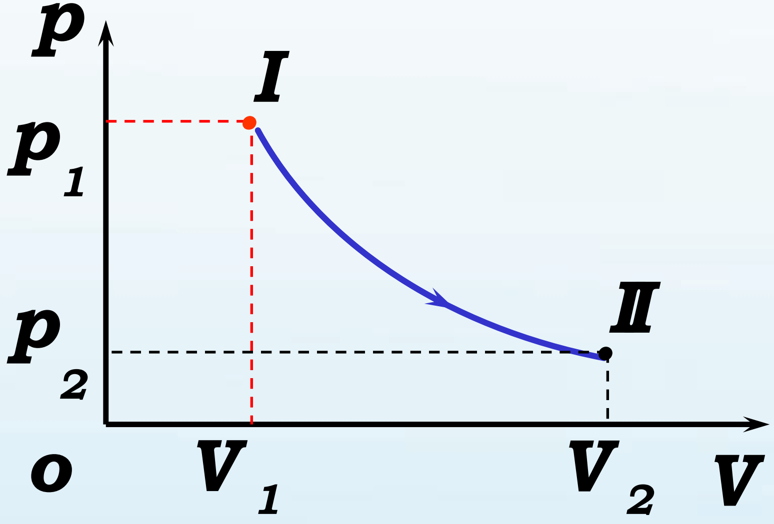
①特征 $T=const.$

②过程方程　$p_1V_1=p_2V_2$

③ $Q, \Delta E, A$

$$\begin{cases} \Delta E = \int_{T_1}^{T_2} \upsilon C_V dT \Rightarrow \Delta E = 0 \\ Q_T = A = \int_{V_1}^{V_2} p dV \xrightarrow{pV=\upsilon RT} \int_{V_1}^{V_2} \frac{\upsilon RT}{V} dV \\ = \upsilon RT \ln(V_2/V_1) = \upsilon RT \ln(p_1/p_2) \end{cases}$$

④ p-V 图



(3) 等压过程

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①特征 $p=const.$

②过程方程 $V_1/T_1=V_2/T_2$

③ Q,ΔE,A

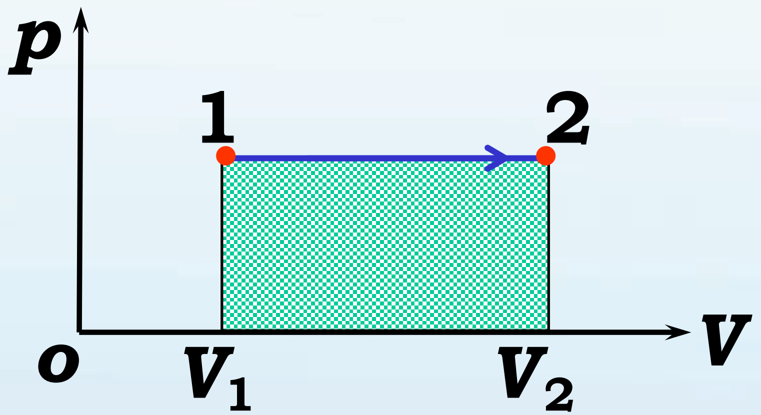
$$dA=pdV \Rightarrow A=p\Delta V$$

$$\upsilon RdT \Rightarrow A=\upsilon R\Delta T$$

$$dQ_p=\upsilon C_p dT \Rightarrow Q_p=\int_{T_1}^{T_2}\upsilon C_p dT$$

$$dE=\upsilon C_V dT \Rightarrow \Delta E=\int_{T_1}^{T_2}\upsilon C_V dT$$

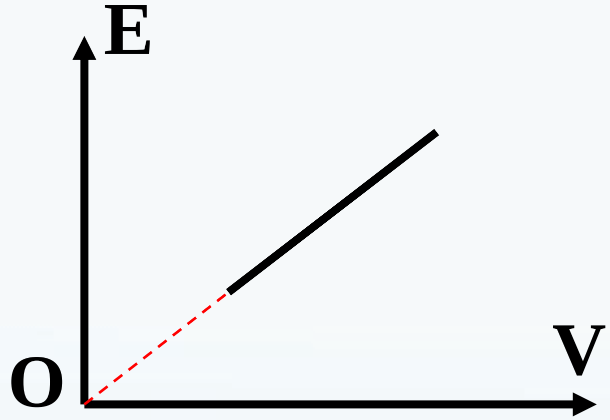
④ p-V图



[讨论1]一定量理想气体E随V变化如图，

则直线表示的过程为：

(A)等温 (B)等压 (C)等容 (D)绝热



解：$E = E(T) = \upsilon \dfrac{i}{2} RT$

$E = k_1 V$

$$\left.\begin{aligned} &\Rightarrow \frac{V}{T} = k \\ &\frac{pV}{T} = \cos t. \end{aligned}\right\} \Rightarrow p\text{为常数}$$

(4)绝热过程

①特征 $dQ=0$

$$
\left.\begin{aligned}
&dQ = dE + dA \Rightarrow pdV = -\upsilon C_V dT \\
&pV = \upsilon RT \Rightarrow pdV + Vdp = \upsilon\, R\, dT
\end{aligned}\right\} \Rightarrow \frac{pdV}{Vdp} = \frac{-1}{\gamma}
$$

$$
\Rightarrow \frac{dp}{p} + \gamma \frac{dV}{V} = 0 \Rightarrow \ln p + \gamma \ln V = c'
$$

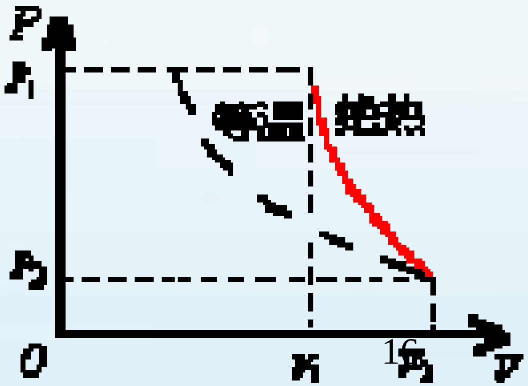
②过程方程 $\left.\begin{aligned} &\boxed{pV^{\gamma} = c} \\ &pV = \upsilon RT \end{aligned}\right\}$

消 p $\quad \boxed{TV^{\gamma-1} = C/\upsilon R}$

消 V $\quad \boxed{p^{\gamma-1}T^{-\gamma} = (\upsilon R)^{\gamma}/C}$

③ $Q, \Delta E, A$ $\left\{\begin{aligned} &Q=0 \\ &A=-\Delta E = -\int_{T_1}^{T_2} \upsilon C_V dT \end{aligned}\right.$

④ p-V图



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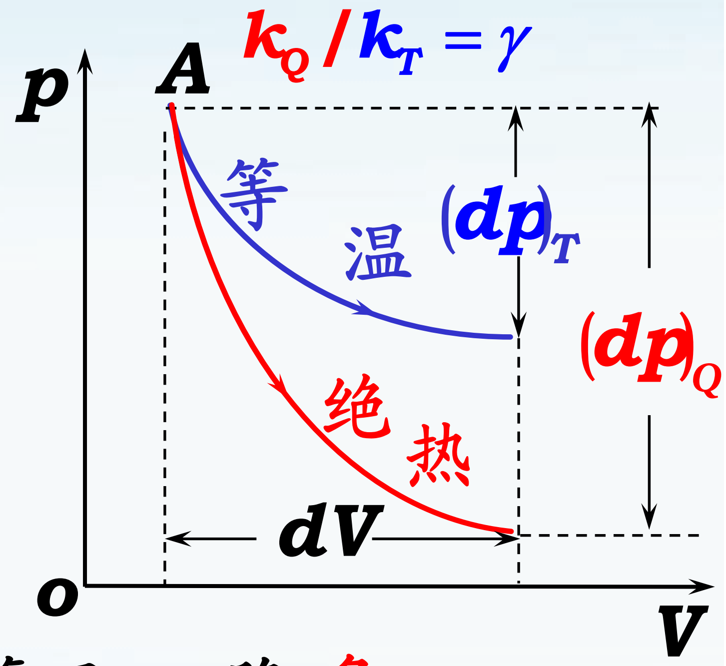
⑤p-V图上绝热线比等温线 陡

❶数学解释

等温 $pV = c_1 \Rightarrow \dfrac{dp}{dV} = -\dfrac{c_1}{V^2} = -\dfrac{p}{V}$

绝热 $pV^{\gamma} = c_2 \Rightarrow \dfrac{dp}{dV} = -\dfrac{c_2\gamma}{V^{\gamma+1}} = -\gamma\dfrac{p}{V}$

对A $\because \gamma > 1 \quad \therefore \left|(dp/dV)_Q\right| > \left|(dp/dV)_T\right|$



❷物理意义:膨胀相同体积绝热比等温p下降 多

$p = nkT$

等温 $V\uparrow \longrightarrow n\downarrow \longrightarrow p\downarrow$

绝热 $V\uparrow \longrightarrow n\downarrow \longrightarrow p\downarrow$

$V\uparrow \longrightarrow T\downarrow \longrightarrow p\downarrow$

$\boxed{TV^{\gamma-1} = C/\upsilon R}$

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[例题1]一定量N_2, 绝热膨胀$p \to 2p$, $\bar{v}$变为原几倍?

解： $\bar{v} = \sqrt{\dfrac{8RT}{\pi M_m}} \Rightarrow \dfrac{\bar{v}_2}{\bar{v}_1} = \sqrt{\dfrac{T_2}{T_1}} = 2^{1/7}$

$$\left.\begin{aligned} p^{\gamma-1}T^{-\gamma} &= c_2 \\ \gamma \overset{def}{=} C_p/C_V &= 1.4 \end{aligned}\right\} \Rightarrow \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{2/7} = 2^{2/7}$$

[讨论2]若上题绝热压缩$V \to V/2$,压缩前后$\bar{Z}$如何变化?

解: $\bar{Z} = \sqrt{2}n\pi d^2\bar{v} = \sqrt{2}\dfrac{N}{V}\pi d^2\sqrt{\dfrac{8RT}{\pi M_m}} = c_3\dfrac{\sqrt{T}}{V} \xrightarrow{TV^{\gamma-1} = c_4} \bar{Z} = c_5 V^{-\frac{1}{2}-\frac{\gamma}{2}}$

$$\Rightarrow \frac{\bar{Z}_2}{\bar{Z}_1} = \left(\frac{V_2}{V_1}\right)^{-\frac{1}{2}-\frac{\gamma}{2}} = 2^{\frac{6}{5}}$$

若为H_2O蒸汽, $\bar{Z}$如何变化? $\gamma = \dfrac{4}{3}$

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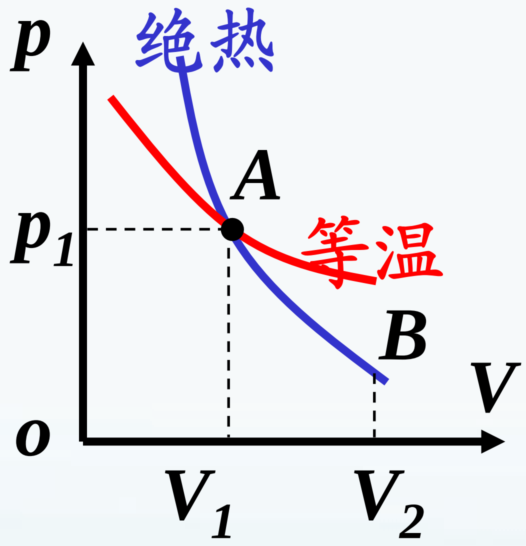
[讨论3] 理想气体A点$p_1=2\times10^5$Pa, $V_1=0.5\times10^{-3}m^3$, 此处斜率比为0.714, 从A绝热至B, 其体积$V_2=1\times10^{-3}m^3$. 求(1) B点处p_2; (2) 此过程气体对外作功.



解: (1) $\dfrac{k_Q}{k_T}=\gamma=\dfrac{1}{0.714}\Rightarrow\gamma=1.4$

$$p_1V_1^\gamma=p_2V_2^\gamma\Rightarrow p_2=p_1\left(\frac{V_1}{V_2}\right)^\gamma$$

$$=0.758\times10^5\ p_a$$

(2) $A=-\Delta E=-\upsilon\dfrac{5R}{2}(T_2-T_1)$

$$=-\frac{5}{2}(p_2V_2-p_1V_1)=60.5J$$

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(5) 多方过程

等容	等温	等压	绝热	多方
$V=c_1$	$pV^1=c_2$	$pV^0=c_3$	$pV^\gamma=c_4$	$pV^n=c$

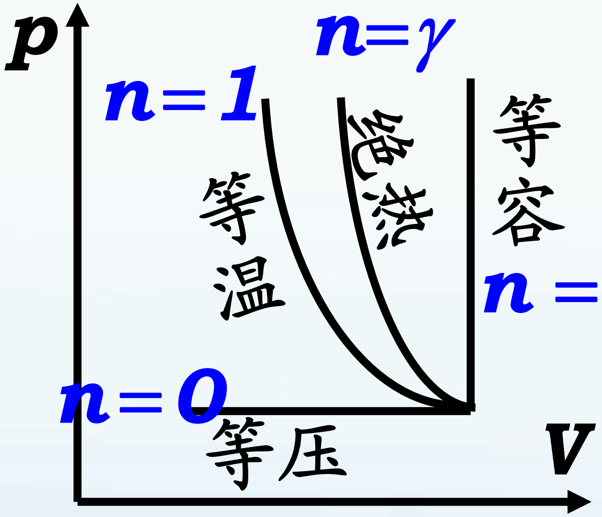
$$p^{\frac{1}{n}}V=const.\ (n=\infty)$$

①特征：满足$pV^n=c$

②过程方程 $\begin{cases} pV^n=c \\ pV=\upsilon RT \end{cases}$

消p $\quad V^{n-1}T=c/(\upsilon R)$

消V $\quad p^{n-1}T^{-n}=(\upsilon R)^n/c$



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③ $Q,\Delta E,A$

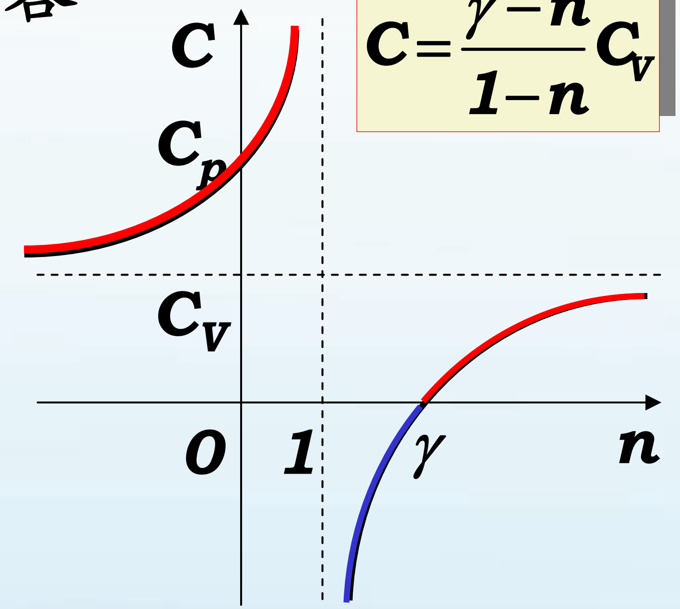
$$A=\int_{V_1}^{V_2} p dV=\int_{V_1}^{V_2} c dV/V^n=\frac{c}{1-n}\left(\frac{1}{V_2^{n-1}}-\frac{1}{V_1^{n-1}}\right)$$

$$=\frac{\upsilon R\Delta T}{1-n}=\frac{p_2V_2-p_1V_1}{1-n}$$

$$\Delta E=\upsilon C_V\Delta T$$

$$Q=\Delta E+A=\upsilon\left(\frac{C_V-nC_V}{1-n}+\frac{R}{1-n}\right)\Delta T=\upsilon\frac{\gamma-n}{1-n}C_V\Delta T$$

④ 摩尔热容

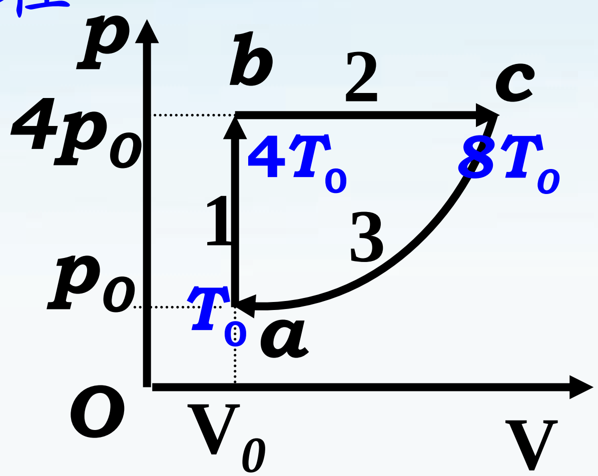


$$\boxed{C=\frac{\gamma-n}{1-n}C_V}$$

$n>\gamma$或$n<1\quad\Rightarrow C>0$

$1<n<\gamma\quad\Rightarrow C<0$

[例题2] 1mol单原子理想气体pV图，ca方程 $p=p_0V^2/V_0^2$，a点温度为T_0，以T_0,R表示1, 2, 3过程中Q



解：$a \to b$等容 $\dfrac{p_0}{T_0} = \dfrac{4p_0}{T_b} \Rightarrow T_b = 4T_0$

$b \to c$等压 $\dfrac{V_0}{4T_0} = \dfrac{V_c}{T_c}$

$c \to a$多方 $(4p_0)V_c^{-2} = p_0V_0^{-2}$ $\Rightarrow V_c = 2V_0$

$\Rightarrow T_c = 8T_0$

$$A_{ca} = \int_{2V_0}^{V_0} pdV = \int_{2V_0}^{V_0} \frac{p_0}{V_0^2}V^2dV = \frac{p_0}{3V_0^2}V^3\Big|_{2V_0}^{V_0} = -\frac{7RT_0}{3}$$

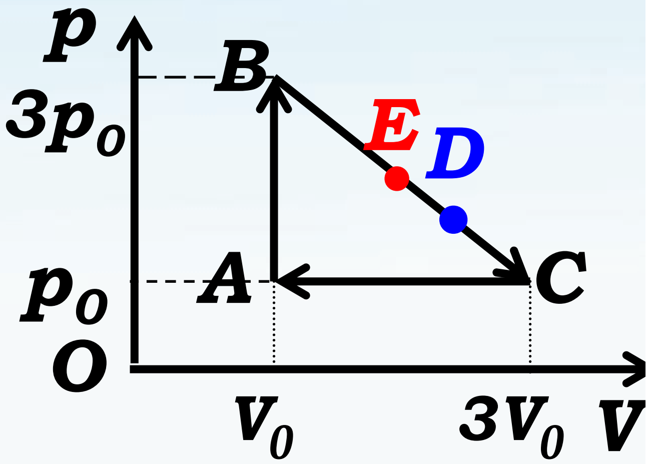
$a \to b$等容 $Q_V = \Delta E = \upsilon C_V\Delta T = 1\times(3R/2)(4-1)T_0 = 4.5RT_0$

$b \to c$等压 $Q_p = \upsilon C_p\Delta T = 1\times(5R/2)(8-4)T_0 = 10RT_0$

$c \to a$多方 $Q_{多方} = \Delta E + A = (1-8)T_0 3R/2 - 7RT_0/3 = -77RT_0/6$

直接用$C_{多方}$与C_V关系求$Q_{多方}$，判断哪种方法简洁？

[讨论4] 1mol单原子理想气体作图示循环,
分析BC过程温度变化及吸放热情况



解: $\begin{cases} p = -\dfrac{p_0}{V_0}V + 4p_0 \\ pV = \upsilon RT \end{cases} \Rightarrow T = \dfrac{1}{R}\left(4p_0V - \dfrac{p_0V^2}{V_0}\right)$

令 $T' = 0 \Rightarrow V = 2V_0$ $\begin{cases} \text{BE: T} \uparrow \\ \text{EC: T} \downarrow \end{cases}$

$$dQ = dE + dA = \upsilon C_V \frac{p_0}{R}\left(4 - \frac{2V}{V_0}\right)dV + \left(-\frac{p_0}{V_0}V + 4p_0\right)dV = 2p_0\left(5 - \frac{2V}{V_0}\right)dV$$

$\Rightarrow V = 2.5V_0$ $\quad V < 2.5V_0 \Rightarrow dQ > 0$ $\quad V > 2.5V_0 \Rightarrow dQ < 0$

$$Q_{BD} = \int_{V_0}^{2.5V_0} 2p_0(5 - 2V/V_0)dV = 4.5p_0V_0 > 0$$

$$Q_{DC} = \int_{2.5V_0}^{3V_0} 2p_0(5 - 2V/V_0)dV = -0.5p_0V_0 < 0$$

[讨论5] 升温一定吸热，吸热一定升温？

T↑不一定吸热　$T\uparrow$

- 等容等压　$Q=Q_{吸}$
- 绝　　热　$Q=0$
- 多方及其它　$C=\dfrac{\gamma-n}{1-n}C_V$　$Q可能=Q_{放}$

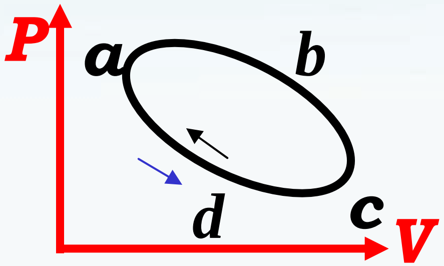
吸热不一定T↑　$Q_{吸}$

- 等容等压　T↑
- 等　　温　T=const
- 多方及其它　T可能↑　T可能↓

4.5对循环过程的应用

1° 基本概念

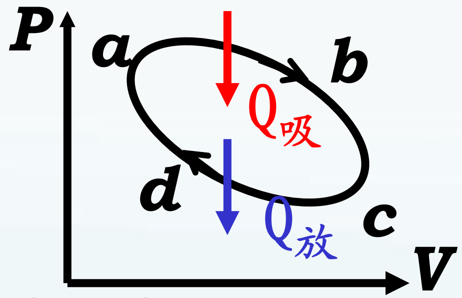
(1) 循环过程: 从初态出发最终回到原态的准静态过程



正（ 热 ）循环: p-V图上沿顺时针循环

逆 (致冷) 循环: .... 反.............

(2) 热机: 连续不断把热转换成功的装置



abcda 循环

$\Delta E=0 \Rightarrow Q=A$

$Q_吸-|Q_放|=A_{对外净}$

(3) 工质: 循环系统的工作物质

(4) 热机效率 $\eta \overset{def}{=} \dfrac{A_{对外净}}{Q_吸} = \dfrac{Q_吸-|Q_放|}{Q_吸}$

物理意义: 热机从外界吸热转化为对外有用净功百分数

[例题3] 判断(图形改画成p-V图)

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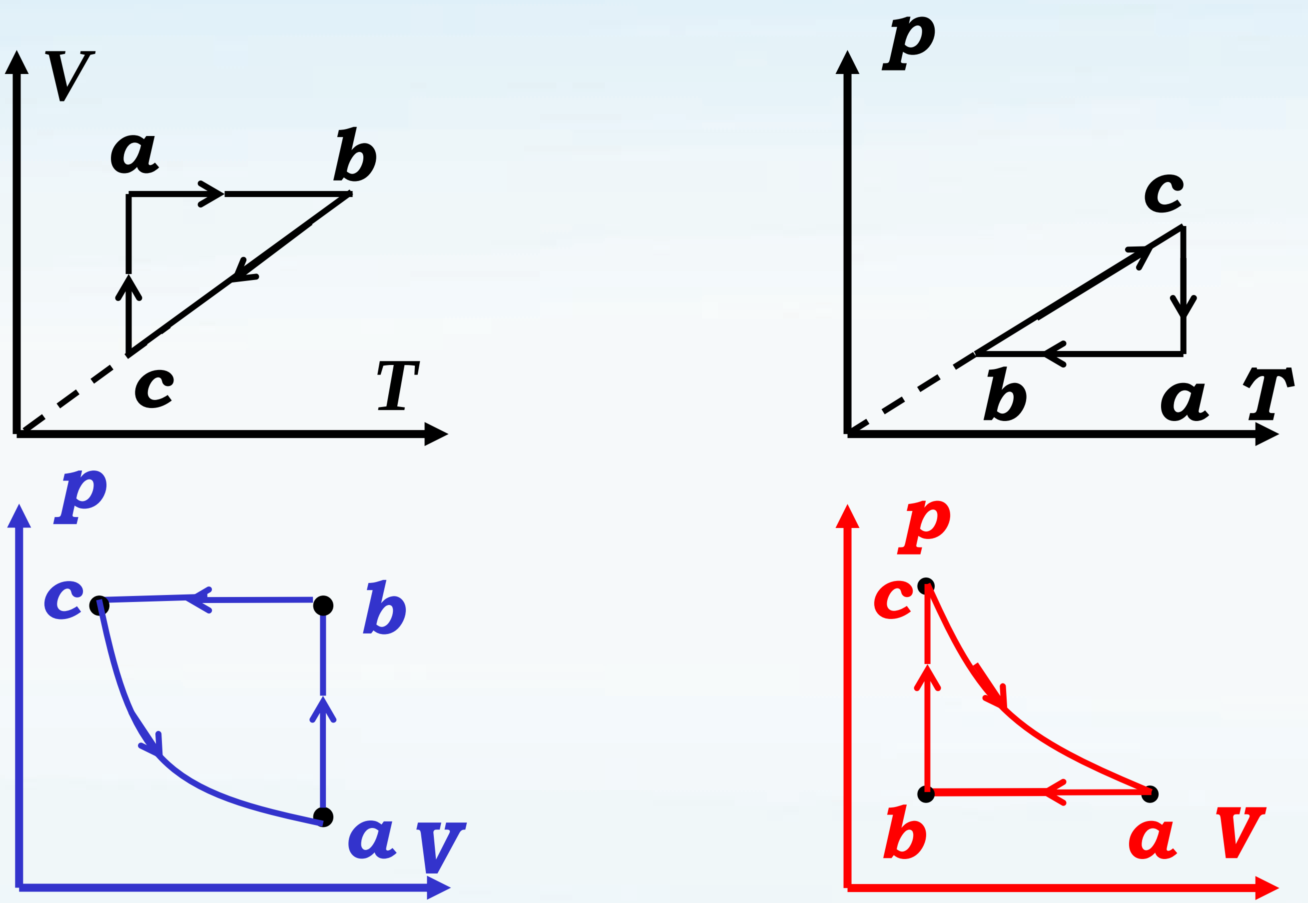


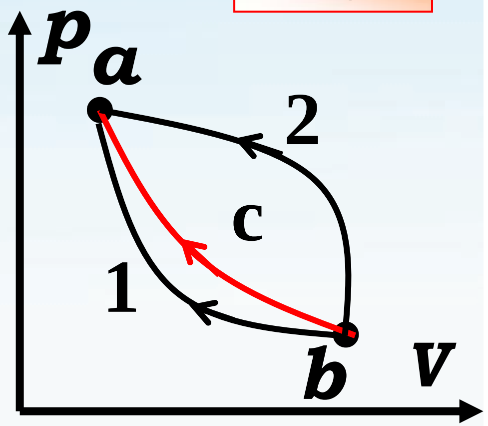
× (1) 该过程正循环 √

√ (2) *ca*对外作正功 √

√ (3) *ab*吸热 ×

√ (4) *bc*等压 ×

[讨论6] **bca**绝热, **b1a,b2a**为任两过程



b1a **b2a**

(1) 放热,负功、放热,负功

(2) 吸热,负功、放热,负功

~~(3) 吸热,正功、吸热,负功~~

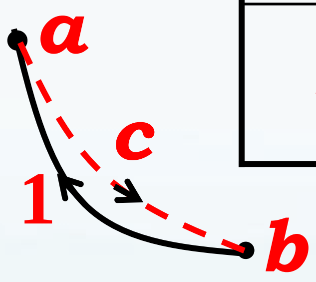
~~(4) 放热,正功、吸热,正功~~

	循环	V单调
A	正>0 逆<0	增>0 减<0

解: $A_{b1a} < 0$

构造循环,由热一律

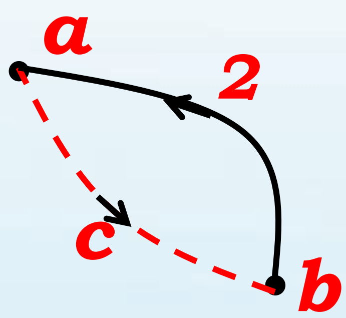
$Q_{b1a} + 0 = A_{acb1a} > 0$



$A_{b2a} < 0$

构造循环,由热一律

$Q_{b2a} + 0 = A_{b2acb} < 0$



[例题4] 1molHe循环: 试求 (1) AB过程的 n (2) ΔE_{AB}

(3) 整个循环 A (4) 整个循环 $Q_{净}$ (5) 该循环的 η

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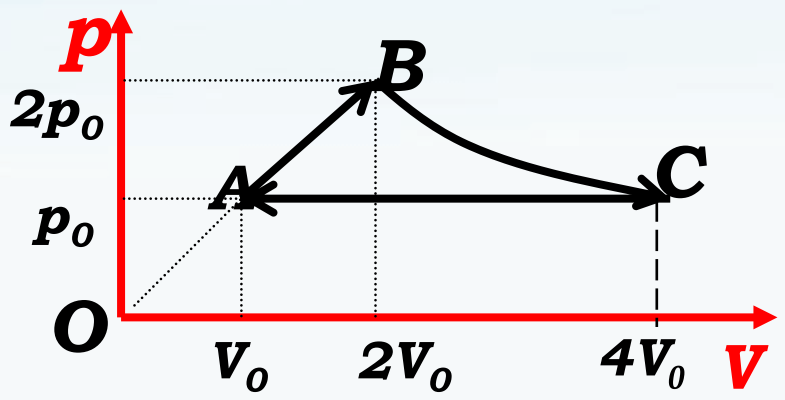
解: (1) $p_0V_0^n = 2p_0(2V_0)^n \Rightarrow n = -1$



(2) $A \to B$ 多方 $\Delta E_{AB} = \upsilon\frac{3}{2}R(T_B - T_A)$

$$= \frac{3}{2}(4p_0V_0 - p_0V_0) = \frac{9}{2}p_0V_0$$

(3) $B \to C$ 等温 $2p_0 \times 2V_0 = p_0 \times V_C \Rightarrow V_C = 4V_0$

$$\left.\begin{aligned} A_{BC} &= \upsilon RT_B \ln(4V_0/2V_0) \\ A_{CA} &= p_0(V_0 - 4V_0) \\ A_{AB} &= (p_0 + 2p_0)V_0/2 \end{aligned}\right\} \Rightarrow A = A_{BC} + A_{CA} + A_{AB}$$

$$= (4\ln 2 - 3/2)p_0V_0$$

(4) 由热一律 $Q_{净吸} = A$

(5) $Q_{AB} = \Delta E_{AB} + A_{AB} = 6p_0V_0 > 0$

$Q_{BC} = A_{BC} = 4p_0V_0\ln 2 > 0$ $Q_{CA} = \Delta E_{CA} + A_{CA} < 0$

$$\eta = A/Q_{吸} = \frac{4\ln 2 - 3/2}{4\ln 2 + 6}$$

(5) 致冷机(逆循环)

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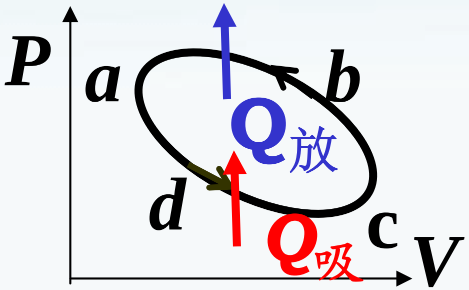
①致冷系数

$$\omega \overset{def}{=} \frac{Q_{吸}}{\left|A_{对系净}\right|} = \frac{Q_{吸}}{\left|Q_{放}\right| - Q_{吸}}$$

$$adcba: \Delta E = 0 \xrightarrow{循环} Q = A$$

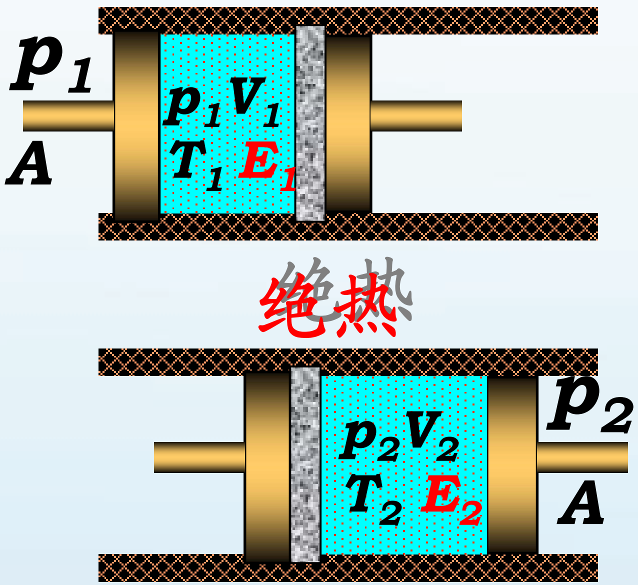
$$Q_{吸} - \left|Q_{放}\right| = A_{adc} + A_{cba} = -\left|A_{对系净}\right|$$



物理意义:用系统从低温热源吸热Q

与对系统作净功的比值表征致冷机吸热本领

②焦耳汤姆孙效应



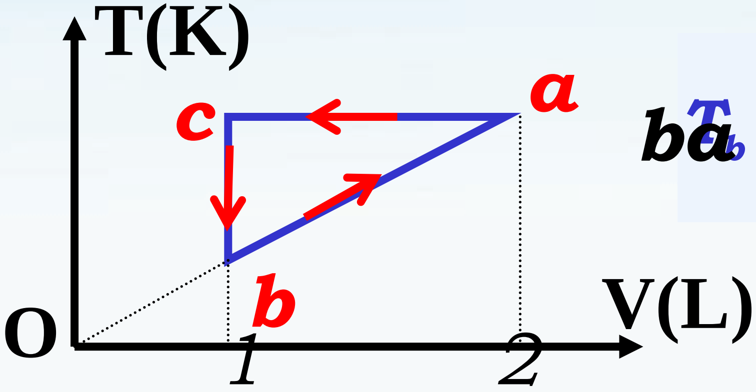
$$O = E_2 - E_1 + p_2V_2 - p_1V_1 \Rightarrow H_2 = H_1$$

理想气体绝热节流过程焓不变 T不变

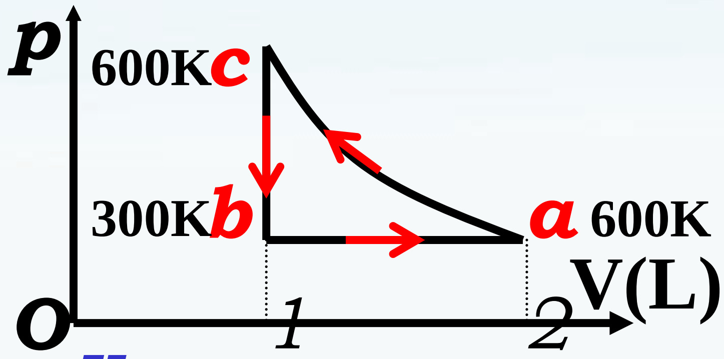
实际气体节流后

T↓ → 正节流　T↑ → 负节流

[讨论7] 1mol单原子分子理想气体循环如T－V图，T_c=600K. 试求 (1) Q_{ac}, Q_{cb}, Q_{ba} (2) 整个循环$A_{净}$ (3) ηORω



ba $T_b = \dfrac{V_b}{V_a} T_a$



解(1) ac等温压缩 $Q_{ac} = A_{ac} = \upsilon RT \ln\dfrac{V_c}{V_a} = (600\ln\dfrac{1}{2})R = -416R$

cb等容降压(温) $Q_{cb} = \Delta E = \upsilon C_V \Delta T = 1\times\dfrac{3R}{2}(300-600) = -450R$

ba等压膨胀 $Q_{ba} = \upsilon C_p \Delta T = 1\times\dfrac{5R}{2}(600-300) = 750R$

(2) 由热一律 $A = Q_{ac} + Q_{cb} + Q_{ba} = -116R$

(3) $\omega = \dfrac{Q_{吸}}{|Q_{放}| - Q_{吸}} = \dfrac{750R}{116R} = 6.47$

2° 卡诺循环

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为了提高热机效率，卡诺提出理想循环——卡诺循环

(1) 卡诺循环

工质只与两个恒温热库交换热量的准静态循环过程

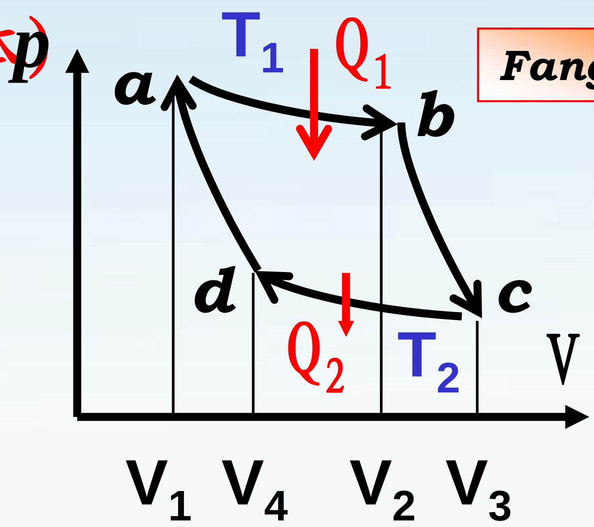
(2) 卡诺机

按卡诺循环工作的热机

(3) 卡诺循环的组成

两等温，两绝热共4个准静态过程

(4) 卡诺热机的效率(工质为理想气体)



$a \rightarrow b$(等温膨胀) $\Delta E_1=0$

$Q_1=A_1=\upsilon RT_1\ln(V_2/V_1)>0$,吸热

$b \rightarrow c$(绝热膨胀)

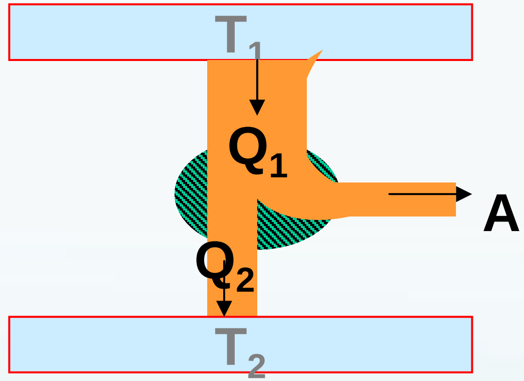
$Q=0$, $A_2=-\Delta E_2=\upsilon C_V(T_1-T_2)$

$c \rightarrow d$(等温压缩) $\Delta E_3=0$

$Q_2=A_3=\upsilon RT_2\ln(V_4/V_3)<0$,放热

$d \rightarrow a$(绝热压缩)

$Q=0$, $A_4=-\Delta E_4=\upsilon C_V(T_2-T_1)$



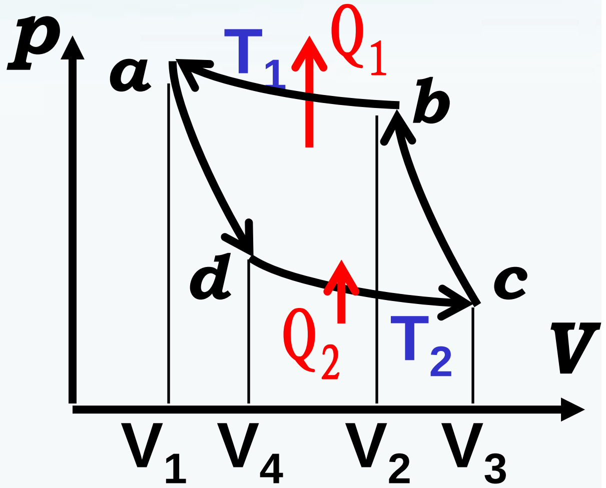
$$\therefore A=A_1+\cancel{A_2}+A_3+\cancel{A_4}=Q_1+Q_2=Q_1-|Q_2|$$

$$\therefore \eta=\frac{A}{Q_1}=\frac{Q_1-|Q_2|}{Q_1}=1-\frac{|Q_2|}{Q_1}=1-\upsilon RT_2\ln(V_3/V_4)/\upsilon RT_1\ln(V_2/V_1)$$

$$\left.\begin{array}{l} bc\text{绝热膨胀}\ V_2^{\gamma-1}T_1=V_3^{\gamma-1}T_2 \\ da\text{绝热压缩}\ V_4^{\gamma-1}T_2=V_1^{\gamma-1}T_1 \end{array}\right\}\Rightarrow \frac{V_2}{V_1}=\frac{V_3}{V_4}\quad \therefore \boxed{\eta=\frac{T_1-T_2}{T_1}}$$

总结：完成一次卡诺循环，必须有高温、低温两个热源
两热源温差越大，从高温热源吸热利用率越高
不可获得$T_1=\infty$或$T_2=0K$，卡诺循环效率恒<1。

(5) 卡诺致冷机 [实例：冰箱、热泵]

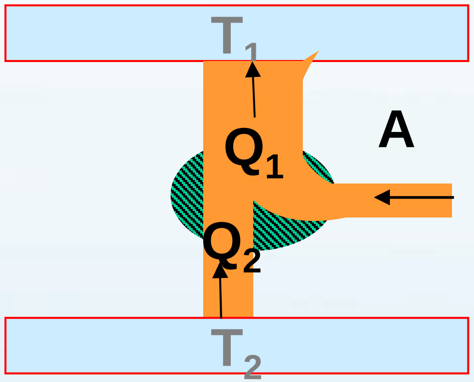


b→a(等温压缩)

$$Q_1=A_1=\upsilon RT_1\ln(V_1/V_2)<0$$

d→c(等温膨胀)

$$Q_2=A_3=\upsilon RT_2\ln(V_3/V_4)>0$$



$$\omega=\frac{Q_2}{|Q_1|-Q_2}=\frac{\upsilon RT_2\ln(V_3/V_4)}{\upsilon RT_1\ln(V_2/V_1)-\upsilon RT_2\ln(V_3/V_4)}=\frac{T_2}{T_1-T_2}$$

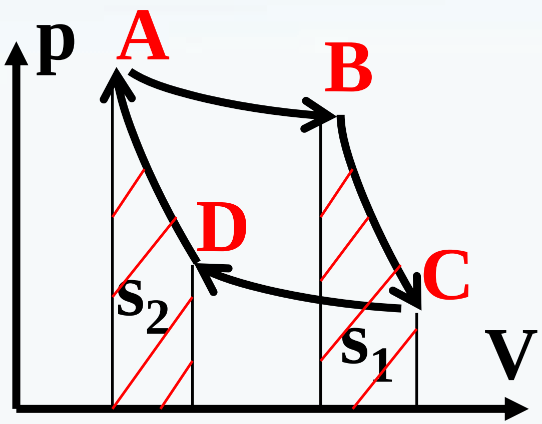
显然，$T_2\downarrow\omega\downarrow$，

即对系统作同样功，低温越低，从低温热源吸热越少；
或者从低温热源吸取同样热量，低温越低，作功越多.

[讨论8]理想气体卡诺循环两绝热线下面积(阴影部分)分别为s_1和s_2,则

(A) $s_1>s_2$;　(B) $s_1=s_2$;

(C) $s_1<s_2$;　(D) 无法确定



解: $s_1 = A_{BC} = -\Delta E_{BC} = \upsilon C_V(T_B - T_C)$

$$s_2 = |A_{DA}| = \Delta E_{DA} = \upsilon C_V(T_A - T_D)$$

$$\because T_A = T_B, T_D = T_C \Rightarrow s_1 = s_2$$

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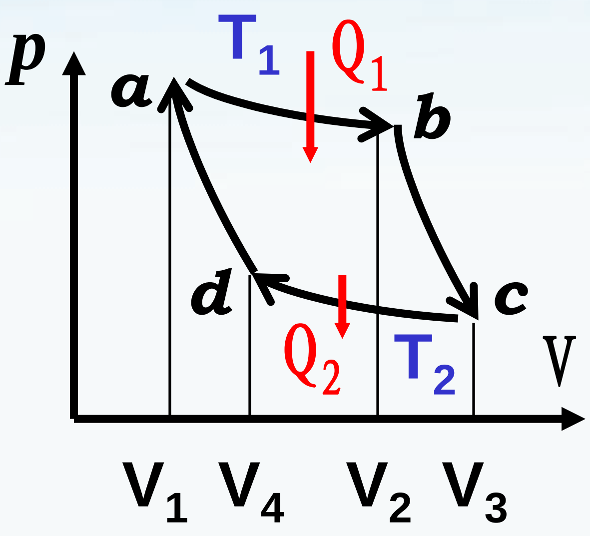
[例题5]

1mol理气在T_1=400K与T_2=300K间作可逆卡诺循环。在400K线上起始$V_1=0.001m^3$，终止$V_2=0.005m^3$，求此气体在每一循环中

(1) 所作净功A

(2) 从高温热源吸热Q_1

(3) 向低温热源放热Q_2



解 (1) $A = A_{ab} + \cancel{A_{bc}} + A_{cd} + \cancel{A_{da}}$

$$= \upsilon RT_1 \ln(V_2/V_1) + \upsilon RT_2 \ln(V_4/V_3)$$

$$\Rightarrow A = R(T_1 - T_2)\ln(V_2/V_1) \Rightarrow A = 8.31\times 100\ln 5 = 1337J$$

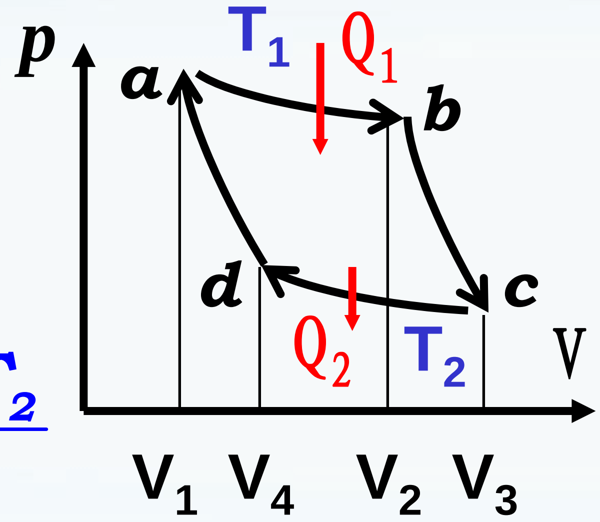
(2) $Q_1 = A_{ab} = \upsilon RT_1 \ln(V_2/V_1) = 5348J$

or. $Q_1 = A/\eta = 1337/25\% = 5348J$ $\qquad \eta = 1 - T_2/T_1 = 25\%$

(3) $Q_2 = A_{cd} = \upsilon RT_2 \ln(V_1/V_2) = -4011J$

or. $|Q_2| = Q_1 - A = 4011J$

[讨论9]卡诺机高、低温热源分别为27ºC、-73ºC，工作物质为10mol的空气,若在等温膨胀过程中气缸体积增大到原来的e倍,确定此热机每一循环作功



解: $\dfrac{A}{A_{ab}} = \dfrac{A}{Q_{吸}} = \eta$

$$\rightarrow A = A_{ab}\eta = \upsilon R T_1 \ln(V_2/V_1)\frac{T_1 - T_2}{T_1}$$

$$= 10 \times 8.31 \times 300 \ln e \times \frac{300 - 200}{300} = 8.31 \times 10^3 \text{J}$$

[讨论10] 某理气分别进行两卡诺循环: 1 ($abcda$) 和2($a'b'c'd'a'$),两循环曲线所围面积相等

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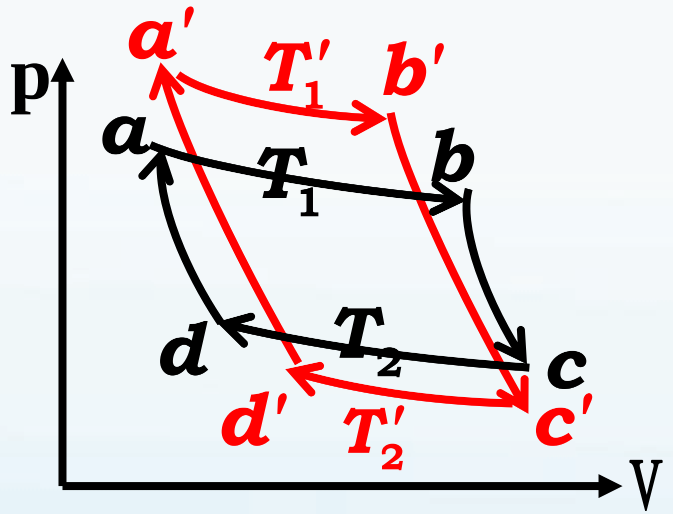
设循环1效率η, 每次循环从高温热源吸热Q;
循环2效率η′, 每次循环从高温热源吸热Q′,
则 (A) $\eta < \eta'$, $Q < Q'$; (B) $\eta < \eta'$, $Q > Q'$; √
(C) $\eta > \eta'$, $Q < Q'$; (D) $\eta > \eta'$, $Q > Q'$.

解: $\left.\begin{aligned} \eta &= 1 - \frac{T_2}{T_1} \\ \eta' &= 1 - \frac{T_2'}{T_1'} \end{aligned}\right\} \xrightarrow{T_2 > T_2',\, T_1 < T_1'} \eta < \eta'$



$\left.\begin{aligned} Q &= \frac{A}{\eta} \\ Q' &= \frac{A'}{\eta'} \end{aligned}\right\} \xrightarrow{A = A',\, \eta < \eta'} Q > Q'$

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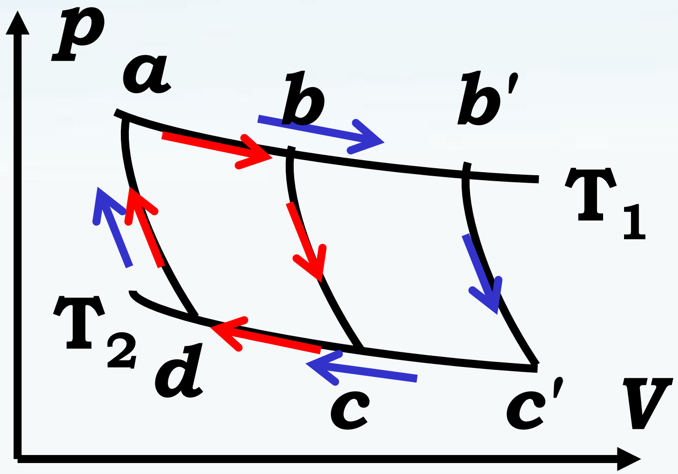
[讨论11]卡诺热机循环曲线从abcda增为ab′c′da,
则其A和η变化是
(A) A增大, η提高;
(B) A增大, η降低;
(C) A和η均不变;
(D) A增大, η不变 √



解: $s_{ab'c'da} > s_{abcda} \Rightarrow A_{ab'c'da} > A_{abcda}$

$$\left.\begin{aligned} \eta_{abcda} &= 1-\frac{T_2}{T_1} \\ \eta_{ab'c'da} &= 1-\frac{T_2}{T_1} \end{aligned}\right\} \Rightarrow \eta_{ab'c'da} = \eta_{abcda}$$

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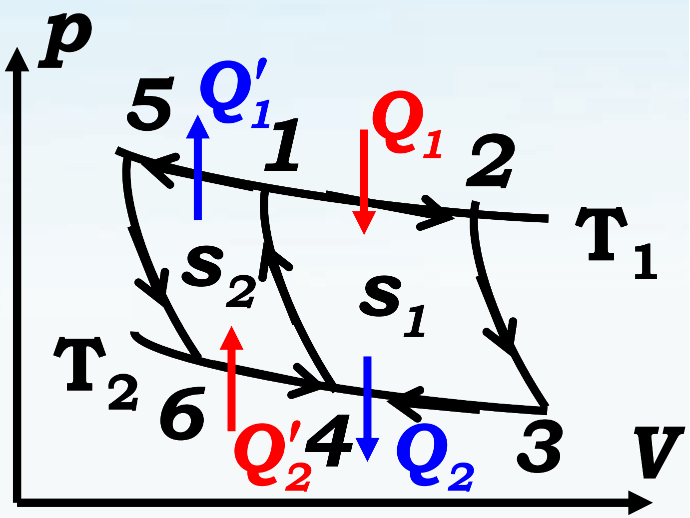
[思考12]*一定量某理气由一卡诺正与逆组成循环, $T_1=4T_2$, $S_1=2S_2$ 求 $\eta_{123415641}$



解: $\eta = 1 - \dfrac{|Q_{放}|}{Q_{吸}} = 1 - \dfrac{T_2}{T_1}$

$$\Rightarrow \eta = 1 - \frac{Q_1' + Q_2}{Q_1 + Q_2'} = \frac{1}{3}$$

$$\left.\begin{aligned} &\frac{Q_1}{Q_2} = \frac{T_1}{T_2} = 4 \\ &Q_1 - Q_2 = S_1 \\ &\frac{Q_1'}{Q_2'} = \frac{T_1}{T_2} = 4 \\ &Q_1' - Q_2' = S_2 \\ &S_1 = 2S_2 \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} &Q_1 = \frac{8}{3}S_2 \\ &Q_2 = \frac{2}{3}S_2 \\ &Q_1' = \frac{4}{3}S_2 \\ &Q_2' = \frac{1}{3}S_2 \end{aligned}\right.$$

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[讨论13] 热源$T_{高}$是$T_{低}$的n倍, 则理想气体一次卡诺循环, 传给低温热源热量是从高温热源吸取的

(A) n倍 **(B)** n-1倍 **(C)** 1/n倍 **(D)** (n+1)/n倍

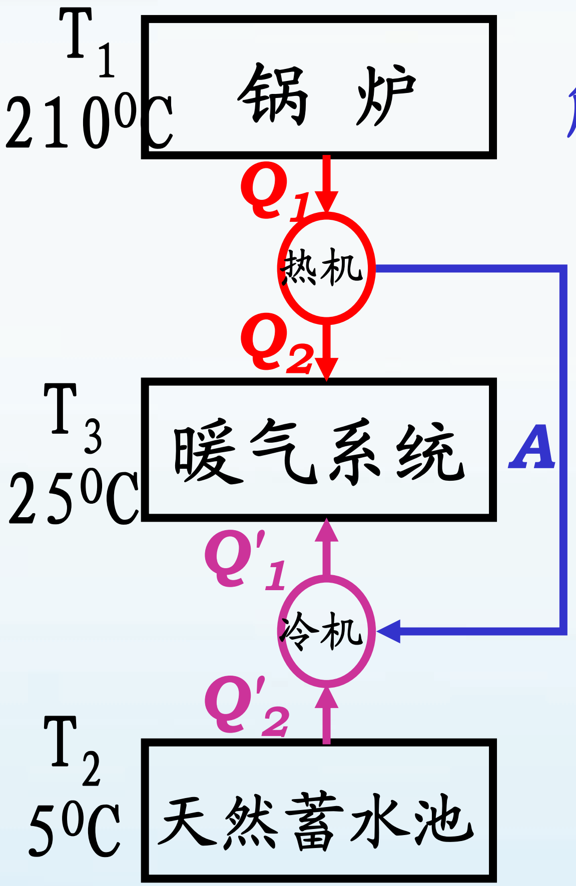
解: 卡诺循环$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{|Q_{放}|}{Q_{吸}} \Rightarrow |Q_{放}| = \frac{T_2}{T_1} Q_{吸} = \frac{1}{n} Q_{吸}$

[讨论14] 可逆卡诺热机η, 其致冷机$\omega = T_2/(T_1 - T_2)$, 则η、ω的关系为

解:

$$\left.\begin{aligned} \eta &= \frac{T_1 - T_2}{T_1} \\ \omega &= \frac{T_2}{T_1 - T_2} \end{aligned}\right\} \Longrightarrow \eta\omega = \frac{T_2}{T_1}$$

[例题6]动力暖气装置由一台卡诺热机与一台卡诺致冷机组成.热机靠燃料燃烧时释放热量工作并向暖气系统放热.同时热机带动致冷机从天然蓄水池中吸热并向暖气系统放热.计算暖气系统得到的热量(已知$Q_1=2.1\times10^7$J)



解: $\eta = 1-\dfrac{T_3}{T_1} = 1-\dfrac{|Q_{放}|}{Q_{吸}} \Rightarrow |Q_2| = \dfrac{T_3}{T_1}Q_1$

$$|Q_1'| = Q_2' + A$$

$$A = \eta Q_1 = \left(1-\frac{T_3}{T_1}\right)Q_1$$

$$\omega = \frac{T_2}{T_3-T_2} = \frac{Q_2'}{|Q_1'|-Q_2'}$$

$$\Rightarrow Q_2' = \frac{T_2}{T_3}|Q_1'|$$

$$\Rightarrow |Q_1'| = \frac{T_3(T_1-T_3)}{T_1(T_3-T_2)}Q_1$$

+

‖

2.08×10^8J

德国的骄傲

1897

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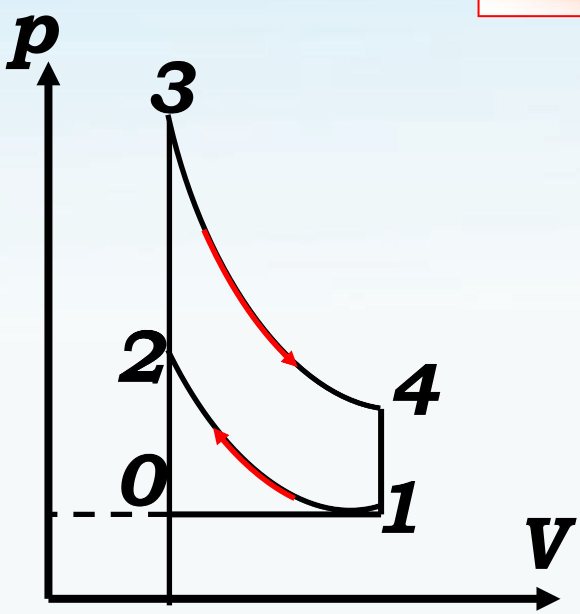
[讨论15] 求奥托循环效率

0进气1绝热压缩2点火3
绝热膨胀4排气1扫气0



解：$Q_{\text{吸}} = \upsilon C_V (T_3 - T_2) > 0$

$Q_{\text{放}} = \upsilon C_V (T_1 - T_4) < 0$

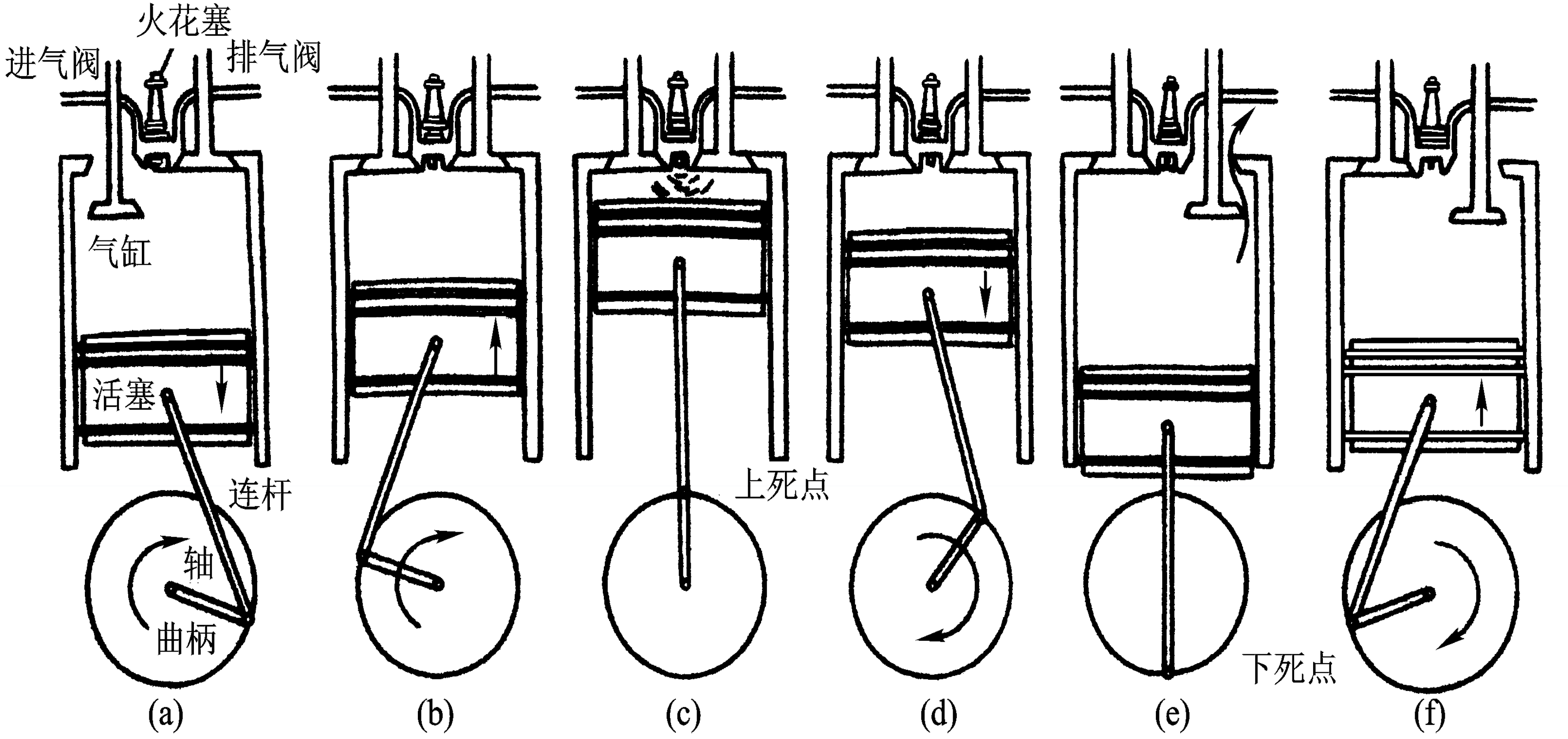
$$\eta = 1 - \frac{|Q_{\text{放}}|}{Q_{\text{吸}}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1}{T_2}$$

$$\left.\begin{aligned} 12:&\quad V_1^{\gamma-1} T_1 = V_2^{\gamma-1} T_2 \\ 34:&\quad V_2^{\gamma-1} T_3 = V_1^{\gamma-1} T_4 \end{aligned}\right\}$$

$$\Rightarrow \frac{T_1}{T_2} = \frac{T_4}{T_3} = \frac{T_4 - T_1}{T_3 - T_2}$$

$$\Rightarrow \eta = 1 - K^{1-\gamma}$$

绝热容积压缩比



0-1 过程：进气　1-2 过程：压缩　2-3 过程：加热　3-4 过程：膨胀　4-1 过程：排气　1-0 过程：扫气

[讨论16] 求狄塞尔循环效率

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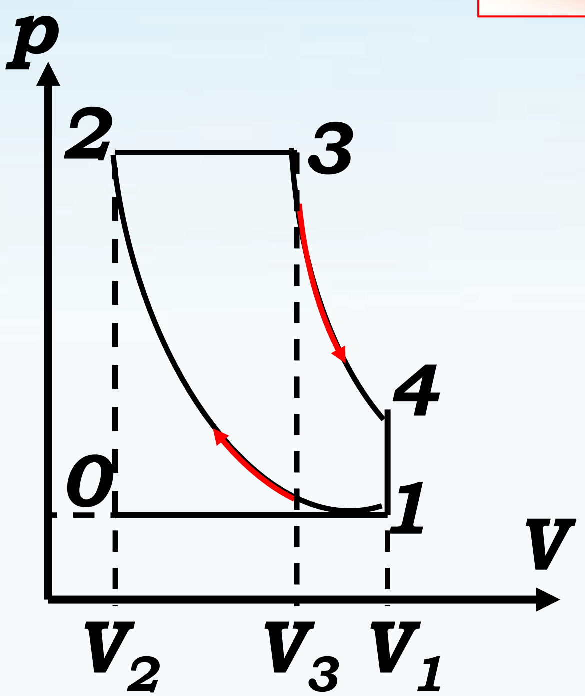
0进气1绝热压缩2等压点火
3绝热膨胀4排气1扫气0



解： $Q_{吸} = \upsilon C_p (T_3 - T_2) > 0$

$Q_{放} = \upsilon C_V (T_1 - T_4) < 0$

$$\eta = 1 - \frac{|Q_{放}|}{Q_{吸}} = 1 - \frac{(T_4 - T_1)}{\gamma\,(T_3 - T_2)}$$

$$12: \frac{T_2}{T_1} = K^{\gamma-1}$$

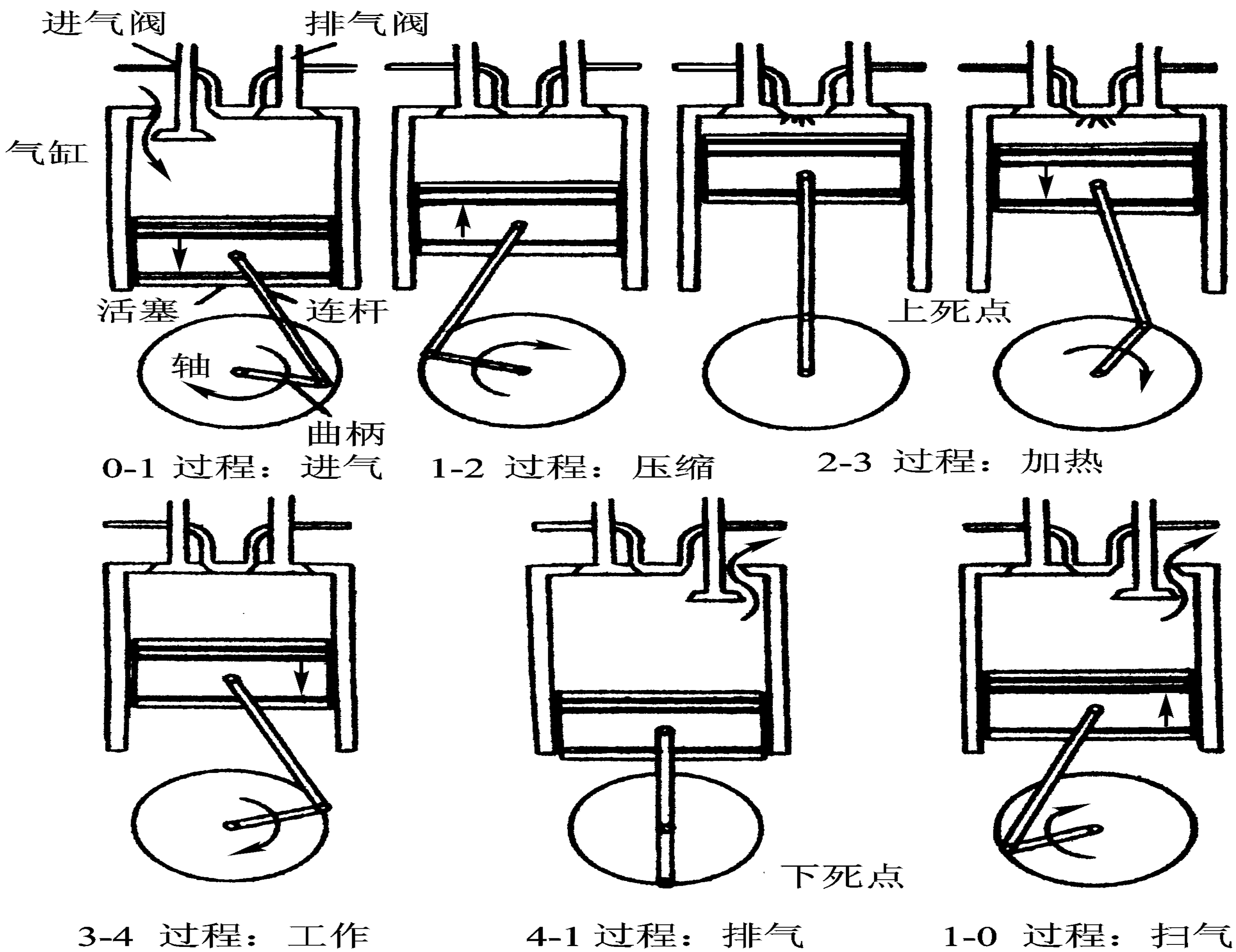
$$23: \frac{T_3}{T_2} = \frac{V_3}{V_2} = \rho$$

$$34: \frac{T_4}{T_3} = \left(\frac{\rho}{K}\right)^{\gamma-1}$$

$$\Rightarrow \eta = 1 - \frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)K^{\gamma-1}}$$

K：绝热容积压缩比

ρ：定压容积压缩比


进气阀
排气阀
气缸
活塞
连杆
轴
曲柄
0-1 过程：进气
1-2 过程：压缩
上死点
2-3 过程：加热
下死点
3-4 过程：工作
4-1 过程：排气
1-0 过程：扫气