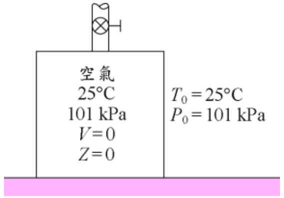
Chapter 8
Exergy: A Measure of Work Potential
可用能:做功能力的度(衡)量

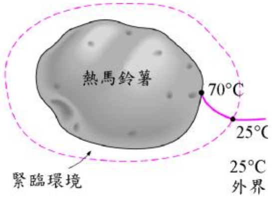
8.1 Exergy: Work Potential of Energy

Exergy (可用能), Availability, Available Energy

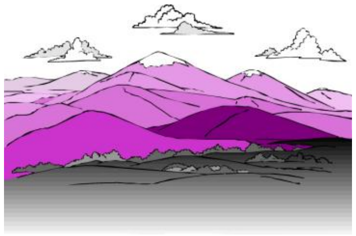


8-1 一系統與其外界處於平衡謂之**停頓狀態 (dead state)**。在停頓狀態，**做功能力(可用能)為零**。

System, immediate surrounding and surrounding

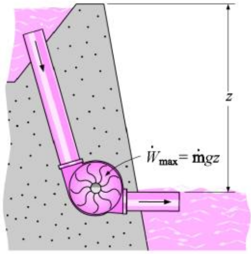


8-3 熱馬鈴薯的緊鄰環境(**immediate surrounding**) 為緊接馬鈴薯旁的空氣溫度梯度區。



8-4 大氣含有非常巨大的能量，但沒有可用能。

Exergy Associated with Potential Energy

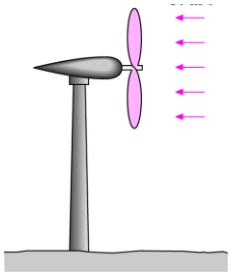


$$x_{pe} = pe = gz$$

8-5 位能的做功能力或可用能等於位能本身。

Exergy Associated with Kinetic Energy

Example 8-1 Wind Energy



$$x_{ke} = ke = V^2/2$$

$$\dot{m} = \rho AV = \rho\frac{\pi D^2}{4}V$$

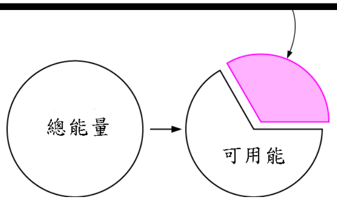
$$X = \dot{m}\cdot ke = \frac{\pi\rho}{8}D^2V^3$$

Betz's Law ？

8-6 動能的做功能力或可用能等於動能本身。

Exergy Associated with a Heat Reservoir

Exergy transfer from a heat reservoir by heat



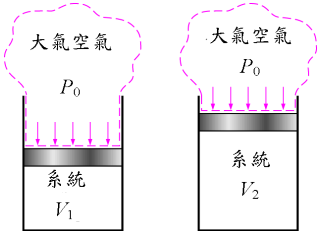
$$\delta W = \delta Q\left(1-\frac{T_o}{T}\right)$$

$$W = \int\left(1-\frac{T_o}{T}\right)\delta Q$$

Example 8-2

能量中藉由可逆熱機亦不能轉換為功的部分，稱為**不可用能 (unavailability, or unavailable energy)**。

8.2 Reversible Work and Irreversibility (可逆功與不可逆性)



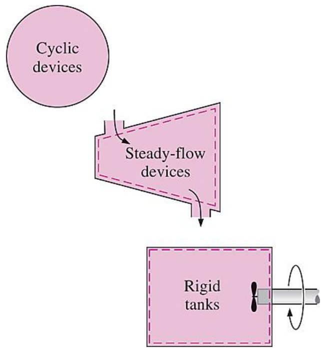
$$W_{surr} = P_o(V_2 - V_1)$$

有效功 (useful work)

$$W_{useful} = W - W_{surr} = W - P_o(V_2 - V_1)$$

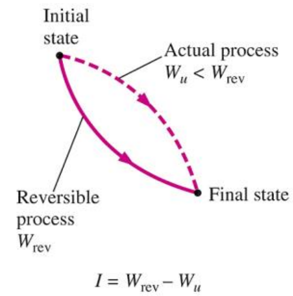
8-8 當一密閉系統膨脹時，必須有部分的功 $W_{surr} = P_o(V_2 - V_1)$ 將大氣推離。

有效功 (useful work)



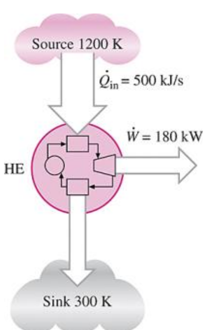
8-9 對於固定容積之系統，**總實際功**和**有效功**是相同 ($W_u = W$)。

可逆功與不可逆性



8-10 可逆功 W_{rev} (**Reversible work**) 與實際有效功 W_u (**Actual useful work**) 之間的差為**不可逆性** I (**Irreversibility, irreversible work**)。

Example 8-3

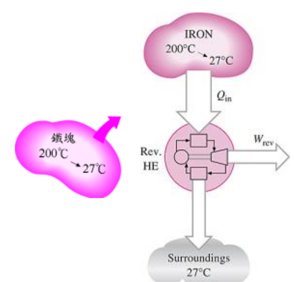


Discussion:

$$W_{rev} = 500 \cdot \left(1 - \frac{300}{1200}\right) = 375 \ kW$$

$$I = 375 - 180 = 195 \ kW$$

Example 8-4



8-13 利用一可逆熱機能將一不可逆的熱傳遞過程成為可逆。

Discussion:

$$W_{rev} = \int_1^2 \left(1 - \frac{T_o}{T}\right) \delta Q = Q - \int_1^2 \left(\frac{T_o}{T}\right) \delta Q \left(T_o \int_1^2 dS\right)$$

$$= Q - T_o (S_2 - S_1) = mC\left[(T_1 - T_o) - \left(T_o \ln T_1 / T_o\right)\right]$$

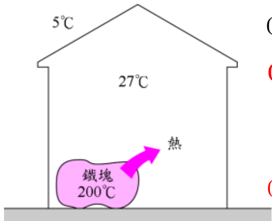
$$= 8191 \ kJ$$

$$Where \ Q = 38925 \ kJ$$

$$I = W_{rev} - W_u = 8191 \ kW$$

Example 8-5

$$COP_{HP}=\frac{T_H}{T_H-T_L}=\frac{1}{1-{T_L}/{T_H}}=\frac{1}{1-{278}/{300}}=13.6$$



(a) $(38925-8191)+8191\times13.6=142132kJ$

(b) $W_{rev}=500\cdot0.45\cdot\left[(473-300)-\left(278\cdot\ln{473}/{300}\right)\right]$

$=10446kJ$

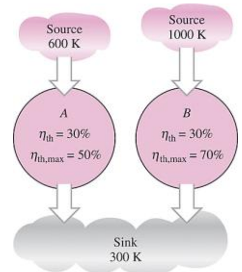
$10446\times13.6=142054kJ$

(c) $W_{rev}=500\cdot0.45\cdot\left[(473-278)-\left(278\cdot\ln{473}/{278}\right)\right]$

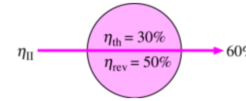
$=10631kJ\cdot$

$10631\times13.6=144585kJ$

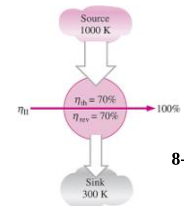
8.3 Second-Law Efficiency, η_{II}



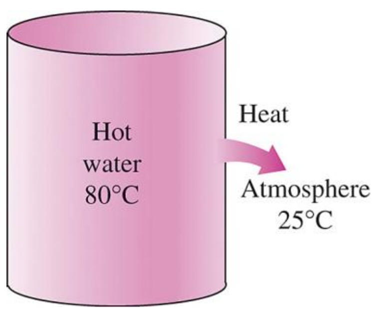
8-15 兩部熱機具有相同熱效率，但具有不同的最大熱效率。



8-16 第二定律效率為設備之性能與其在可逆狀況下之性能的度量。

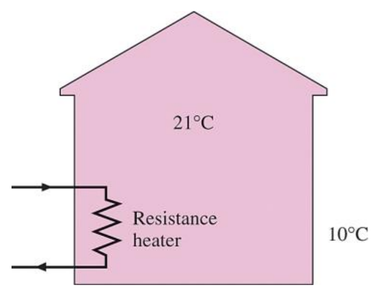


8-17 所有可逆設備第二定律效率為100%。



8-18 若無任何的作功，則自然發生過程的第二定律效率為零。

Example 8-6

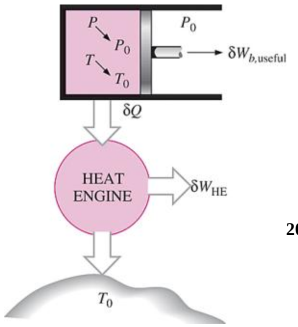


$$COP_{HP,rev}=\frac{1}{1-T_L/T_H}=26.7$$

$$\eta_{II}=1/26.7=3.7\%$$

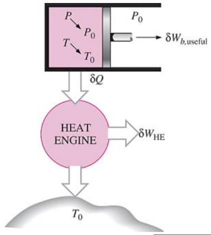
8.4 Exergy Change of a System

Exergy of a fixed mass system



20 固定質量系統的可用能：在指定狀態 (P, T)下經歷一可逆過程，至外界狀態 (P_o, T_o)時，所產生的**有效功**。

8.4 Exergy Change of a System



$$\delta E_{in} - \delta E_{out} = dE_{system}$$

$$\delta Q - \delta W = dU$$

$$\delta W = PdV = (P - P_o)dV + P_o dV = \delta W_{b,useful} + P_o dV$$

$$\delta W_{HE} = (1 - \frac{T_o}{T})(-\delta Q) = -\delta Q + T_o dS$$

$$\delta W_{total\ useful} = \delta W_{HE} + \delta W_{b,useful} = -dU - P_o dV + T_o dS$$

$$W_{total\ useful} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o)$$

Exergy, ψ

$$X = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) + m\frac{V^2}{2} + mgz$$

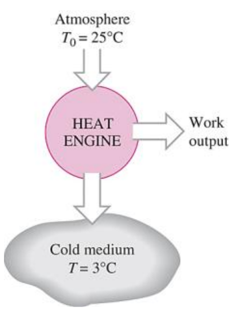
$$\phi = (u - u_o) + P_o(v - v_o) - T_o(s - s_o) + \frac{V^2}{2} + gz$$

$$= (e - e_o) + P_o(v - v_o) - T_o(s - s_o)$$

From state 1 to 2

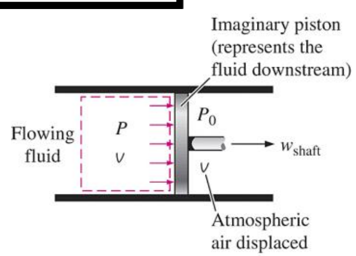
$$W_{rev} = W_{total\ useful} = X_1 - X_2 = m(\phi_1 - \phi_2)$$

Note:



8-21 因藉由傳熱至冷媒介而產生功，所以冷媒介之可用能為正值。

Exergy of a flow mass

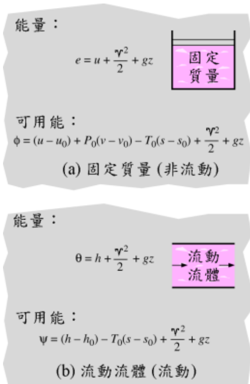


$$Pv = P_0 v + w_{\text{shaft}}$$

$$x_{flow} = Pv - P_o v = (P - P_o)v$$

8-22 流動流體可用能可藉由流動截面的假想活塞所傳遞的有效功而得。

(a) 固定質量,及(b) 流動流體之**能量**及**可用能**。



Nonflow exergy, ψ

$$\boldsymbol{\phi = (u-u_o)+P_o(v-v_o)-T_o(s-s_o)+\frac{V^2}{2}+gz}$$

$$\boldsymbol{=(e-e_o)+P_o(v-v_o)-T_o(s-s_o)}$$

Flow exergy, Ψ

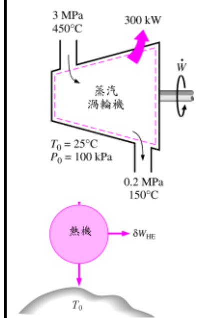
$$x_{flowing\ \ fluid} = x_{nonflowing\ \ fluid} + x_{flow}$$

$$=(u-u_o)+P_o(v-v_o)-T_o(s-s_o)+\frac{V^2}{2}+gz+(P-P_o)v$$

$$=(u+Pv)-(u_o+P_ov_o)-T_o(s-s_o)+\frac{V^2}{2}+gz$$

$$=(h-h_o)-T_o(s-s_o)+\frac{V^2}{2}+gz$$

$$\boldsymbol{\psi=(h-h_o)-T_o(s-s_o)+\frac{V^2}{2}+gz}$$



$$dE_{CV} = \delta Q - \delta W + md(h+ke+pe)$$

$$dS_{CV} = mds + \frac{\delta Q}{T} + dS_{gen}$$

If steady and internal reversible

$$\delta W = \delta Q + md(h+ke+pe) \qquad 0 = mds + \frac{\delta Q}{T}$$

$$\delta W_{HE} = (1-\frac{T_o}{T})(-\delta Q)$$

$$\delta W_{total\ \ useful} = \delta W + \delta W_{HE} = \delta Q + md(h+ke+pe) + (1-\frac{T_o}{T})(-\delta Q)$$

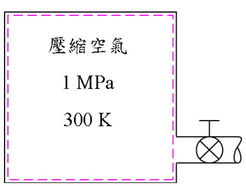
$$= md(h+ke+pe) - mT_o ds = md(h+ke+pe-T_o s)$$

$$W_{total\ \ useful} = m\lfloor (h+ke+pe-T_o s)-(h-T_o s)_o \rfloor$$

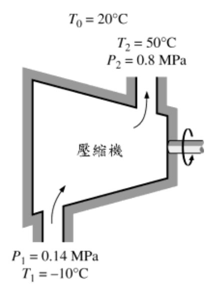
Or, $\boldsymbol{W_{rev} = m\psi,\ \ \psi = (h+ke+pe-T_o s)-(h_o-T_o s_o)}$

From state 1 to 2 $\boldsymbol{W_{rev} = W_{totalusefue} = m(\psi_1-\psi_2)}$

Example 8-7



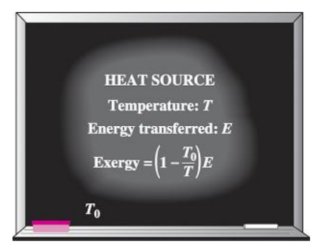
Example 8-8



Discussions:

8.5 Exergy Transfer by Heat, Work, and Mass

Exergy Transfer by heat, Q

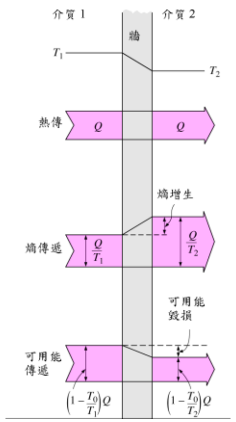


Or,

$$\delta X_{heat} = \left(1-\frac{T_o}{T}\right)\delta Q$$

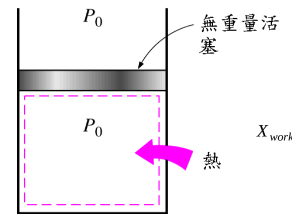
$$X_{heat} = \int\left(1-\frac{To}{T}\right)\delta Q$$

8-26 熱傳之可用能：溫度 T 之熱源，在T_o的外界中，
熱源能量 E 之最大轉換功的量
= 熱源能量 E x 卡洛轉換效率 $\eta_C = 1-\frac{T_o}{T}$



8-27 經由有限溫差的熱傳遞過程之可用能的傳遞及毀損。

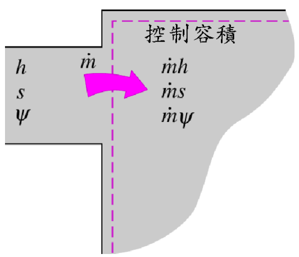
Exergy Transfer by Work, *W*



$$X_{work} = \begin{cases} W - W_{surr} & (\textit{for boundary work}) \\ W & (\textit{for other forms of work}) \end{cases}$$

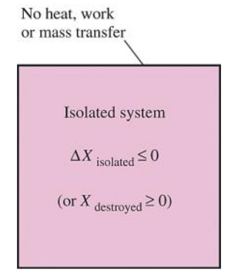
8-28 當系統的壓力維持在大氣壓力下，則無伴隨邊界功之有效功的傳遞。

Exergy Transfer by Mass, *m*



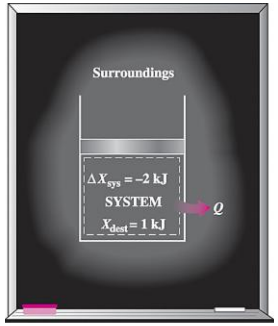
8-29 質量具有能量、和可用能。因此，質量流入或流出系統時，將伴隨**能量**、及**可用能**的傳遞。

8.6 The Decrease of Exergy Principle and Exergy Destruction



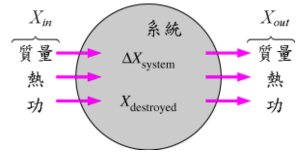
8-30 可用能減損原理中所考慮的隔絕系統。

Decrease of exergy or Exergy destruction



8-31 一系統的可用能改變可能為負，但可用能毀損不能為負。

8.7 Exergy Balance: Closed Systems



8-32 一般系統可用能的傳遞機制。

Exergy balance

$$X_{in} - X_{out} - X_{destroyed} = \Delta X_{system}$$

In rate form

$$\dot{X}_{in} - \dot{X}_{out} - \dot{X}_{destroyed} = \dot{X}_{system}$$

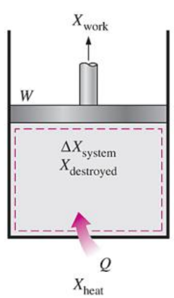
Unit mass

$$x_{in} - x_{out} - x_{destroyed} = \Delta x_{system}$$

$$\dot{X}_{heat} = (1 - T_o / T)\dot{Q} \qquad \dot{X}_{work} = \dot{W}_{useful}$$

$$\dot{X}_{destroyed} = T_o \dot{S}_{gen} \qquad \dot{X}_{system} = dX_{system}/dt$$

Exergy balance for closed systems



$$X_{heat} - X_{work} - X_{destroyed} = \Delta X_{system}$$

8-33 熱傳遞方向取傳至系統，功的方向為傳出系統之密閉系統的可用能平衡。

$$X_{in} - X_{out} - X_{destroyed} = \Delta X_{system}$$

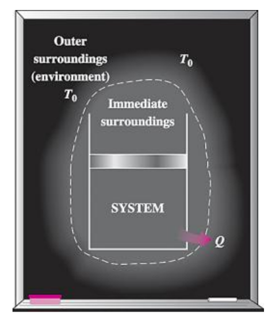
Unit mass

$$x_{in} - x_{out} - x_{destroyed} = \Delta x_{system}$$

Exergy balance equations

$$\sum\left(1 - \frac{T_o}{T_k}\right)Q_k - \left[W - P_o(V_2 - V_1)\right] - T_o S_{gen} = X_2 - X_1$$

$$\sum\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k - \left[\dot{W} - P_o\dot{V}_{system}\right] - T_o\dot{S}_{gen} = \dot{X}_{system}$$



8-34 藉由包含系統與其緊鄰環境的延伸系統的可用能平衡，可計算系統邊界外的可用能毀損。

$$\sum\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k - \left[\dot{W} - P_o\dot{V}_{system}\right] - T_o\dot{S}_{gen} = \dot{X}_{system}$$

Exergy Balance: Closed Systems

Example 8-9

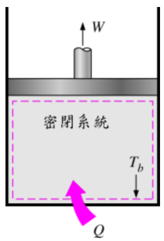


圖 8-35

$$E_{in} - E_{out} = \Delta E_{system} \rightarrow Q - W = E_2 - E_1 \qquad (1)$$

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system} \rightarrow \int_1^2 \left(\frac{\delta Q}{T}\right)_{boundary} + S_{gen} = S_2 - S_1 \qquad (2)$$

$(1) - T_o \times (2) \rightarrow$

$$\int_1^2 \left(1 - \frac{T_o}{T_{boundary}}\right)\delta Q - W - T_o S_{gen}$$
$$= E_2 - E_1 - T_o(S_2 - S_1) = X_2 - X_1 - P_o(V_2 - V_1)$$

$$W_{useful} = [W - P_o(V_2 - V_1)] = X_1 - X_2 + \int_1^2 \left(1 - \frac{T_o}{T_{boundary}}\right)\delta Q - T_o S_{gen}$$

$$\sum\left(1 - \frac{T_o}{T_k}\right)Q_k - [W - P_o(V_2 - V_1)] - T_o S_{gen} = X_2 - X_1$$

Exergy Balance: Closed Systems

Example 8-10

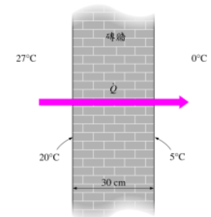


圖 8-36

$$\sum\left(1 - \frac{T_o}{T_k}\right)Q_k - [W - P_o(V_2 - V_1)] - T_o S_{gen} = X_2 - X_1$$

$$\left(1 - \frac{T_o}{T_{high}}\right)Q - \left(1 - \frac{T_o}{T_{low}}\right)Q - 0 - (T_o S_{gen} = X_{destroy}) = 0$$

$$X_{destroy} = Q\left(\frac{T_o}{T_{low}} - \frac{T_o}{T_{high}}\right)$$

$$X_{in} - X_{out} - X_{destroy} = \Delta X = X_2 - X_1$$

Exergy Balance: Closed Systems

Example 8-11

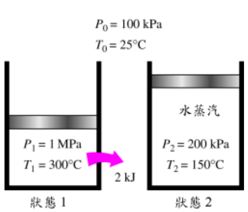


圖 8-37

X_1=35kJ, X_2=25.4kJ, W_{rev}=9.6kJ,

W_{useful}=W-Po(V_2-V_1)=5.3kJ,

I=$X_{destroyed}$=4.3kJ

Or,

S_2-S_1 = Q/T_o+ S_{gen}, S_{gen}=0.0144kJ/K,

I=$T_o S_{gen}$=4.3kJ

Discussion:

Q = 2kJ, $X_{destroyed}$=4.3kJ ? ,

Internal irreversible,

S_2- S_1 = Q/T_{avg}+ $S_{gen,int}$,

>0   <0   thus >0

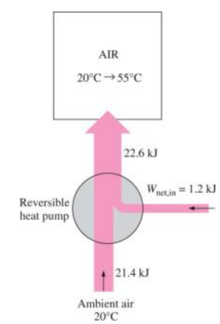


圖 8-39 藉由僅需消耗1.2 kJ 功的可逆熱泵，
於系統上可完成相同的效果。

Exergy Balance: Closed Systems

Example 8-14

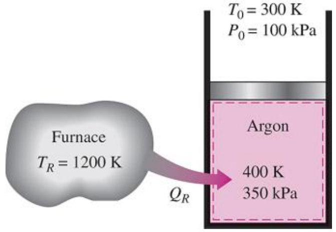
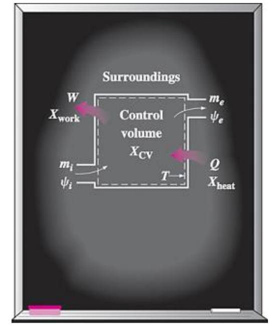


圖 8-41

p.451-452

Discussions:

8.8 Exergy Balance: Control Volumes



$$X_{in} - X_{out} - X_{destroyed} = \Delta X_{system}$$

Unit mass

$$x_{in} - x_{out} - x_{destroyed} = \Delta x_{system}$$

In rate form

$$\dot{X}_{in} - \dot{X}_{out} - \dot{X}_{destroyed} = \dot{X}_{system}$$

$$\dot{X}_{heat} = (1 - T_o/T)\dot{Q} \quad \dot{X}_{work} = \dot{W}_{useful} \quad \dot{X}_{mass} = \dot{m}\varphi$$

$$\dot{X}_{destroyed} = T_o\dot{S}_{gen} \quad \dot{X}_{system} = dX_{system}/dt$$

圖 8-42 如同熱與功的傳遞，也可由質量傳入或傳出控制容積。

Exergy Balance: Control Volumes

$$\sum\left(1-\frac{T_o}{T_k}\right)Q_k - [W - P_o(V_2 - V_1)] + \sum m_i\psi_i - \sum m_e\psi_e - T_oS_{gen} = (X_2 - X_1)_{CV}$$

$$\sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k - [\dot{W} - P_o(dV/dt)_{CV}] + \sum \dot{m}_i\psi_i - \sum \dot{m}_e\psi_e - T_o\dot{S}_{gen} = (dX/dt)_{CV}$$

Steady-flow

$$\sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{m}_i\psi_i - \sum \dot{m}_e\psi_e - T_o\dot{S}_{gen} = 0$$

, and single stream

$$\sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k - \dot{W} + \dot{m}(\psi_i - \psi_e) - T_o\dot{S}_{gen} = 0$$

$$\psi = (h - h_o) - T_o(s - s_o) + \frac{V^2}{2} + gz$$

$$\psi_1 - \psi_2 = (h_1 - h_2) - T_o(s_1 - s_2) + \left(\frac{V_1^2 - V_2^2}{2}\right) + g(z_1 - z_2)$$

Reversible work

$$\dot{W}_{rev} = \sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k + \dot{m}(\psi_i - \psi_e), \text{ as } \dot{S}_{gen} = 0$$

, and adiabatic

$$\dot{W}_{rev} = \dot{m}(\psi_i - \psi_e), \text{ as } \dot{S}_{gen} = 0 \text{ and adiabatic}$$

Exergy Balance: Control Volumes

Second-Law Efficiency, η_{II}

$$\eta_{II} = \frac{\textit{Exergy recovered}}{\textit{Exergy supplied}}$$

Turbine

$$\eta_{II,turb} = \frac{w}{w_{rev}} = \frac{h_1 - h_2}{\psi_1 - \psi_2}, \quad \eta_{II,turb} = 1 - \frac{T_o s_{gen}}{\psi_1 - \psi_2}$$

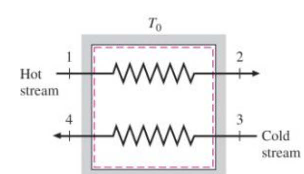
Compressor

$$\eta_{II,comp} = \frac{w_{rev,in}}{w} = \frac{\psi_2 - \psi_1}{h_2 - h_1}, \quad \eta_{II,comp} = 1 - \frac{T_o s_{gen}}{h_2 - h_1}$$

Heat Exchanger

$$\eta_{II,heat\ exchanger} = \frac{\dot{m}_{cold}(\psi_4 - \psi_3)}{\dot{m}_{hot}(\psi_1 - \psi_2)},$$

$$\eta_{II,HX} = 1 - \frac{T_o S_{gen}}{\dot{m}_{hot}(\psi_1 - \psi_2)}$$



Exergy Balance: Control Volume

Example 8-15

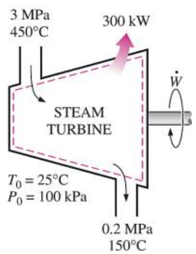


圖 8-45

Example 8-16

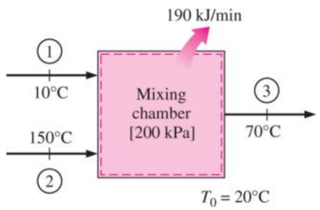


圖 8-46

Exergy Balance: Control Volume

Example 8-17

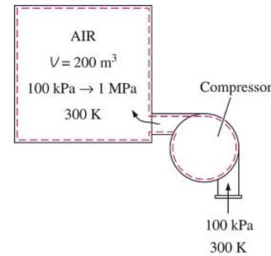


圖 8-47

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