Engineering Thermodynamics

1 Basic Definition

1.1 能量转换装置

- **热能动力装置：**
  - **蒸汽动力装置(Vapor Power Systems)**：工质：Steam/Water
  - **燃气动力装置(Gas Power Systems)**：工质：燃气
    - 内燃机
    - 燃气轮机
    - 喷气发动机
- **制冷和热泵装置（Refridgeration and Heat Pump Systems）**：工质：制冷剂

1.2 热力系

物质交换：

- 闭口系（closed system）：控制质量（C.M.）——与外界无物质交换
- 开口系（open system）：控制体积（C.V.）——与外界有物质交换

能量交换：

- 简单热力系：与外界只交换热量和一种形式的准静功
- （简单压缩系（simple compressive system）：准静功为可逆体积变化功）
- 绝热系（adiabatic system）：与外界无热量交换
- 孤立系（isolated system）：与外界无能量交换也无物质交换

1.3 热力状态与基本状态参数

- **Thermodynamic State**
  - steady state: 状态参数不随时间变化
  - equilibrium state：所有参数达到平衡，即不再变化
- **State Properties**
  - extensive property: M, V, U, E, H, S
  - intensive property: T, p, 广延量的比参数（v, u, h, s）
  - Basic Properties: T, p, v
- **Process**

  irreversibility:

  - reversible:(quasi-steady & non-dissipative)（准稳态及无耗散）
  - irreversible

  thermodynamic:

  - quasi-steady 准静态
  - isothermal 等温
  - adiabatic 绝热
  - isentropic 等熵
- **Process para**
  - Q, W

1.4 Zeroth law of thermodynamics

> “It`s a matter of experience that when two objects are in thermal equilibrium with a third object, they are in thermal equilibrium with one another. ”

1.5 Temperature Scales

- **Kelvin scale**
- **Rankine scale**

$$T(^{\circ}R) = 1.8T(K)$$

- **Celsius scale**

$$T(^{\circ}C) = T(K) - 273.15$$

- **Fahrenheit scale**

$$T(^{\circ}F) = T(^{\circ}R) - 459.67 = 1.8T(^{\circ}C) + 32$$

开尔文温标	摄氏度	华氏度
$0K$	-273.15$^{\circ}C$	-459.67$^{\circ}F$
273.15K	0$^{\circ}C$	32$^{\circ}F$
373.15K	100$^{\circ}C$	212$^{\circ}F$

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2 Energy and the First law of Thermodynamics

2.1 Energy

- **Internal energy:** U
- **Kinetic energy:** E_k
- **Potential energy:** E_p

  Total energy:

$$E = U + E_k + E_p$$
$$\Delta E = \Delta U + \Delta E_k + \Delta E_p$$

2.2 Work

- **输出功 Output work（对外输出总功量）：**W'
- **净输出功：**W_{net}、**轴功（叶轮机械净输出功）：**W_s
- **膨胀功/压缩功/体积功 Expansion or Compression work:**

$$W = p\Delta V$$
$$\delta W = pdV$$
$$\delta w = pdv$$

- **推动功/推挤功：**
  流体进出系统系统所对流体做出的推动功量

$$W_p = pV$$

- **流动功 Flow work/energy(State property)**:

$$W_f = \sum_i W_{p,i} = \Delta(pV)$$
$$\delta W_f = Vdp + pdV$$
$$\delta w_f = vdp + pdv$$

- **技术功 Technical work**:

$$W_t = \Delta E_k + \Delta E_p + W_{net}$$
$$\delta W_t = \delta W - \delta W_f = -Vdp$$
$$\delta w_t = -vdp$$

Relation:

$$W' = W_{net} + W_f$$
$$W_t = \Delta E_k + \Delta E_p + W_{net}$$
$$W = W_t + W_f$$

2.3 Heat

Conduction:

$$\dot{Q} = -\kappa A \frac{dT}{dx}$$

Radiation:

$$\dot{Q} = \varepsilon \sigma A T^4$$

Convection:

$$\dot{Q} = hA\Delta T$$

2.4 The first law of Thermodynamics

> "During an interaction, energy can change from one form to another but the total amount of energy remains constant."

general form:

$$\Delta E = Q - W$$
$$\Delta E_k + \Delta E_p + \Delta U = Q - W$$

differential form:

$$dE = \delta Q - \delta W'$$

time rate form:

$$\frac{dE}{dt} = \dot{Q} - \dot{W}'$$

CLOSED SYSTEMS(C.M.)

1. differential form:

闭口系热一定律基本表达式:

$$dU = \delta Q - \delta W \tag{1}$$

$$du = dq - pdv \tag{2}$$

OPEN SYSTEMS(C.V.)

1. differential form:

热一定律:

$$dE = \delta Q - \delta W'$$

输出总功量转化为净功量和流动功:

$$\delta W' = \delta W_{net} + d(pV)$$

技术功、焓的定义:

$$\delta W_t = \delta W_{net} + dE_k + dE_p$$
$$dH = dU + d(pV)$$

开口系-热力学第一定律基本表达式:

$$dH = \delta Q - \delta W_t \tag{1.1}$$

$$dU = \delta Q - \delta W \tag{1.2}$$

$$dh = du + vdp + pdv$$
$$dh = dq + vdp \tag{2.1}$$

$$du = dq - pdv \tag{2.2}$$

2. time rate & intergral form:

热一定律:

$$\frac{dE}{dt} = \dot{Q} - \dot{W}'$$
$$e = u + \frac{V^2}{2} + gz$$
$$E = \int_{CV} edm = \int_{CV} e\rho d\mathcal{V} \tag{1}$$

differential form:

$$dE_{CV} = \delta Q - \delta W + d(ms)$$

Steady Flow:

$$0 = \delta Q - \delta W + mds$$

积分形式(Reynolds Transport Theorem)

$$\frac{d}{dt}(E_{sys}) = \dot{Q} - \dot{W}' = \frac{d}{dt}(\int_{CV} e\rho d\mathcal{V}) + \int_{CS} e\rho V_n dA$$

输出总功量转化为净功量和流动功:

$$\dot{W}' = \dot{W}_{net} + \int_{CS} pV_n dA$$

焓的定义:

$$h = u + pv$$
$$\int_{CS} h\rho V_n dA = \int_{CS} (u + \frac{p}{\rho})\rho V_n dA$$

连续介质力学形式:

$$\dot{Q} - \dot{W}_{net} = \frac{d}{dt}(\int_{CV} e\rho d\mathscr{V}) + \int_{CS} (h + \frac{V^2}{2} + gz)\rho V_n dA$$
$$or$$
$$\dot{Q} - \dot{W}_{net} = \frac{\partial}{\partial t}\int_{CV} e\rho d\mathscr{V} + \int_{CS} (h + \frac{V^2}{2} + gz)\rho V_n dA$$
$$or$$
$$\dot{Q} - \dot{W}_{net} = \frac{\partial}{\partial t}\int_{CV} e\rho d\mathscr{V} + \sum (h + \frac{V^2}{2} + gz)_e \dot{m}_e - \sum (h + \frac{V^2}{2} + gz)_i \dot{m}_i$$

2.5 application

- 气轮机叶轮 Turbine Wheel

$$\dot{W}_{net} = \dot{m}(\frac{V_1^2 - V_2^2}{2})$$

- 热力发动机 Gas And Steam Turbine

$$0 = \dot{Q}_{CV} - \dot{W}_{net} + \dot{m}(h_1 - h_2)$$
$$\dot{W}_{net} = \dot{m}(h_1 - h_2)$$

- 压气机/泵 Compressor and Pump

$$0 = \dot{Q}_{CV} - \dot{W}_{net} + \dot{m}(h_1 - h_2)$$
$$\dot{W}_{net} = \dot{m}(h_1 - h_2)$$

- 喷管/扩散器 Nozzle/Diffuser

$$0 = Q_{CV} + \dot{m}(h_1 + \frac{V_1^2}{2}) - \dot{m}(h_2 + \frac{V_2^2}{2})$$
$$0 = (h_1 - h_2) + (\frac{V_1^2 - V_2^2}{2})$$

- 换热器 Heat Exchanger

$$\dot{Q}_{CV} = \dot{m}(h_2 - h_1)$$

- 节流 Throttling Process

$$h_1 = h_2$$

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3 Entropy and the Second Law of Thermodynamics

3.1 The Second Law of Thermodynamics

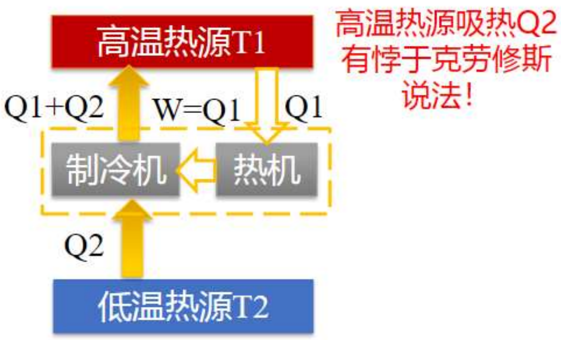
Clausius statement:
Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time.

Kelvin Statement:
It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects.

Planck's Proposition:
It is impossible to construct an engine which will work in a complete cycle, and produce no effect except the raising of a weight and cooling of a heat reservoir.

- **克劳修斯说法：**
  - 热传导的不可逆性
  - 无法制造理想制冷机
- **开尔文-普朗克说法：**
  - 热工转换的不可逆性
  - 无法制造第二类永动机
  - 单一热源下不可能做正输出功

$$\oint W_{cycle} = \oint Q_{cycle} \leq 0$$



- **熵增原理（能量贬值原理）**：孤立系统总是朝着熵增方向进行
- 永动机：
  - 第一类永动机（违背热一定律）凭空产生能量
  - 第二类永动机（违背热二定律）热量100%转化为功
- **卡诺定理：**
  - 卡诺第一定理：不可能制造出在两个温度不同的热源间工作的热机，而使其效率超过在**同样热源**间工作的可逆热机

- 卡诺第二定理：在两个热源间工作的一切可逆热机具有**相同的效率**
- 卡诺定理推论：在**相同两个恒温热源**间工作的一切不可逆热机的效率必小于可逆热机的效率

- 能量品位：

能量转换方向性的实质是能质有差异

- **无限可转换能—机械能，电能**
- **部分可转换能—热能**
- **不可转换能—环境介质的热力学能**

3.2 Reversible Process

Reversible Process $\Longleftrightarrow$ No internal irreversibilities

$$\oint W_{cycle} \leq 0 \begin{cases} < 0: & Internal\ irreversibilities\ present \\ = 0: & No\ internal\ irreversibilities \end{cases} \quad (single\ reservoir)$$

3.3 Propositions of The Second Law of Thermodynamics

I. Kelvin Scales

In Carnot Heat Engines:

$$(\frac{Q_C}{Q_H})_{cycle}^{rev} = \phi(T_C, T_H) \stackrel{def}{=} \frac{T_C}{T_H}$$

II. Clausius Inequality

$$\oint \left(\frac{Q}{T}\right)_b = -\sigma_{cycle},\ \sigma_{cycle} \begin{cases} > 0: & Internal\ irreversibilities\ present \\ = 0: & No\ internal\ irreversibilities \end{cases} \quad (system\ boundary\ heat\ exchange)$$

III. Entropy

Definition:

$$dS = \left(\frac{\delta Q}{T}\right)_{rev}$$
$$\Delta S = \int_1^2 \left(\frac{\delta Q}{T}\right)_{rev}$$

TdS equation in reversible system:

$$TdS = dU + pdV$$
$$Tds = dH - Vdp$$

$$Tds = du + pdv$$
$$Tds = dh - vdp$$

Closed System

basic relation:

$$\oint \left(\frac{Q}{T}\right)_b = \int_1^2 \left(\frac{Q}{T}\right)_b + \int_2^1 \left(\frac{Q}{T}\right)_{rev}$$
$$\int_1^2 \left(\frac{Q}{T}\right)_b + S_1 - S_2 = -\sigma$$

differiential form:

$$dS = \left(\frac{\delta Q}{T}\right)_b + \delta\sigma$$
$$or$$
$$dS = dS_f + \delta S_g$$

Condition Relation:

Common:

$$dS = \left(\frac{\delta Q}{T}\right)_b + \delta\sigma$$

Adiabatic:

$$dS = \delta\sigma$$

Reversible:

$$dS = \left(\frac{\delta Q}{T}\right)_b$$

Isentropic:($\iff$ Adiabatic+Reversible)

$$dS = 0$$

IV Increase of Entropy Principle

In isolated system:

$$\left(\frac{\delta Q}{T}\right)_b = 0$$
$$dS_{iso} = \delta S_g \geq 0$$

Open System

differential form:

$$dS_{CV} = \frac{\delta Q}{T} + \delta S_{g,CV} + d(ms)$$

Steady Flow:

$$0 = \frac{\delta Q}{T} + \delta S_{g,CV} + mds$$

time rate & intergral form:

$$(\frac{dS}{dt})_{sys} = \sum \frac{\dot{Q}}{T} + \dot{\sigma}$$

$$\sum \frac{\dot{Q}}{T} + \dot{\sigma} = \frac{\partial}{\partial t}\int_{CV} \rho s d\mathcal{V} + \int_{CS} s\rho V_n dA$$
$$or$$
$$\sum \frac{\dot{Q}}{T} + \dot{\sigma} = \frac{\partial}{\partial t}\int_{CV} \rho s d\mathcal{V} + \sum \dot{m}_e s_e - \sum \dot{m}_i s_i$$

3.4 Heat Engine and Heat Pump/Refrigerator

Heat Engine

Thermal efficiency:

$$\eta = \frac{W_{cycle}}{Q_H} = 1 - \frac{Q_C}{Q_H}$$
$$\eta_{max} = 1 - \frac{T_C}{T_H}$$

Refrigerator

Thermal efficiency:

$$\varepsilon = \frac{Q_C}{W_{cycle}} = \frac{Q_C}{Q_H - Q_C}$$
$$\varepsilon_{max} = \frac{T_C}{T_H - T_C}$$

Heat Pump

Thermal efficiency:

$$\varepsilon' = \frac{Q_H}{W_{cycle}} = \frac{Q_H}{Q_H - Q_C}$$
$$\varepsilon'_{max} = \frac{T_H}{T_H - T_C}$$

3.5 application-efficiency

- isentropic turbine efficiency

$$\frac{\dot{W}_{net}}{\dot{m}} = (h_1 - h_2)$$
$$\eta_t = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

- isentropic compressor and pump efficiency

$$\frac{-\dot{W}_{net}}{\dot{m}} = (h_2 - h_1)$$
$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1}$$

- isentropic nozzle efficiency

$$\frac{V_2^2}{2} = h_1 - h_2 + \frac{V_1^2}{2}$$
$$\eta_{nozzle} = \frac{V_2^2/2}{(V_2^2/2)_s}$$

3.6 Exergy 㶲 Anergy 炁

- **Exergy and Anergy in Heat**

Environment at T_0, System at T
Exergy：

$$E_{x,Q} = W_{max} = (1 - \frac{T_0}{T})Q$$

Anergy:

$$E_{n,Q} = Q - E_{x,Q} = \frac{T_0}{T}Q = Q_{emit}$$

- **Exergy and Anergy in System**

Definition: Maximum theoretical work from system and environment to reach an equilibrium

Closed System

Overall：

$$0 = dU_s + dU_e + dW_x$$
$$\delta S_g = dS_{iso} = dS_s + dS_e$$

System：

$$\delta Q_{rev} = dU_s + \delta W_{max}$$
$$\delta W_{max} = \delta W_x + p_0 dV_s$$

Environment,at T_0, p_0：

$$-\delta Q_{rev} = dU_e + p_0 dV_e$$
$$-\delta Q_{rev} = T_0 dS_e$$

Maximum Work:

$$\delta W_x = -dU_s - p_0 dV_s - T_0(dS_g - dS_s)$$
$$W_x = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + (E_k + E_p) - T_0 S_g$$

Exergy(a kind of Potential):

$$E_x = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + (E_k + E_p)$$
$$or$$
$$E_x = (U - U_0) + p_0(V - V_0) - T_0(S - S_0)$$

$$e_x = (u + p_0 v - T_0 s) - (u_0 + p_0 v_0 - T_0 s_0)$$

Exergy Change:

$$dE_x = dU + p_0 dV - T_0 dS$$
$$dE_x = \delta Q - (\delta W - p_0 dV) - T_0(\frac{\delta Q}{T_b} + \delta S_g)$$

$$dE_x = (1 - \frac{T_0}{T_b})\delta Q - (\delta W - p_0 dV) - T_0 \delta S_g$$
$$E_2 - E_1 = \int_1^2 (1 - \frac{T_0}{T_b})\delta Q - [W - p_0(V_2 - V_1)] - T_0 \Delta S_g$$

- Exergy transfer of Heat transfer

$$\int_1^2 (1-\frac{T_0}{T_b})\delta Q$$

- Exergy transfer of Work

$$[W - p_0(V_2 - V_1)]$$

- Exergy destruction

$$T_0 \Delta S_g$$

Simplization

$$E_2 - E_1 = E_q - E_w - E_d$$

Isolated and no work process:

$$\Delta E = -E_d$$

time rate form:

$$\dot{E}_x = \sum_j (1-\frac{T_0}{T})\dot{Q}_j - [\dot{W} - p_0(\frac{dV}{dt})] - T_0\dot{\sigma}$$

steady state:

$$0 = \sum_j (1-\frac{T_0}{T})\dot{Q}_j - \dot{W} - T_0\dot{\sigma}$$

Open System

Exergy:

$$E_x = (H - H_0) - T_0(S - S_0) + (E_k + E_p)$$
$$or$$
$$E_x = (H - H_0) - T_0(S - S_0)$$

$$e_x = (h - T_0 s) - (h_0 - T_0 s_0)$$

Exergy Change
time rate form:

$$\sum_j (1-\frac{T_0}{T_j})\dot{Q}_j - (\dot{W}_{CV} - p_0\frac{dV_{CV}}{dt}) - T_0\dot{\sigma} = \frac{d}{dt}\int_{CV} e_x \rho d\mathcal{V} + \int_{CA} e_x \rho dV_n$$

steady state:

$$0 = \sum_j (1-\frac{T_0}{T_j})\dot{Q}_j - \dot{W}_{CV} + \sum_i \dot{m}_i e_{fi} - \sum_e \dot{m}_e e_{fe} - T_0\dot{\sigma}$$

specific flow exergy:

$$e_f = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$
$$e_f = e_x + v(p - p_0)$$

Other System

存在非体积功输出:

$$TdS = dU + \delta W + \delta W_u$$
$$\delta W_{u,max} = TdS - dU - pdV$$

- 定温-定容

$$F = U - TS$$
$$f = u - Ts$$
$$E_x = W_{u,v,max} = (U - TS) - (U_0 - T_0S_0) = F - F_0$$

F为亥姆霍兹自由能[强度量]

- 定温-定压

$$G = H - TS$$
$$g = h - Ts = u + pv - Ts$$
$$E_x = W_{u,p,max} = (H - TS) - (H_0 - T_0S_0) = G - G_0$$

G为吉布斯自由能（自由焓）[强度量]

- **Exergetic Efficiency**

Turbines

$$e_{f1} - e_{f2} = \frac{\dot{W}}{\dot{m}} + \frac{\dot{E}_d}{\dot{m}}$$
$$\varepsilon = \frac{\dot{W}/\dot{m}}{e_{f1} - e_{f2}}$$

Compressors and Pumps

$$-\frac{\dot{W}}{\dot{m}} = e_{f2} - e_{f1} + \frac{\dot{E}_d}{\dot{m}}$$
$$\varepsilon = \frac{e_{f2} - e_{f1}}{-\dot{W}/\dot{m}}$$

Heat Exchanger Without Mixing

$$\dot{m}_h(e_{f1} - e_{f2}) = \dot{m}_c(e_{f4} - e_{f3}) + \dot{E}_d$$
$$\varepsilon = \frac{\dot{m}_c(e_{f4} - e_{f3})}{\dot{m}_h(e_{f1} - e_{f2})}$$

Heat Exchanger With Mixing

$$\dot{m}_h(e_{f1} - e_{f3}) = \dot{m}_c(e_{f3} - e_{f2}) + \dot{E}_d$$
$$\varepsilon = \frac{\dot{m}_c(e_{f3} - e_{f2})}{\dot{m}_h(e_{f1} - e_{f3})}$$

- **Cost Rate**

4 Evaluating Properties

4.1 Ideal gas