Today's lecture:
- Fundamental concepts and definitions
- Energy

MidTerm = 21 Aban
24 Azar

INTRODUCTION AND BASIC CONCEPTS

SYSTEMS AND CONTROL VOLUMES

System

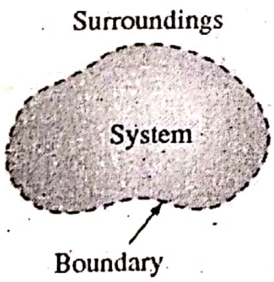
سیستم: مقدار ماده یا ناحیه‌ای از فضا که برای مطالعه استفاده می‌شود

Surroundings

محیط: جرم یا ناحیه بیرون سیستم

Boundary

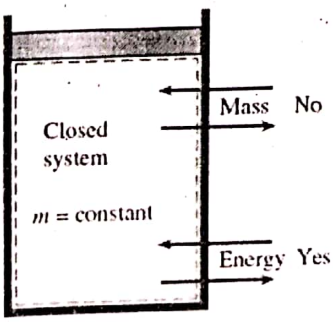
مرز: سطح (فرضی یا واقعی) که سیستم را از محیط اطرافش جدا می‌کند، می‌تواند ثابت یا متحرک باشد، در سطح مشترک بین سیستم و محیط است. از نظر ریاضی دارا ضخامت صفر است. نه جرمی دارد و نه حجمی را اشغال می‌کند



Closed system (control mass)

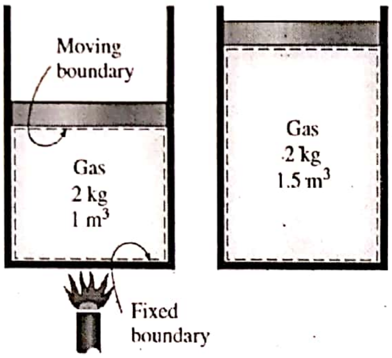
سیستم بسته: شامل مقادیر معین و ثابتی از جرم است

هیچ جرمی از مرز سیستم عبور نمی‌کند. حجم سیستم بسته می‌تواند تغییر کند



Isolated system

سیستم منزوی: حالت خاصی از سیستم بسته است که تبادل انرژی
در مرز ندارد.



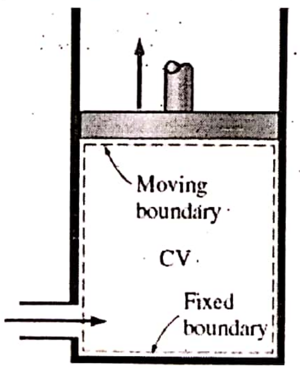
Open system (control volume)

سیستم باز (حجم کنترل): هم جرم و هم انرژی از مرز حجم کنترل عبور می‌کند.

اختیاری

In general, *any arbitrary region in space* can be selected as a control volume. There are no concrete rules for the selection of control volumes, but the proper choice certainly makes the analysis much easier.

The boundaries of a control volume are called a *control surface,* and they can be real or imaginary.



A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

Properties of a system

خاصیت سیستم: هر مشخصه‌ای از سیستم، دو نوع هستش، شدتی یا متمرکز، غیرشدتی یا گسترده

Intensive properties

خواص شدتی: مستقل از جرم داخل سیلندر مثل: دما، فشار، چگالی

Extensive properties

خواص گسترده: به جرم و حجم سیستم وابسته است مثل: حجم سیستم، جرم سیستم

Specific properties

خواص ویژه: خواص غیرشدتی در واحد جرم $e = E/m$

STATE AND EQUILIBRIUM

حالت و تعادل: شرایط سیستم که توسط خواص سیستم توصیف می‌شود

State

حالت: هر سیستم در یک حالت معلوم همه خواص سیستم ثابت و معین است

Equilibrium state

تعادل: هیچ پتانسیل یا نیروی محرکه‌ی نامتوازن در سیستم وجود ندارد.

سیستمی که در حالت تعادل قرار دارد، اگر از محیط منزوی شود، دچار تغییر نمی‌شود

۱) تعادل گرمایی: هیچ اختلاف دمایی نباید داخل سیستم وجود داشته باشد

۲) تعادل مکانیکی: فشار داخل سیستم با زمان تغییر نکند.

۳) تعادل فازی: مقدار جرم درون هر فاز، به یک سطح تعادلی رسیده باشد و تغییر نکند

۴) تعادل شیمیایی: ترکیب شیمیایی سیستم با زمان تغییر نکند. واکنش شیمیایی رخ ندهد

The State Postulate

اصل موضوع حالت: حالت سیستم تراکم‌پذیر ساده توسط دو خاصیت شدتی مستقل از هم تعیین می‌شود.

Simple compressible state

سیستم تراکم پذیر ساده : یک سیستم در غیاب اثرات تنش سطحی، گرانش و میدان مغناطیسی و الکتریکی تراکم پذیر ساده می‌گویند

PROCESSES AND CYCLES

فرایندها و سیکل‌ها : هر تغییری که در آن سیستم از یک حالت تعادل به یک حالت به یک حالت تعادل دیگری می‌رود

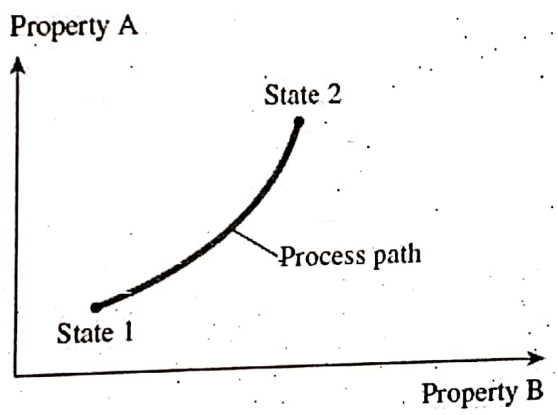
Process

فرایند : برای بیان یک فرایند باید مسیر فرایند ، حالت‌های ابتدایی و انتهایی و تعادل آن با محیط مشخص شود

Path

مسیر فرایند: مجموعه حالت‌هایی که سیستم طی یک فرایند از آن‌ها عبور می‌کند

سیکل : اگر بعد از انتهای فرایند ، سیستم به حالت اولیه برگردد .



Quasi-equilibrium process

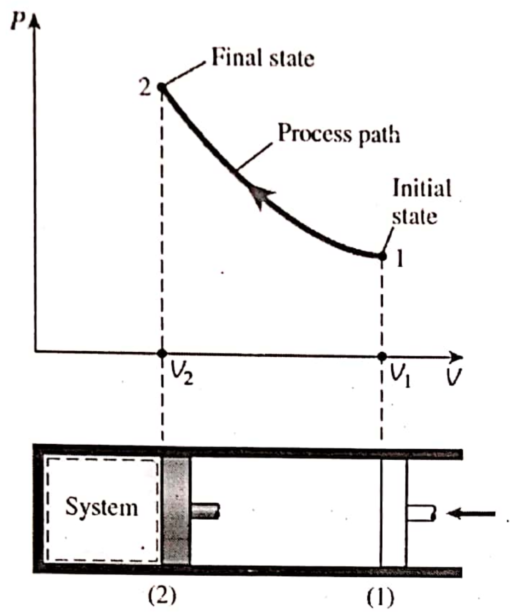
فرایند شبه تعادلی : سیستم در همه لحظات در حالت تعادلی متناظر با آن لحظه بی‌نهایت نزدیک شود

1) فرایند هم دما (دما ثابت)

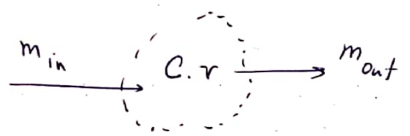
2) فرایند هم فشار (فشار ثابت)

3) فرایند هم حجم (حجم ثابت)

Scanned by CamScanner

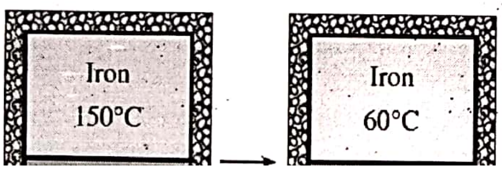


The Steady-flow Process



فرایند جریان پایا ، با زمان خواص تغییر نمی کند. (برای سیستم بسته)

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS



FORMS OF ENERGY

Total energy E

مجموع انرژی‌های مکانیکی، شیمیایی، هسته‌ای، الکتریکی، مغناطیسی $e=\frac{E}{m}\left(\frac{kJ}{kg}\right)$

$E=K+P+U$

Macroscopic forms of energy

انرژی ماکروسکوپیک: شکل‌هایی از انرژی که سیستم به عنوان یک کل نسبت به یک مرجع بیرونی دارد.

مثل: انرژی جنبشی، انرژی پتانسیل

Microscopic forms of energy

انرژی میکروسکوپیک: شکل‌هایی از انرژی که به ساختار مولکولی سیستم بستگی دارند و به میزان فعالیت مولکولی آن بستگی دارد مستقل از مرجع بیرونی هستند.

Internal energy

همه شکل‌های میکروسکوپیک انرژی

1. انرژی محسوس — Sensible Energy — مربوط به انرژی جنبشی مولکول‌ها — دما
2. انرژی نهان — Latent Energy — نیروی بین مولکول‌ها — تغییر فاز
3. انرژی شیمیایی — Chemical Energy — پیوند اتمی داخل مولکول‌ها
4. انرژی هسته‌ای — Nuclear Energy — پیوندها داخل هسته اتم

Kinetic energy

انرژی سیستم به خاطر حرکتش نسبت به یک مرجع

- $K = \frac{mV^2}{2}$ (kJ)
- $k = \frac{V^2}{2}$ ($\frac{kJ}{kg}$)

V: سرعت سیستم نسبت به مرجع معین

Potential energy

انرژی سیستم به خاطر موقعیتش نسبت به یک سطح مرجع انتخابی در یک میدان گرانشی

- $P = mgz$ (kJ)
- $p = gz$ ($\frac{kJ}{kg}$)

Stationary system

سیستم ساکن: تغییر انرژی جنبشی و پتانسیل صفر است

$\Delta E = \Delta U$

Mass flow rate

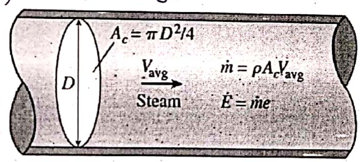
جریان جرم: مقدار جرمی که در واحد زمان از یک مقطع عبور می‌کند

- $\dot{m}$ ($\frac{kg}{s}$)

Volume flow rate

جریان حجم

- $\dot{V}$ ($\frac{m^3}{s}$) , * $\dot{E} = \dot{m}e$ (kJ or kW)
- $\dot{m} = \rho\dot{V} = \rho A_c V_{avg}$



Energy transfer

دو مکانیزم انتقال انرژی هست:

۱) گرما: انتقال انرژی به خاطر اختلاف دما است.

۲) کار: انتقال انرژی که به علت اختلاف دما نباشد. * هر دو تابع مسیر هستند

* هر دو فقط در حین عبور از مرزهای سیستم قابل شناسایی هستند. پدیده‌ها مرزی هستند
* هر سیستم دارای انرژی است اما دارای گرما یا کار نیست
* هر دو حین انجام فرایند مطرح می‌شوند که به حالت سیستم ارتباط ندارد

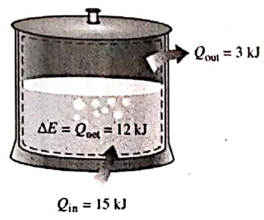
* هر حرف کوچک نشانی واحد جرم است

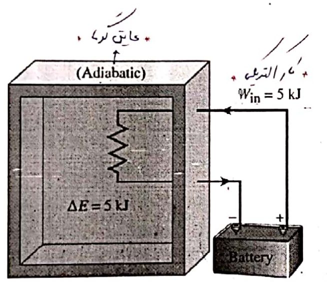
Today's lecture: A4, A5, A6, تمارین

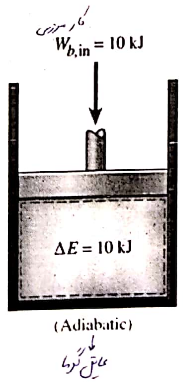
- First law of thermodynamics
- Properties of pure substances

FIRST LAW OF THERMODYNAMICS

قانون اول ترمودینامیک : طبق این قانون انرژی نه بوجود می‌آید و نه از بین می‌رود بلکه از شکلی به شکل دیگر تغییر می‌کند.







Energy Balance

$$E_{in} - E_{out} = \Delta E_{system}$$

Energy Change of a System ΔE_{system}

$$\Delta E_{system} = E_f - E_i$$

$$\Delta U + \Delta K + \Delta P$$

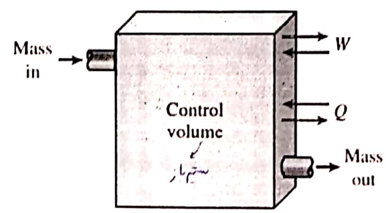
Mechanisms of Energy Transfer

$$Q, W, \dot m$$

$$e_{in} - e_{out} = \Delta e_{system} \quad (kJ/kg)$$

$$\dot E_{in} + \dot E_{out} = \frac{dE_{system}}{dt} \quad (kW)$$

$$\Delta E_{system} = E_f - E_i = 0$$

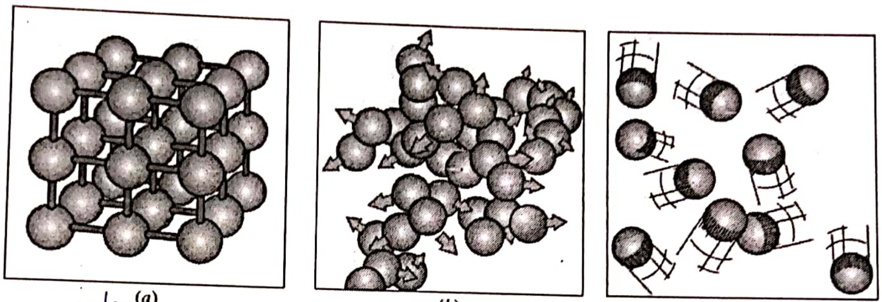


PROPERTIES OF PURE SUBSTANCES

Pure substance

ماده‌ای که ترکیب شیمیایی آن در تمام ماده ثابت است.

Phases of a Pure Substance



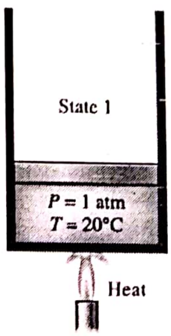
(a) جامد — امکان حرکت مولکول‌ها در اطراف مکانهای تعادلشان

(b) مایع — امکان حرکت گروه‌ها مولکول نسبت به هم

(c) گاز — حرکت تصادفی مولکول‌ها نسبت به هم

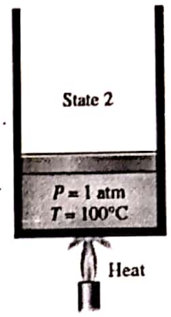
Phase-change Processes of Pure Substances

(1) Compressed liquid مایع متراکم

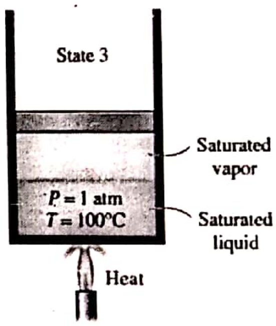


(2) Sturated liquid مایع اشباع

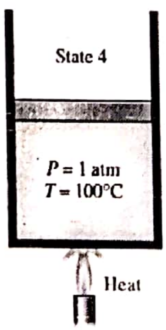
با کمی انتقال گرما تبخیر شروع می‌شود.



(3) Saturated liquid-vapor mixture



(4) Saturated vapor بخار اشباع



(5) Superheated vapor

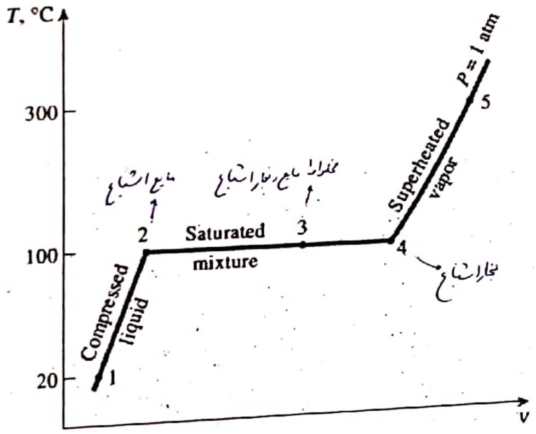
Saturation Temperature And Saturation Pressure

T_{sat}

دمای اشباع: دمایی که در آن یک ماده خالص تغییر فاز می‌دهد. (در فشار معین)

فشار اشباع: در یک دمای معین، فشاری که در آن یک ماده خالص تغییر فاز می‌دهد.

* به ازای هر دمای اشباع یک فشار اشباع هست و بالعکس



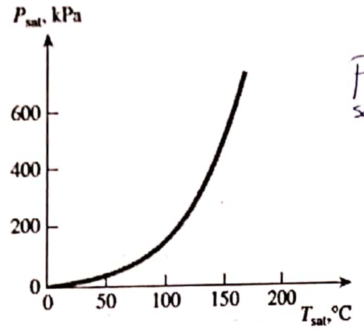
Latent heat

گرمای نهان: مقدار گرمایی که در یک فرایند تغییر فاز جذب یا آزاد می‌شود

Latent heat of fusion

Latent heat of vaporization

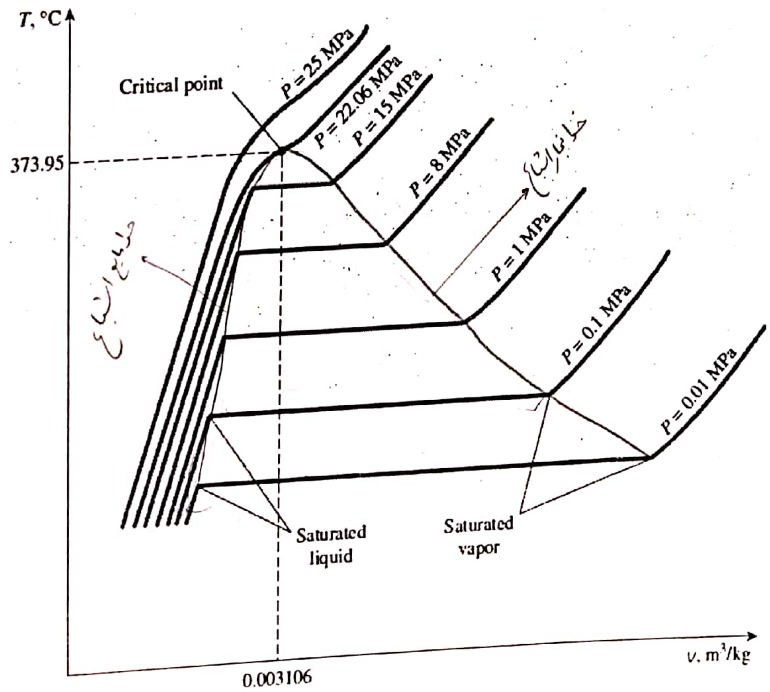
Liquid-vapor saturation curve منحنى بخار التشبع ودرجة التشبع



$P_{sat} = f(T_{sat})$

Property Diagrams for Phase-change Processes

(1) The T-v diagram

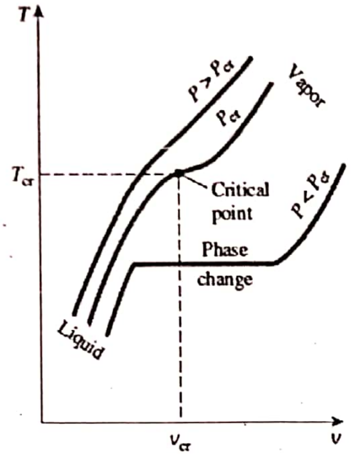


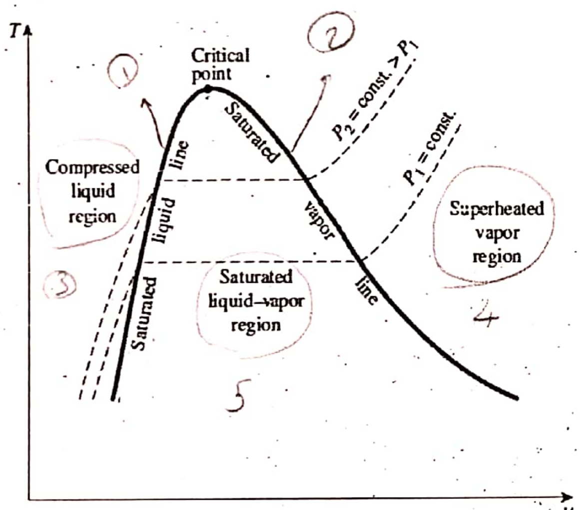
Critical point

حالت که مایع اشباع و بخار اشباع برابرند

$T_{cr} = 373.95\,^{\circ}C$, $P_{cr} = 22.06\,MPa$

$v_{cr} = 0.003106\ \frac{m^3}{kg}$

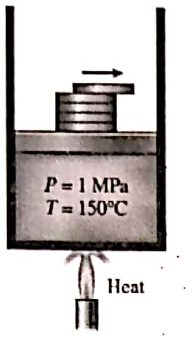


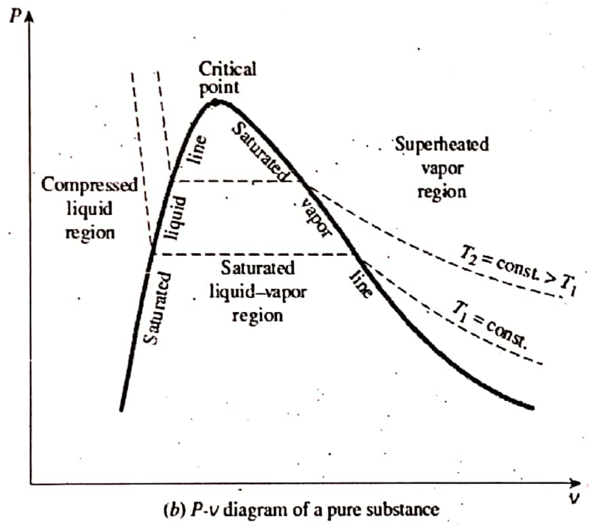


(a) T-v diagram of a pure substance

1. Saturated liquid line
2. Saturated vapor line
3. Compressed liquid region
4. Superheated vapor region
5. Saturated liquid-vapor mixture region

(2) The P-v diagram



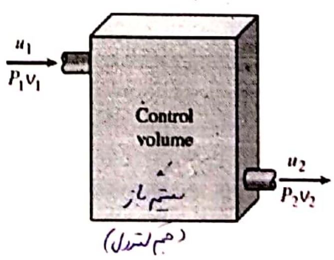


(*b*) *P*-*v* diagram of a pure substance

Property Tables

Enthalpy

- $e = u + k + P + Pv$
- $u + Pv = h$



1a Saturated liquid and saturated vapor states

حجم مخصوص مایع اشباع v_f

حجم مخصوص گاز اشباع v_g

$v_{fg} = v_g - v_f$

Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m³/kg — Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

temperature

Corresponding saturation pressure

Specific volume of saturated liquid

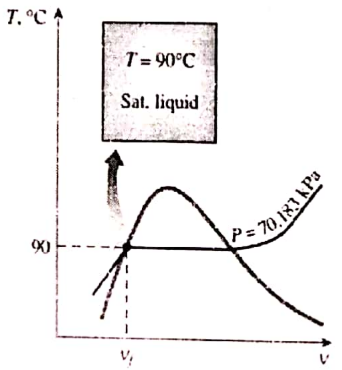
Specific volume of saturated vapor

Enthalpy of vaporization (or latent heat of vaporization)

مقدار انرژی لازم برای تبخیر واحد جرم مایع اشباع در دما و فشار معلوم.

EXAMPLE 1

A rigid tank contains 50 kg of saturated liquid water at 90 °C. Determine the pressure in the tank and the volume of the tank.



$T = 90°C \longrightarrow P_{sat\,90°C} = 70.183$ kg

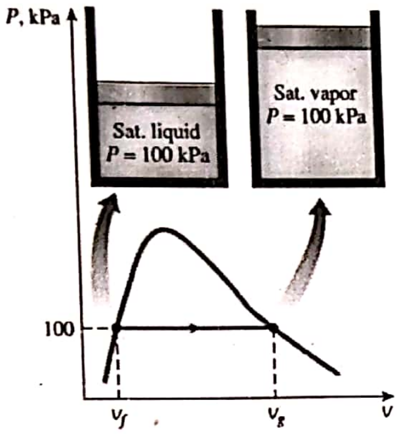
$v_{f\,90°C} = 0.001036\ m^3/kg$

$V = mv = (50)(0.001036) = 0.0518\ m^3$

Scanned by CamScanner

EXAMPLE 2

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) the volume change and (b) the amount of energy transferred to the water.



$P = 100\,kPa \xrightarrow{A\text{-}5} v_f = 0.001043\ m^3/kg$

$v_g = 1.6941\ m^3/kg$

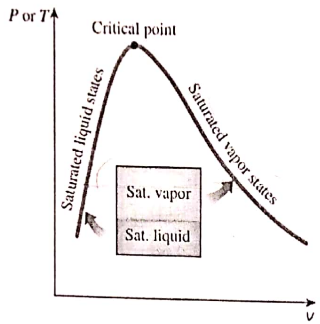
$v_{fg} = v_f - v_g = 1.6931\ m^3/kg$

$\Delta V = m v_{fg} = 0.2 \times (1.6931) = 0.3386\ m^3$

$P = 100\,kPa \xrightarrow{A\text{-}5} h_{fg} = 2257.5\ kJ/kg \longrightarrow m h_{fg} = (0.2)(2257.5) = 451.5\ kg$

$h_{fg} \longrightarrow$ اختلاف انتالپی تبخیر (بخار) و مایع اشباع

1b Saturated liquid-vapor mixture



Quality

$$* \quad x = \frac{m_g}{m_{total}} \quad , \; * \; m_{total} = m_f + m_g \; , \quad 0 < x < 1$$

بخار

مجموع جرم بخار و مایع

$$* \quad V = V_f + V_g \longrightarrow m_{total} v_{avg} = m_f v_f + m_g v_g$$

$$* \quad v_{avg} = \frac{m_f v_f + m_g v_g}{m_{total}} = \frac{m_f}{m_{total}} v_f + \frac{m_g}{m_{total}} v_g = (1-x) v_f + x v_g \Rightarrow v_f - x v_f + x v_g = v_f + x v_{fg}$$

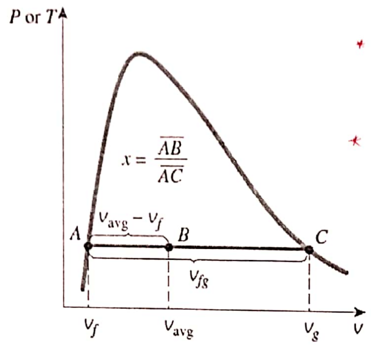
$m_{total} - m_g$

$$v_{avg} = \quad * \; v = v_f + x v_{fg} \quad , \; v_{fg} = v_g - v_f \; *$$

$$x = \frac{v - v_f}{v_{fg}}$$

* نقطه برای محدوده اشباع کیفیت تعریف می‌شود

پس برای نقطه‌ی مایع متراکم x معنا ندارد.



* $u = u_f + x u_{fg}$ * $u_{fg} = u_g - u_f$

* $h = h_f + x h_{fg}$ * $h_{fg} = h_g - h_f$

زیرنویس Avg را حذف می‌کنیم، برای راحتی

* $y = y_f + x y_{fg}$, $y = u, v, h$

* $y_f \leq y \leq y_g$ ⟶ یعنی مخلوط بخار و مایع اشباع

EXAMPLE 1

A rigid tank contains 10 kg of water at 90°C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (*a*) the pressure in the tank and (*b*) the volume of the tank.

$T = 90^\circ C \xrightarrow{A-4} P_{sat @ 90^\circ C} = 70.183 \text{ kPa}$,

$v = v_f + x v_{fg}$

$T = 90^\circ C \xrightarrow{A-4} v_f = 0.001036 \frac{m^3}{kg}$; $v_g = 2.3593 \frac{m^3}{kg}$

$x = \frac{m_g}{m_{total}} = \frac{2}{10} = \frac{1}{5}$, $v = v_f + x v_{fg} = (0.001036) + \frac{1}{5}((2.3593) - (0.001036)) = 0.473 \frac{m^3}{kg}$

$V = m v = 10 \times 0.473 = 4.73 m^3$

EXAMPLE 2

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (*a*) the temperature, (*b*) the quality, (*c*) the enthalpy of the refrigerant, and (*d*) the volume occupied by the vapor phase.

Table A-12

$h_f = 31.18 \ \frac{kJ}{kg}$, $h_{fg} = 209.96 \ \frac{kJ}{kg}$

$P_{sat} = 160 \ kPa \longrightarrow T_{sat @ 160 kPa} = -15.6^\circ C$

$h = 31.18 + (0.157)(209.96) = 64.1 \ \frac{kJ}{kg}$

$x = \frac{v - v_f}{v_{fg}}$, $v = \frac{V}{m} = \frac{0.08}{4} = 0.02 \ \frac{m^3}{kg}$

$x = \frac{m_g}{m_{total}} = 0.157 = \frac{m_g}{4} \Rightarrow m_g = 0.628 \ kg$

$V_g = m_g v_g = (0.628)(0.12355) = 0.0776$,

$P = 160 \ kPa \longrightarrow v_f = 0.0007435 \ \frac{m^3}{kg}$, $v_g = 0.12355 \ \frac{m^3}{kg}$

, $v_{fg} = v_g - v_f = 0.12355 - 0.0007435 =$

$v_f < v < v_g \longrightarrow$ خليط مشبع

$x = \frac{0.02 - 0.0007435}{0.12355 - 0.0007435} = 0.157$,

2 Superheated vapor

- $P < P_{sat}$, $h > h_g$
- $T > T_{sat}$, $u > u_g$
- $v > v_g$

EXAMPLE 3

Determine the temperature of water at a state of P=0.5 MPa and h=2890 kJ/kg.

$P = 0.5\,MPa \xrightarrow{A\text{-}5} h_g = 2748.1\ kJ/kg \ ,\ h > h_g$ درحالت سوپرهیت

A-6

T	h
200	2855.8
x	2890
250	2961

$T \longrightarrow 216.3°$

3 Compressed liquid

P, T

$P > P_{sat}$ $\quad h < h_f$

$T < T_{sat}$ $\quad v < v_f$

$u < u_f$

$$v \cong v_{f@T} \ ,\ h \cong h_{f@T} + v_{f@T}(P - P_{sat@T})$$

* باید دنبال دما بریم نه فشار.

EXAMPLE 4

Determine the internal energy of compressed liquid water at 80°C and 5 MPa, using (*a*) data from the compressed liquid table and (*b*) saturated liquid data.

$T = 80°C \ ,\ P_{sat@80°C} = 47.614\ kPa$

$P = 5\,MPa > P_{sat}$ $\quad$ stat: compressed liquid

(a) A-7 $\quad P = 5\,MPa$, $T = 80°C \longrightarrow u = 333.82\ kJ/kg$

(b) A-4: $u = u_{f@T=80°C} = 334.97\ kJ/kg$

$$= \frac{334.97 - 333.82}{333.82} \times 100 = 0.34\%$$

Err

Reference state and reference values

مقادیر u ، h ، s را نمی‌توان مستقیماً اندازه‌گیری کرد. این مقادیر با استفاده از روابط بین خواص ترمودینامیک از طریق خواص قابل اندازه‌گیری محاسبه می‌شوند. روابط بین خواص، تغییرات خواص را می‌دهند. بنابراین لازم است که یک حالت مرجع مناسب انتخاب کنیم.

EXAMPLE 5 آب $0.01°C$ مایع اشباع , $u=0$, $s=0$, R-134a . $-40°C$ مایع اشباع $s=0$, $h=0$

Determine the missing properties and the phase descriptions in the following table for water:

	T, °C	P, kPa	u, kJ/kg	x	Phase description
(a)		200		0.6	
(b)	125		1600		
(c)		1000	2950		
(d)	75	500			
(e)		850		0.0	

(a) $x = 0.6$. state: saturated liquid-vapor

$T = T_{sat@200kPa} = 120.21°C$ (A-5)

$P = 200kPa \xrightarrow{A-5} u_f = 504.5 \frac{kJ}{kg}$, $u_{fg} = 2024.6 \frac{kJ}{kg}$, $u = u_f + x u_{fg} = 1719.2 \frac{kJ}{kg}$

(e) $x = 0 \Rightarrow$ state: Saturated liquid, $P = 850kPa \rightarrow T_{sat@850kPa} = 172.94°C$

$u = u_{f@850} = 731 \frac{kJ}{kg}$

(b) $T = 125°C \xrightarrow{A-4} u_f = 524.83 \frac{kJ}{kg}$, $u_g = 2534.3 \frac{kJ}{kg}$, $u_f < u < u_g \rightarrow$ state: Saturated mixture

$P = P_{sat@125°C} = 232.23 kPa$ (A-4) , $x = \frac{u - u_f}{u_{fg}} = 0.535$

(c) $P = 1000kPa \rightarrow u_f = 761.39 \frac{kJ}{kg}$, $u_g = 2582.8 \frac{kJ}{kg}$, $u > u_g \Rightarrow$ state: Superheated vapor

A-6 : $T = 395.2°C$ x = undefined

(d) $P = 500kPa \longrightarrow T_{sat@500kPa} = 151.83°C$, $T < T_{sat} \Rightarrow$ state: compressed liquid

x = undefined , $u \cong u_{f@T=151.83°C} = 313.99 \frac{kJ}{kg}$

THE IDEAL-GAS EQUATION OF STATE

* گاز بخاری هست که از دمای بحرانی فاصله گرفته باشد.

Equation of state

هر معادله ای که P ، T ، V را در یک ماده را بهم ارتباط دهد.

Ideal-gas equation of state

گاز ایده آل: به هر گازی که در این رابطه صدق کند

* $P = R\left(\frac{T}{v}\right) \Rightarrow Pv = RT$, $P = \text{kpa}$ (کیلوپاسکال) , $T = K$ (کلوین) , $v = m^3$ (متر مکعب)

حجم مخصوص: v

Gas constant

* $R = \frac{R_u}{M}$ $\frac{kJ}{kg\,K}$ یا $\frac{kPa.m^3}{kg.K}$

جرم یک کیلومول از ماده برحسب کیلوگرم = جرم مولی = M ،

Universal gas constant

* $R_u = 8.31447 \; \frac{kJ}{kmol.K}$

* $V = n\bar{v}$ = $P\bar{v} = R_u T$ → برحسب حجم مخصوص مولی است. $\frac{m^3}{kmol}$

حجم مخصوص مول: $\bar{v}$

* $m = MN$ (A-1 : M, R)

* $V = mv \longrightarrow PV = mRT$

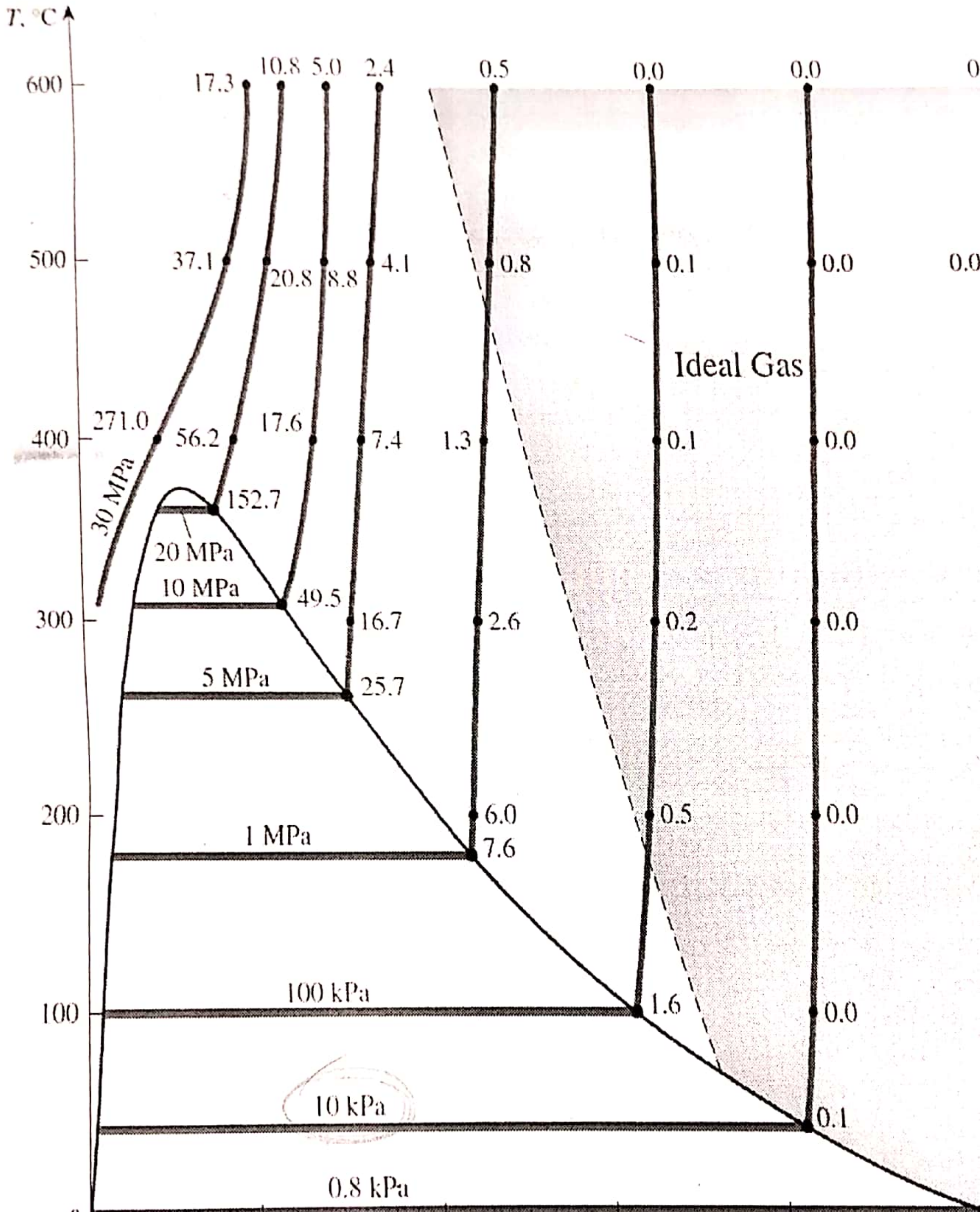
حجم کل (غیرمخصوص): V

* $mR = MNR = R_u N \longrightarrow PV = nR_uT$

* $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

Is water vapor an ideal gas?

ز ایده‌آل برای بخار آب صادق است.



Scanned by CamScanner

EXAMPLE 1

A 1-m³ tank containing air at 10°C and 350 kPa is connected through a valve to another tank containing 3 kg of air at 35°C and 200 kPa. Now the valve is opened, and the entire system is allowed to reach thermal equilibrium with the surroundings, which are at 20°C. Determine the volume of the second tank and the final equilibrium pressure of air.

$$A\text{-}1 \rightarrow R_{air} = 0.283 \frac{kJ}{kg \cdot K}, \quad V_B = \left(\frac{m_1 R_1 T_1}{P_1}\right) = \frac{(3)(0.283)(308)}{200} = 1.326\, m^3$$

$$m_A = \left(\frac{P_1 V_1}{R T_1}\right) = \frac{(350)(1)}{0.283 \times 283} = 4.309\ kg, \quad V_T = V_1 + V_2 = 1 + 1.326 = 2.326\, m^3, \quad m_T = m_A + m_B = 4.309 + 3 = 7.307$$

$$P_2 = \frac{m R T_2}{V_T} = \frac{(7.307)(0.283)(293)}{2.326} = 264\, kPa$$

COMPRESSIBILITY FACTOR – A MEASURE OF DEVIATION FROM IDEAL-GAS BEHAVIOR

* هرچی به یک نزدیکتر باشد ، یعنی انحراف گازها ، از گاز ایده آل کمتر است

+ **Compressibility factor**

ضریب تراکم پذیری

$$Z = \frac{PV}{RT}, \quad PV = ZRT \qquad Z = 1 \text{ برای گاز ایده‌آل}, \quad Z = \frac{V_{act}}{V_{id}}, \quad V_{id} = \frac{RT}{P}$$

Reduced pressure and reduced temperature

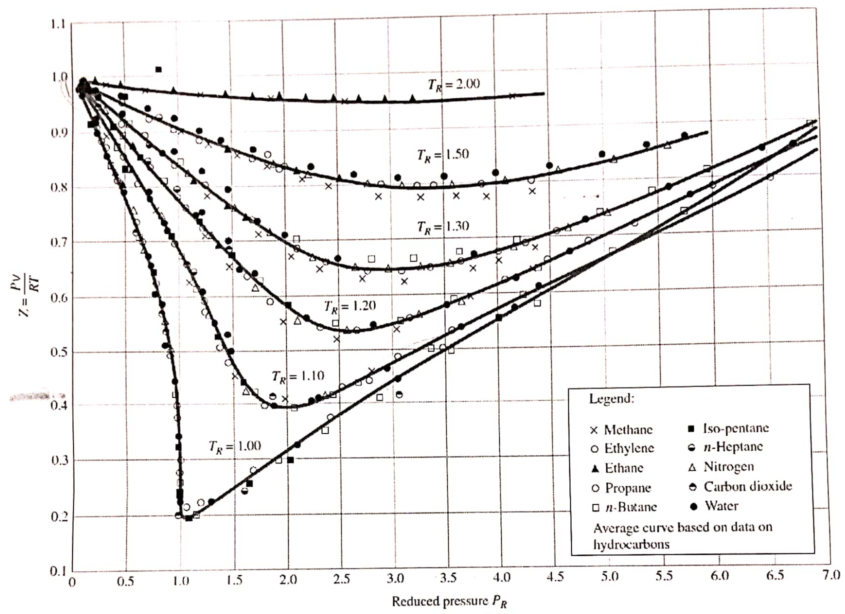
$$P_R = \frac{P}{P_{cr}}, \quad T_R = \frac{T}{T_{cr}}$$

(P_{cr} ← بحرانی، T_{cr} ← بحرانی)

Principle of corresponding states

اصل حالت‌ها متناظر

فاکتور تراکم پذیری Z برای همه گازها در T_R و P_R تقریباً یکسان است



* در فشارهای پایین $P_R \ll 1$ گازها مستقل از دما، رفتار ایده‌آل خواهند داشت

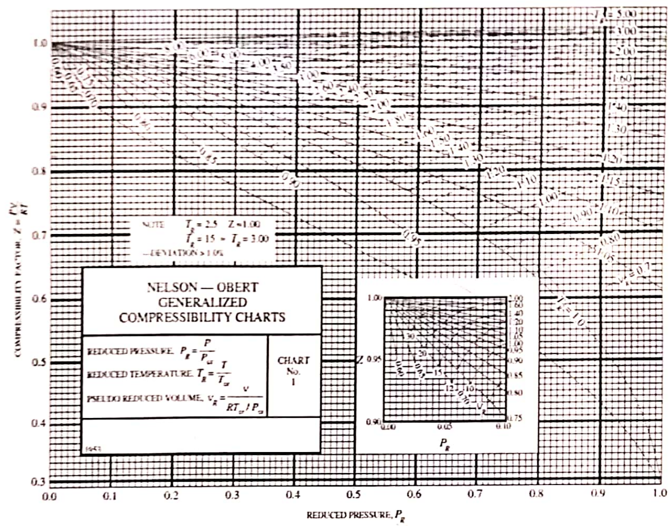
* در دماهای بالا $T_R > 2$ گازها مستقل از فشار، رفتار گاز ایده‌آل خواهند داشت

به استثنا موارد $P_R \gg 1$ باشد

* نزدیک نقطه بحرانی بیشترین انحراف از رفتار گاز ایده‌آل داریم.

Generalized compressibility chart

(a) Low pressures, $0 < P_R < 1.0$



(b) Intermediate pressures, $0 < P_R < 7$

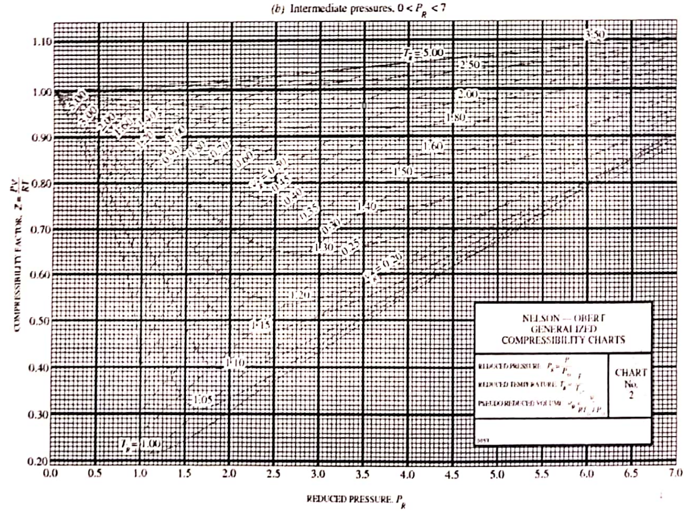


FIGURE A–15

EXAMPLE 2

Determine the specific volume of refrigerant-134a at 1 MPa and 50°C, using (a) the ideal-gas equation of state and (b) the generalized compressibility chart. Compare the values obtained to the actual value of 0.021796 m³/kg and determine the error involved.

a) R-134a $\xrightarrow{A\text{-}1}$ $R = 0.0815 \frac{kJ}{kg \cdot k}$, $P_{cr} = 4.059 MPa$, $T_{cr} = 374.2 K$

$v = \frac{RT}{P} \rightarrow 0.026325 \frac{m^3}{kg}$, $\frac{0.026325 - 0.021796}{0.021796} \times 100 = 20.8\%$ error

b) $P_R = \frac{P}{P_{cr}} = 0.246$,

$T_R = \frac{T}{T_{cr}} = 0.863$ $\xrightarrow{A\text{-}15}$ $Z = 0.84$, $v = v_{ideal} Z = (0.84)(0.026325) = 0.022113 \frac{m^3}{kg}$

$\frac{0.02211 - 0.021796}{0.021796} \times 100 = 0.017 = 1.45\%$

Pseudo-reduced specific volume

م تعرف $v_R = \frac{v_{act}}{R\, T_{cr} / P_{cr}}$

EXAMPLE 3

A closed, rigid tank filled with water vapor, initially at 20 MPa, 520°C, is cooled until its temperature reaches 400°C. Using the compressibility chart, determine (a) the specific volume of the water vapor in m³/kg at the initial state and (b) the pressure in MPa at the final state.

a) $T_{cr} = 647.3 kPa$, $P_{cr} = 22.09 MPa$, $T_R = \frac{793}{647.1} = 1.23$, $P_R = \frac{20}{22.09} =$

$\xrightarrow{A\text{-}15}$ $Z = 0.83$, $v = \frac{ZRT_1}{P_1} \rightarrow 0.015 \frac{m^3}{kg}$

b) $v_R = \frac{v}{R\, T_{cr} / P_{cr}} = \frac{(0.015)(22.09 \times 10^3)}{647.3} = 1.12$, $T_R = 1.04$

$P = P_{cr} \cdot P_R = 22.09 \times 0.69 = 15.24 \times 10^3 \, kPa$

van der Waals Equation of State

* $\left(P+\frac{a}{v^2}\right)(v-b)=RT$

* نیروهای بین مولکولی $\longrightarrow \frac{a}{v^2}$
* حجم اشغال شده توسط مولکول‌های گاز $\longrightarrow v-b$

* $a=\frac{27R^2T_{cr}^2}{64P_{cr}}$, $b=\frac{RT_{cr}}{8P_{cr}}$

EXAMPLE 4

Predict the pressure of nitrogen gas at T =175 K and v = 0.00375 m³/kg on the basis of (a) the ideal-gas equation of state, (b) the van der Waals equation of state. Compare the values obtained to the experimentally determined value of 10,000 kPa.

a) $R \xrightarrow{A-1} 0.2968\,\frac{kJ}{kg\cdot k}$. $P=\frac{RT}{v} \longrightarrow \frac{(0.2968)(175)}{0.00375}=13851\,kPa$

$\frac{10{,}000-13851}{10000}\times 100=38.5\%$

b) $a=0.175\,\frac{m^6 kPa}{kg^2}$, $b=0.00138\,\frac{m^3}{kg}$

$P=\frac{RT}{v-b}-\frac{a}{v^2}=9471\,kPa$, $\frac{10000-9471}{10000}\times 100=5.3\%$

Today's lecture:

- Moving boundary work
- Polytropic process
- Energy balance for closed systems

ENERGY ANALYSIS OF CLOSED SYSTEMS

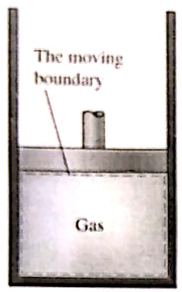
Moving Boundary Work کار مرز متحرک

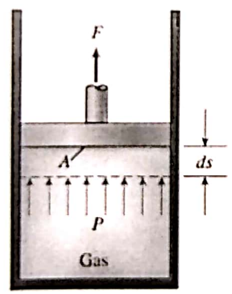
نوعی کار مکانیکی

انبساط یا انقباض گاز داخل سیلندر-پیستون

فرایند شبه تعادلی فرض می‌کنیم

که در هر لحظه سیستم نزدیک است به حالت تعادلی آن لحظه





$\delta W_b = F\,ds = \underbrace{PA\,ds}_{dV} = P\,dV$

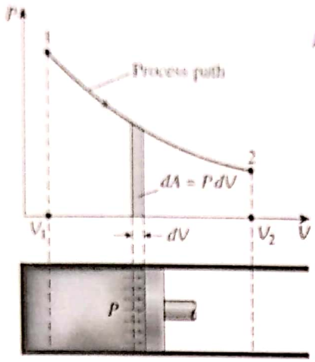
- P فشار اولیه گاز = مطلق
- V حجم کل
- A سطح مقطع پیستون

- انبساط → افزایش حجم پس کار مثبت = یعنی سیستم کار انجام داده $W_b > 0$
- انقباض → کاهش حجم پس کار منفی = یعنی محیط روی سیستم کار انجام داده $W_b < 0$

$P = f(V)$ باید معلوم باشد تا بتوانیم از انتگرال استفاده کنیم

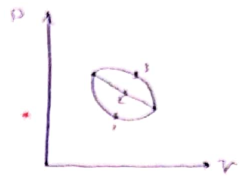
$\star\ W_b = \int_1^2 P\,dV \quad (kJ)$

$\Delta E = Q - W_b$



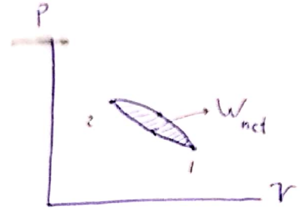
$A = \int_1^2 P dV = W_b$

* کار تابع مسیر فرایند است



* در سیکل کار خالص می‌شود سطح داخل منحنی

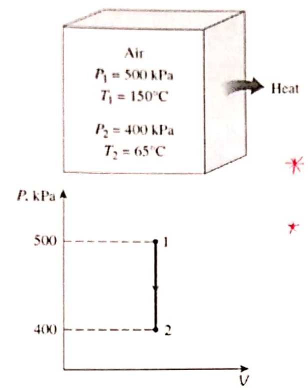
سیکل



* در فرایند غیر شبه تعادلی $W_b = \int P_i dV$
* P_i : فشار گاز روی سطح داخلی پیستون
* در فرایند حجم ثابت : $W_b = \int P dV = 0$ زیرا dV نداریم

EXAMPLE 1

A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.



$W_b = \int_1^2 P\,dV^{\,0} = 0$

* a rigid tank has a constant volume

* $dV = \Delta V = 0$

EXAMPLE 2

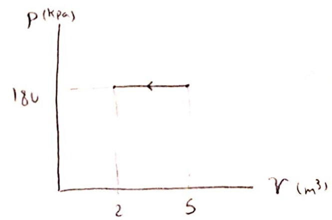
The volume of 1 kg of helium in a piston-cylinder device is initially 5 m^3. Now helium is compressed to 2 m^3 while its pressure is maintained constant at 180 kPa. Determine the initial and final temperatures of helium as well as the work required to compress it, in kJ.

$T_1 = \frac{Pv}{R} \Rightarrow \frac{V}{m} = v = \frac{5}{1} = 5\,\frac{m^3}{kg}$, $R \xrightarrow{A-1} 2.0769$

$T_1 = \frac{(180)(5)}{2.0769} = 433.3k$, $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$. $T_2 = T_1 \frac{V_2}{V_1} = 433.3 \times \frac{2}{5} = 173.3k$

$W_b = \int p\,dV \Rightarrow 180 \int_5^2 dV \rightarrow (180)(2-5) = -540kJ \longrightarrow$ [illegible] $W_{b,in}$

$W_{b,in} = 540kJ$



EXAMPLE 3

cubic meters

A piston–cylinder device initially contains 0.4 m^3 of air at 100 kPa and 80°C. The air is now compressed to 0.1 m^3 in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

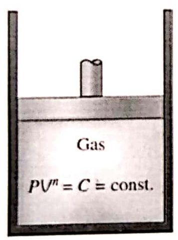
$PV = mRT = c \rightarrow P = \frac{c}{V}$

$W_b = \int_1^2 \frac{c}{V} dV = c \ln \frac{V_2}{V_1} = P_1V_1 \ln \frac{V_2}{V_1}$

$W_b = (100)(0.4) \ln \frac{0.1}{0.4} = -55.5 \text{ kJ}$

$W_{b,in} = 55.5 \text{ kJ}$

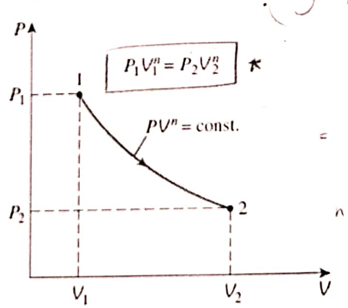
Polytropic Process



$PV^n = C$

n, c ثابت هستند .

اگر طرف آمده رابطه کار مرزی را بدست آوریم



$\int \frac{c}{V^n} dV$

$W_b = \int_1^2 P dV = \int_1^2 c V^{-n} dV$

$= c \left[\frac{V_2^{-n+1} - V_1^{-n+1}}{1-n} \right] \Rightarrow c \left[\frac{P_2V_2 - P_1V_1}{1-n} \right]$

$n = 1$

$PV = mRT \quad W_b = \int_1^2 P dV = \int_1^2 c V^{-1} dV$

$= c \ln \frac{V_2}{V_1}$

معادله زیر برای T ثابت

$W_b = \frac{mR(T_2 - T_1)}{1-n} \quad (n \neq 1)$

Energy Balance for Closed Systems

$E_{in} - E_{out} = \Delta E_{system}$ (kJ) → انتقال خالص انرژی از طریق گرما، کار و جرم ماده

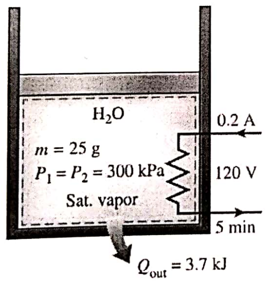
$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt}$ (kW)

$e_{in} - e_{out} = \Delta e_{system}$ (kJ/kg)

اگر نرخ ثابت باشد $Q = \dot{Q}\Delta t$, $W = \dot{W}\Delta t$, $\Delta E = \frac{dE}{dt}\Delta t$

EXAMPLE 4

A piston–cylinder device contains 25 g of saturated water vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. At the same time, a heat loss of 3.7 kJ occurs. (*a*) Show that for a closed system the boundary work W_b and the change in internal energy ΔU in the first-law relation can be combined into one term, ΔH, for a constant pressure process. (*b*) Determine the final temperature of the steam.



a) $E_{in} - E_{out} = \Delta E_{system}$, $\Delta KE = \Delta PE = 0$

$-Q_{out} - W_b - W_{other} = \Delta U = U_2 - U_1$ $\xrightarrow{W_b = P(\Delta V)}$

$-Q_{out} - P_1(V_2 - V_1) - W_{other} = U_2 - U_1$ $\xrightarrow{h = U + PV}$

$-Q_{out} - W_{other} = \underbrace{(U_2 + P_2V_2)}_{H_2} - \underbrace{(U_1 + P_1V_1)}_{H_1} = -Q_{out} - W_{other} = \Delta H$

$W_{ele} = VI\Delta t = (120)(0.2)(300) \times 10^{-3} = 7.2\,kJ$

$W_{ele} - Q_{out} - W_b = \Delta U \rightarrow W_{ele} - Q_{out} = \Delta H = m(h_2 - h_1) = 7.2 - 3.7 = (0.025) \times (h_2 - 2724.9)$

$= h_2 = 2864.9\ kJ/kg$

State 1) $P_1 = 300\,kPa$, Sat. vapor $\longrightarrow h_1 = h_g = 2724.9\ kJ/kg$ (A-5)

State 2) $P_2 = 300\,kPa$, $h_2 = 2864.9$ $\xrightarrow{A-6}$ $T = 200^\circ C$

Today's lecture:

- Specific heats
- Internal energy, enthalpy, and specific heats of ideal gases
- Internal energy, enthalpy, and specific heats of solids and liquids

Specific Heats

گرمای ویژه: انرژی مورد نیاز برای بالا بردن دمای یک واحد جرم از یک ماده به اندازه یک درجه

به مسیر فرایند بستگی دارد.

Specific heat at constant volume C_v

انرژی مورد نیاز برای بالا بردن دمای یک واحد جرم از یک ماده به اندازه یک درجه در صورتی که حجم آن ثابت نگهداشته شود.

Specific heat at constant pressure C_p

تعریف گرمای ویژه اما در صورتی که فشار ثابت نگهداشته شود.

* $C_p > C_v$

* رابطه گرمای ویژه برحسب خواص ترمودینامیکی:

دیفرانسیل [illegible]

- $\delta e_{in} - \delta e_{out} = du$

- $C_v dT = du$ * فرایند حجم ثابت

$$\boxed{C_v = \left(\frac{\partial u}{\partial T}\right)_v}$$

$$\boxed{C_p = \left(\frac{\partial h}{\partial T}\right)_p}$$

INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF IDEAL GASES

- جدول
- $C_p(T)$, $C_v(T)$
- مقادیر متوسط C_p , C_v (در دمای ...)

Specific Heat Relations of Ideal Gases

$h = u + Pv = u + RT$

$dh = du + RdT$

$C_p dT = C_v dT + R dT$ $\boxed{C_p = C_v + R}$ — $\frac{kJ}{kg \cdot K}$

$\bar{C}_p = \bar{C}_v + R_u$ $\frac{kJ}{kmol}$

★ $k = \frac{C_p}{C_v}$ $\begin{cases} k = 1.667 & \text{تک اتمی} \\ k = 1.4 & \text{دو اتمی} \end{cases}$

EXAMPLE 1

Air at 300 K and 200 kPa is heated at constant pressure to 600 K. Determine the change in internal energy of air per unit mass, using (a) data from the air table (Table A–17), (b) the functional form of the specific heat (Table A–2c), and (c) the average specific heat value (Table A–2b).

a) A-17: $T_1 = 300K \longrightarrow u_1 = 214.07 \frac{kJ}{kg}$
$T_2 = 600K \longrightarrow u_2 = 434.78$ $\longrightarrow \Delta u = 220.71$

b) $\bar{C}_p(T) = a + bT + cT^2 + dT^3$

$a = 28.11$, $b = 0.1967 \times 10^{-2}$, $c = 0.4802 \times 10^{-5}$, $d = -1.966 \times 10^{-9}$

$\Delta \bar{u} = \int_1^2 \bar{C}_v dT = \int_1^2 [(a - R_u) + bT + cT^2 + dT^3] \, dT$

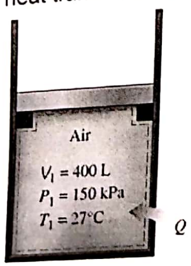
$\Delta\bar{u} = 6447 \text{ kJ/kmol}$, $\Delta u = \frac{\Delta\bar{u}}{M} = \frac{6447}{28.97} = 222.5 \text{ kJ/kg}$

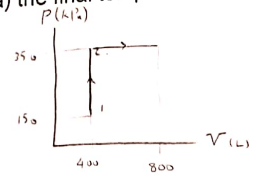
c) $C_{v,avg} = C_{v@450K} = 0.733 \text{ kJ/kg·K}$

$\Delta u = C_{v,avg}(T_2 - T_1) = (0.733)(600-300) = 220 \text{ kJ/kg}$

EXAMPLE 2

A piston–cylinder device initially contains air at 150 kPa and 27°C. At this state, the piston is resting on a pair of stops, as shown, and the enclosed volume is 400 L. The mass of the piston is such that a 350-kPa pressure is required to move it. The air is now heated until its volume has doubled. Determine (a) the final temperature, (b) the work done by the air, and (c) the total heat transferred to the air.





a) $\frac{P_1 V_1}{T_1} = \frac{P_3 V_3}{T_3}$

$\Rightarrow \frac{(150)(V_1)}{300} = \frac{350(2V_1)}{T_3}$

$\Rightarrow T_3 = 1400 K$

b) $W_b = \int_2^3 P dv$

$W_b = P(\Delta V) = (350)(0.4) = 140 kJ = W_{13}$

c) $E_{in} - E_{out} = \Delta E_{system}$, $Q_{in} - W_b = \Delta U = m(u_3 - u_1) \Rightarrow$

$T_1 = 300 K \xrightarrow{A-17} u_1 = 214$, $T_3 = 1400 K \xrightarrow{A-17} u_3 = 1113$

$m = \frac{P_1 V_1}{R T_1} = \frac{(150)(0.4)}{(0.287)(300)} = 0.697\, kg$, $Q_{in} - 140 = (0.697)(1113.52 - 214.07) = 767\, kJ = Q_{in}$

EXAMPLE 3 [illegible]

A piston–cylinder device initially contains 0.5 m^3 of nitrogen gas at 400 kPa and 27°C. An electric heater within the device is turned on and is allowed to pass a current of 2 A for 5 min from a 120-V source. Nitrogen expands at constant pressure, and a heat loss of 2800 J occurs during the process. Determine the final temperature of nitrogen.

$E_{in} - E_{out} = \Delta E_{system}$,

$W_{e,in} - Q_{out} - W_{b,out} = \Delta U$, $W_{e,in} - Q_{out} = P\Delta V + \Delta U = \Delta H = m(h_2 - h_1) = mC_p(T_2 - T_1)$

$W_{e,in} = VI\Delta t = (120)(2)(300) = 72\, kJ$

با فرض گرمای ویژه ثابت در دمای اتاق

Table A–2a : $C_p = 1.039\, kJ/kg \cdot k$

هوا، این مورد فقط در گرمای ویژه ثابت صدق می‌کند

$72 - 2.8 = (2.245)(1.039)(T_2 - 27) \longrightarrow T_2 = 55.47\,°C$

INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF SOLID AND LIQUIDS

Incompressible substance ماده تراکم ناپذیر

ماده‌ای که حجم مخصوص آن در یک فرایند ثابت می‌ماند.

* $C_p = C_v = C$ *

* $du = C_v dT = C(T) dT$, * $\Delta u = \int C(T) dT$

* $\Delta u = C_{avg} \cdot \Delta T \ \left(\frac{kJ}{kg} \right)$

ثابت

* $h = u + pv \longrightarrow dh = du + \cancel{pdv} + vdp$

* $\Delta h = \Delta u + v\Delta p = C_{avg} \cdot \Delta T + V\Delta P \quad \frac{kJ}{kg}$ *

$\Delta h \cong \Delta u = C_{avg} \Delta T$ فشار ثابت

$\Delta h = V\Delta P$ دما ثابت

EXAMPLE 4

Determine the enthalpy of liquid water at 100°C and 15 MPa (a) by using compressed liquid tables, (b) by approximating it as a saturated liquid, and (c) by using the correction.

اول باید حالت را چک کنیم

رابطه تصحیح شده

a) $\begin{cases} T = 100^\circ C \\ P = 15\,MPa \end{cases} \longrightarrow$ compressed liquid

A-7: $h = 430.39 \frac{kJ}{kg.K}$

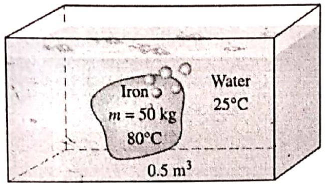
b) $h \cong h_{f@100^\circ C} = 419.17 \frac{kJ}{kg}$

c) $h \cong h_{f@100^\circ C} + v_{f@T}(P - P_{sat@T}) = (419.17) + (0.001)(15000 - 101.42) = 434.07 \, kJ/kg$

EXAMPLE 5

عایق شده

A 50-kg iron block at 80°C is dropped into an insulated tank that contains 0.5 m^3 of liquid water at 25°C. Determine the temperature when thermal equilibrium is reached.



سیستم: هم آب و هم آهن داخل مخزن

$E_{in} - E_{out} = \Delta E_{system}$

چون ساکن است ، $0 = \Delta KE = \Delta PE$

$0 = \Delta U$

$\Delta U_{system} = \Delta U_{water} + \Delta U_{Iron} = [mC(\Delta T)]_{water} + [mC(\Delta T)]_{Iron} = 0$

$m_{water} = \frac{V}{v} = \frac{0.5}{0.001} = 500\,kg$, $C_{water} = 4.18\,\frac{kJ}{kg \cdot k}$, $C_{Iron} = 0.45\,\frac{kJ}{kg \cdot k}$

A-4 جدول

$(500)(4.18)(T_2 - 25) + (50)(0.45)(T_2 - 80) = 0 \Rightarrow T_2 = 25.6\,°C$

EXAMPLE 1

A rigid 10-L vessel initially contains a mixture of liquid water and vapor at 100°C with 12.3 percent quality. The mixture is then heated until its temperature is 150°C. Calculate the heat transfer required for this process.

$E_{in} - E_{out} = \Delta E_{system}$, $Q_{in} = \Delta U = m(u_2 - u_1)$

$m = \frac{V_1}{v}$, $T_1 = 100°C \xrightarrow[A-4]{Sat\ mix} v = v_f + x v_{fg} \Rightarrow (0.001043) + (0.123)(1.6720 - 0.001043)$

$= v_1 = 0.2066\ m^3/kg$; $u_1 = u_f + x u_{fg} = 419.06 + (0.123)(2087) = 675.76\ kJ/kg$

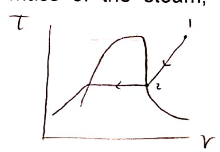
$m = \frac{0.01}{0.2066} = 0.0484\ kg$; $T_2 = 150°C$, $v_2 = v_1 = 0.2066 \longrightarrow x_2 = \frac{v_2 - v_f}{v_{fg}}$

$= \frac{0.2066 - 0.001091}{0.39248 - 0.001091} = 0.52$, $u_2 = u_{f_2} + x_2 u_{fg_2} = 631.66 + (0.52)(1927.4) = 1643\ kJ/kg$

$Q_{in} = m(u_2 - u_1) = (0.04841)(1643.5 - 675.76) = 46.9\ kJ$

EXAMPLE 2

A piston–cylinder device contains steam initially at 1 MPa, 450°C, and 2.5 m³. Steam is allowed to cool at constant pressure until it first starts condensing. Show the process on a T-v diagram with respect to saturation lines and determine (a) the mass of the steam, (b) the final temperature, and (c) the amount of heat transfer.



a) $P = 1 MPa$, $T = 450°C \xrightarrow[State]{check}$ State : Superheated ,

Superheated table $\longrightarrow v = 0.33045\ m^3/kg$

b) $m = \frac{V}{v} = \frac{2.5}{0.33045} = 7.565\ kg$, $P_2 = P_1 = 1 MPa$. $T_2 = T_{sat} \xrightarrow{A-5} 179.9°C$

$W_{out} = \int P dV$

$W_{out} = P\Delta V = P(V_2 - V_1)$

$W_{in} = P(V_1 - V_2)$

c) $E_{in} - E_{out} = \Delta E_{system}$, $-Q_{out} + W_{b,in} = \Delta U = m(u_2 - u_1)$ $\Delta PE = \Delta KE = 0$

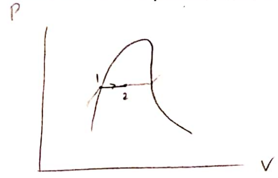
Constant Press. $W_{b,in} = P\Delta V \Rightarrow -Q_{out} + P\Delta V = \Delta U \Rightarrow -Q_{out} = \Delta h = m(h_2 - h_1)$

Superheated chart $\longrightarrow h_1 = 3371.3\ kJ/kg$, sat. vap $\longrightarrow h_g = h_2 = 2777.1\ kJ/kg$.

$-Q_{out} = (7.565)(2777 - 3371) = 4495\ kJ$

EXAMPLE 3

An insulated piston–cylinder device contains 5 L of saturated liquid water at a constant pressure of 175 kPa. Water is stirred by a paddle wheel while a current of 8 A flows for 45 min through a resistor placed in the water. If one-half of the liquid is evaporated during this constant-pressure process and the paddle-wheel work amounts to 400 kJ, determine the voltage of the source. Also, show the process on a P-v diagram with respect to saturation lines.

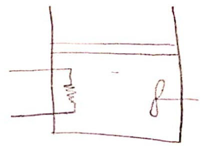


$E_{in} - E_{out} = \Delta E_{system}$

$W_{e,in} + W_{pw,in} - W_{b,out} = \Delta U$

برقي

Constant Press. , $W_b = P\Delta V$



$W_{e,in} + W_{pw} = \Delta h = m(h_2 - h_1)$,

① state ① : sat. liq, $P = 175\ kPa$ $\longrightarrow h_1 = h_f = 487.01\ kJ/kg$

$v_1 = v_f = 0.001057\ m^3/kg$

② state ② : $P = 175\ kPa$, نصف آب بخار شده $\leftarrow x = 0.5$ $\longrightarrow h_2 = h_f + x h_{fg} = (487.01) + (0.5)(2231.1)$

$= 1593.6\ kJ/kg$

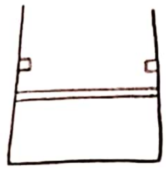
$m = \frac{V}{v} = \frac{0.005}{0.001057} = 4.731\ kg$, $VI\Delta T + 400 = (4.731)(1593.6 - 487.01) =$

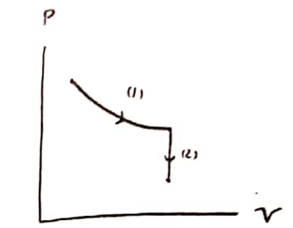
$V = \frac{4835}{(8)(45)(60)} \times 1000 = \boxed{223.9\ V}$, $\boxed{1\ kJ/s = 1000\ VA}$

EXAMPLE 4

Air is contained in a piston-cylinder device at 600 kPa and 927°C, and occupies a volume of 0.8 m^3. The air undergoes and isothermal (constant temperature) process until the pressure in reduced to 300 kPa. The piston is now fixed in place and not allowed to move while a heat transfer process takes place until the air reaches 27°C.
(a) Sketch the system showing the energies crossing the boundary and the P-V diagram for the combined processes.
(b) For the combined processes determine the net amount of heat transfer, in kJ, and its direction.
Assume air has constant specific heats evaluated at 300 K.

a)





b) $E_{in} - E_{out} = \Delta E_{system}$, $Q_{in} - W_b = \Delta U = m C_v (\Delta T)$

$m = \frac{P_1 V_1}{R T_1} = \frac{(600)\times(0.8)}{(0.287)(1200)} = 1.394\,kg$. $W_{b,out} = \int_1^2 P\,dV = \int_1^2 \frac{mRT}{V} dV = mRT \int_1^2 \frac{dV}{V}$

$P_1 V_1 = P_2 V_2$

$mRT \ln \frac{V_2}{V_1} = (1.394)(0.287)(1200) \ln \frac{600}{300} = 332.8\,kJ$

$Q_{in} = W_{b,out} + mC(\Delta T) = 332.8 + (1.394)(0.718)(300-1200) = -568\,kJ$, $Q_{out} = 568\,kJ$

MASS AND ENERGY ANALYSIS OF CONTROL VOLUMES

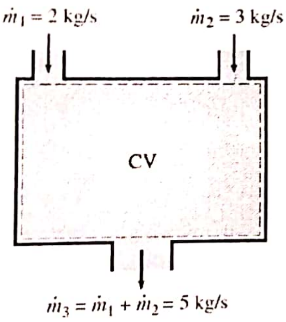
Conservation of Mass Principle

The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) of the total mass within the control volume during Δt.

* $m_{in} - m_{out} = \Delta m_{cv}$ (kg) , * $m_{cv} = m_f - m_i$, * $\dot{m}_{in} - \dot{m}_{out} = \frac{dm_{cv}}{dt}$ $(\frac{kg}{s})$

Mass Balance for Steady-flow Processes

جریان پایا



* m_{cv} = Constant

* $m_{in} = m_{out}$, $\dot{m}_{in} = \dot{m}_{out}$

* $\sum \dot{m}_{in} = \sum \dot{m}_{out}$

* one inlet and one outlet : (single stream)

* $\dot{m}_1 = \dot{m}_2$ چگالی

$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$ سرعت

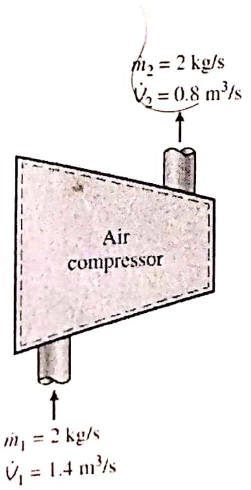
* $v_g = \frac{1}{\rho_g}$ ← حجم مخصوص

Special Case: Incompressible Flow

(تراکم ناپذیر)

چگالی تغییر نکند . (حجم مخصوص ثابت باشد)

(فقط برای مایعات)



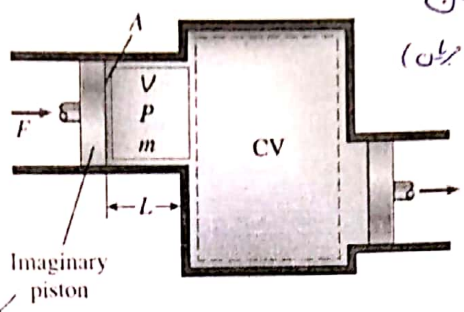
* $\sum \dot{V}_{in} = \sum \dot{V}_{out}$ $(\frac{m^3}{s})$

$\dot{V}_{in} = \dot{V}_{out} \longrightarrow V_1 A_1 = V_2 A_2$ سرعت

Scanned by CamScanner

FLOW WORK AND THE ENERGY OF THE FLOWING FLUID

کار جریان
(انرژی جریان)



پیستون فرضی

نیرویی که از طرف پیستون فرضی به المان سیال وارد می‌شود

$F = PA$

فشار سیال

سطح مقطع المان سیال

- $W_{Flow} = PAL = PV \ (kJ)$
- $w_{flow} = Pv \ (kJ/kg)$

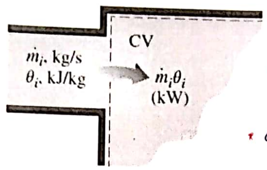
Total Energy of a Flowing Fluid

- $e = u + ke + pe = u + \frac{V^2}{2} + gz \ (kJ/kg) \longrightarrow$ در سیستم بسته
- $\theta = \underbrace{Pv + u}_{h} + ke + pe = h + ke + pe = h + \frac{V^2}{2} + gz \longrightarrow$ Total flow energy

$PV =$ Flow energy

$h - u = PV$

Energy Transport by Mass

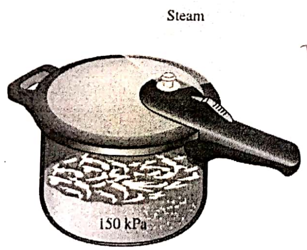


- $E_{mass} = m\theta = m(h + \frac{V^2}{2} + gz)$
- $\dot{E}_{mass} = \dot{m}\theta = \dot{m}(h + \frac{V^2}{2} + gz)$
- $\dot{E}_{mass} = \dot{m}h$ $\longrightarrow$ اگر پتانسیل و جنبشی را کم در نظر بگیریم

$ke \cong 0$
$Pe \cong 0$

EXAMPLE 1

Steam is leaving a 4-L pressure cooker whose operating pressure is 150 kPa. It is observed that the amount of liquid in the cooker has decreased by 0.6 L in 40 min after the steady operating conditions are established, and the cross-sectional area of the exit opening is 8 mm^2. Determine (a) the mass flow rate of the steam and the exit velocity, (b) the total and flow energies of the steam per unit mass, and (c) the rate at which energy leaves the cooker by steam.



Pressure cooker

a) $\Delta m = \frac{\Delta V_{liq}}{v_f} = \frac{0.6\times10^{-3}}{0.001053} = 0.57\,kg$ جرم بخار

$v_f \xrightarrow[P=150kPa]{A\text{-}5} 0.001053$

$\dot{m} = \frac{\Delta m}{\Delta t} = \frac{0.57}{(40)(60)} = 2.37\times10^{-4}\ kg/s$

Exit velocity $V = \frac{\dot{m}}{\rho_g A_c} = \frac{(2.37\times10^{-4})(1.1594)}{8\times10^{-6}} = 34.3\ m/s$

b) $P = 150kPa \longrightarrow v_g = 1.1594\ m^3/kg$

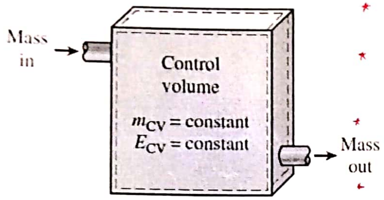
$e_{flow} = Pv = h_g - u_g = 2698.1 - 2519.2 = 173.9\ kJ/kg$, $\theta = h + ke + Pe = h = 2693.1\,kJ/kg$

$\frac{V^2}{2} = 0.588\ kJ/kg \ll h$

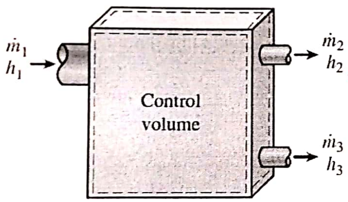
c)

$E_{mass} = \dot{m}\theta = \dot{m}h = (2.34\times10^{-4})(2693.1) = 0.638\,W$

ENERGY ANALYSIS OF STEADY FLOW SYSTEMS



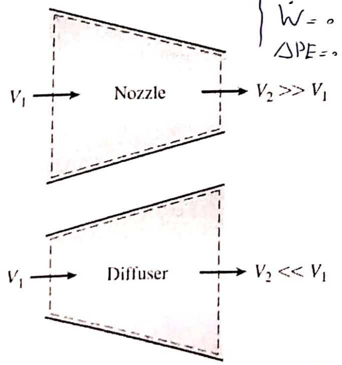
* $V_{cv} = \text{constant}$
* $m_{cv} = \text{constant}$ $\quad W_b = 0$
* $m_{in} - m_{out} = \Delta m_{cv} = 0 \Rightarrow m_{in} = m_{out}$
* $\dot{m}_1 = \dot{m}_2 \rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2$ (سرعت، چگالی)



* $\sum \dot{m}_{in} = \sum \dot{m}_{out}$ $\quad (kg/s)$
* $\dot{E}_{in} = \dot{E}_{out}$, $\quad \dot{E}_{in} - \dot{E}_{out} = \cancel{\dfrac{dE_{system}}{dt}}^{\,0}$
* $Q_{in} + W_{in} + \sum m_{in}\theta = Q_{out} + W_{out} + \sum \dot{m}_{out}\theta$

Nozzles and Diffusers

$$\begin{cases} \dot{Q} = 0 \\ \dot{W} = 0 \\ \Delta PE = 0 \end{cases}$$



* تغییرات انرژی جنبشی قابل ملاحظه است
چون تغییرات سرعت زیاد است.
* از انرژی جنبشی در ورود نازل ها و خروج دیفیوزرها صرف نظر می‌شود
* برای هردو $\dot{Q}$ و $\dot{W}$ برابر صفر است.

EXAMPLE 2

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (a) the mass flow rate of the air and (b) the temperature of the air leaving the diffuser.

W_{out}

Turbines and Compressors

W_{in}

$Q=0$ $\Delta Pe \cong 0$, $\Delta kE \cong 0$

EXAMPLE 3

جلسه بعد

Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.

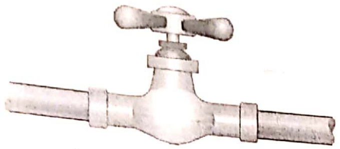
بالانس انرژی

Some Steady-Flow Engineering Devices

1- Nozzles and Diffusers

2- Turbines and Compressors

3- Throttling Valves



(a) An adjustable valve

(b) A porous plug

(c) A capillary tube

↳ لوله مویین

* $Q \cong 0$
* $W \cong 0$
* $\Delta PE \cong 0$
* $\Delta KE \cong 0$
* $e_{in} - e_{out} = \Delta e_{system}$
* $h_1 \cong h_2 \longrightarrow u_1 + P_1 v_1 \cong u_2 + P_2 v_2$
* $(T_1 \cong T_2)$ Ideal gas

EXAMPLE 1

Refrigerant-134a enters the capillary tube of a refrigerator as saturated liquid at 0.8 MPa and is throttled to a pressure of 0.12 MPa. Determine the quality of the refrigerant at the final state and the temperature drop during this process.

$e_{in} = e_{out} \longrightarrow h_1 = h_2$

$$\left\{\begin{array}{l} P_1 = 0.8\,MPa \\ \text{Sat liq} \end{array}\right. \xrightarrow{A-12} h_1 = h_f = 95.47\ kJ/kg$$

$T_1 = T_{sat} = 31.31\,°C$

$h_2 = h_1 = 95.47\ kJ/kg$, $P_2 = 0.12\,MPa$, $h_f = 22.49\ kJ/kg$

$h_g = 236.97\ kJ/kg \longrightarrow h_f < h_2 < h_g$

$\longrightarrow$ Sat mix

$\longrightarrow T_2 = T_{sat} = -22.32\,°C$

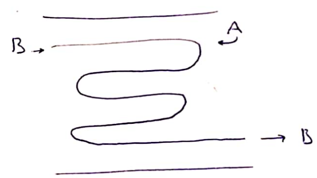
$$x = \frac{h_2 - h_f}{h_{fg}} = 0.34$$

$\Delta T = T_2 - T_1 = -53.63\,°C$

4a Mixing Chambers

- $W \cong 0$
- $Q \cong 0$
- $\Delta KE \cong 0$
- $\Delta PE \cong 0$
- $E_{in} = E_{out}$

4b Heat Exchangers



EXAMPLE 2

Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enter the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops, determine (a) the mass flow rate of the cooling water required and (b) the heat transfer rate from the refrigerant to water.

mass balance

$\dot{m}_1 = \dot{m}_2 = m_w$

$R\text{-}134a: \dot{m}_1 = \dot{m}_2 = m_R$

Energy Balance.

$$\dot{E}_{in} - \dot{E}_{out} = \cancel{\frac{dE_{system}}{dt}}^{\nearrow 0,\ \text{steady}} \qquad \dot{Q} \cong 0,\ \Delta KE = \Delta PE \cong 0,\ \dot{W} \cong 0$$

$$\dot{m}_w h_1 + \dot{m}_R h_3 = \dot{m}_w h_2 + \dot{m} h_4 \longrightarrow \dot{m}_w (h_1 - h_2) = \dot{m}_R (h_4 - h_3)$$

water: $P = 300\,kPa \rightarrow T_{sat} = 133.52°C$ $\longrightarrow$ comp. liq

$T < T_{sat}$

$h_1 \cong h_{f @ 15°C} = 62.982\ kJ/kg$

$h_2 = h_{f @ 25°C} = 104.83\ kJ/kg$

R-134a: $P = 1MPa$, $T = 70°C$ $\longrightarrow$ Superheated vapor

A-13 $\longrightarrow$ $h_3 = 303.85\ kJ/kg$

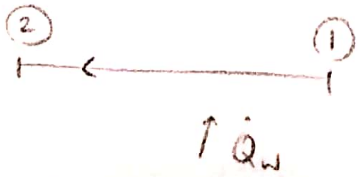
$P = 1MPa$, $T = 35°C$ $\longrightarrow$ Comp. liq

$h_4 = h_{f @ 35°C} = 100.87\ kJ/kg$

$\dot{m}_w = 29.1\ kg/min$

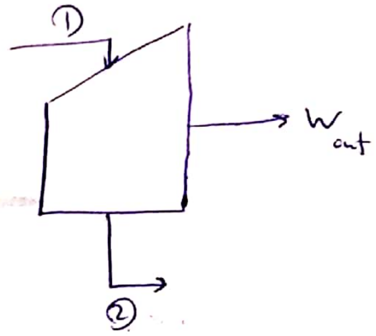
$$\dot{m}_w h_1 + \dot{Q}_w = \dot{m}_w h_2$$

$$\rightarrow \dot{Q}_w = \dot{m}(h_2 - h_1) = 1218\ kJ/min$$



EXAMPLE 1

Steam flows steadily through an adiabatic turbine. The inlet conditions of the steam are 4 MPa, 500°C, and 80 m/s, and the exit conditions are 30 kPa, 92 percent quality, and 50 m/s. The mass flow rate of the steam is 12 kg/s. Determine (a) the change in kinetic energy, (b) the power output, and (c) the turbine inlet area.



① $\begin{cases} P_1 = 4\,MPa \\ T_1 = 500^\circ C \end{cases} \longrightarrow h_1 = 3446 \,,\ v_1 = 0.086442\ m^3/kg$

② $\begin{cases} P_1 = 30\,kPa \\ x_2 = 0.92 \end{cases} \longrightarrow h_2 = h_f + x h_{fg} = 289.27 + (0.92)(2335.3) = 2437.7\ kJ/kg$

ⓐ $\Delta KE = \dfrac{V_2^2 - V_1^2}{2} = \dfrac{50^2 - 80^2}{2} = 1095\ kJ$

ⓑ $\dot{E}_{in} - \dot{E}_{out} = \cancel{\dfrac{dE_{system}}{dt}}^{\,steady}$, $\dot{m}\left(h_1 + \dfrac{V_1^2}{2}\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \dfrac{V_2^2}{2}\right)$

$\dot{W}_{out} = \dot{m}\left(h_1 - h_2 + \dfrac{V_1^2 - V_2^2}{2}\right) = (12)(3446 - 2437.7) + 1.95 = 12123\,kW$

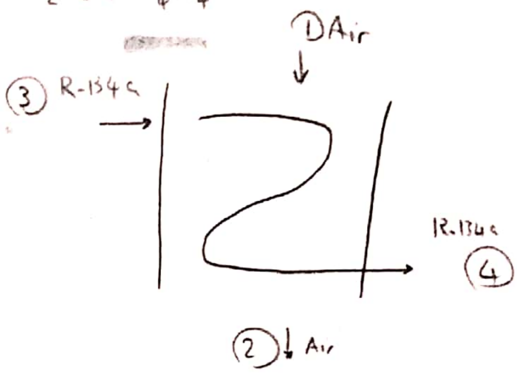
ⓒ

$\dot{m} = \dfrac{A_1 V_1}{v_1} \Rightarrow A_1 = \dfrac{(12)(0.086442)}{(80)} = 0.013\ m^2$

EXAMPLE 2

Refrigerant-134a at 1 MPa and 90°C is to be cooled to 1 MPa and 30°C in a condenser by air. The air enters at 100 kPa and 27°C with a volume flow rate of 600 m³/min and leaves at 95 kPa and 60°C. Determine the mass flow rate of the refrigerant.

$$\dot{E}_{in} - \dot{E}_{out} = \cancel{\frac{dE_{system}}{dt}}^{\,0,\ steady} \quad , \quad \dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$



$$\dot{m}_{in} - \dot{m}_{out} = \cancel{\frac{dm_{system}}{dt}}^{\,0,\ steady}$$

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_a$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

$$\left\{ \begin{array}{l} P_3 = 1\,MPa \\ T = 90^\circ C \end{array} \right. \xrightarrow{table} h_3 = 324.66 \ \frac{kJ}{kg}$$

$$\left\{ \begin{array}{l} P_4 = 1\,MPa \\ T = 30^\circ C \end{array} \right. \xrightarrow{table} h_4 \cong h_{f @ 30^\circ C} = 93.58 \ \frac{kJ}{kg} \quad , \text{comp. liq}$$

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} , \quad v_1 = \frac{RT_1}{P_1} = \frac{(0.287)(300)}{(100)} = 0.861 \ \frac{m^3}{kg}$$

$$= \frac{600}{0.861} = 696.9 \ \frac{kg}{min}$$

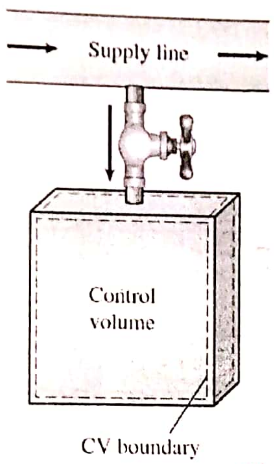
$$\dot{m}_R = \frac{(h_2 - h_1)}{h_3 - h_4} \dot{m}_a \cong \frac{C_p (T_2 - T_1)}{h_3 - h_4}$$

تغییرات گرما ویژه را ثابت فرض می‌کنیم. (دمای اتاق)

C_p از جدول می‌خوانیم

$$\frac{(1.005)(60-27)}{324.66 - 93.58} (696.9) = 100 \ \frac{kg}{min} = \dot{m}_R$$

ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES



* Mass Balance = $m_{in} - m_{out} = \Delta m_{system}$ (kg)

* $\Delta m_{system} = m_f - m_i$, [illegible] [illegible] $m_i - m_e = (m_2 - m_1)_{cv}$

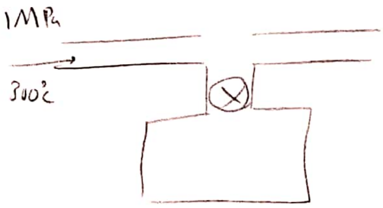
* Energy Balance = $E_{in} - E_{out} = \Delta E_{system}$

Uniform-Flow ([illegible])

* Charging of a rigid tank ~~with~~ from a supply line is an unsteady-flow process , $\boxed{\theta = h + PE + KE \text{ , } e = u + PE + KE}$

EXAMPLE 3 * $E_{in} - E_{out} = \Delta E_{system} \longrightarrow \boxed{Q_{in} + W_{in} + \sum_{in} m\theta - (Q_{out} + W_{out} + \sum_{out} m\theta) = m_2 e_2 - m_1 e_1}$

A rigid, insulated tank that is initially evacuated is connected through a valve to a supply line that carries steam at 1 MPa and 300°C. Now the valve is opened, and steam is allowed to flow slowly into the tank until the pressure reaches 1 MPa, at which point the valve is closed. Determine the final temperature of the steam in the tank.



$m_{in} - m_{out} = \Delta m_{system}$

$m_{in} - \cancel{m_e}^{0} = m_2 - \cancel{m_1}^{0}$

$E_{in} - E_{out} = \Delta E_{system}$, $m_i h_i = \Delta u = m_2 u_2 - \cancel{m_1 u_1}^{0} \Rightarrow m_i h_i = m_2 u_2$

$h_i = u_2$,

$\left\{ \begin{array}{l} P_i = 1MPa \\ T_i = 300°C \end{array} \right. \longrightarrow h_i = 3051.6 \ kJ/kg =$

$\left\{ \begin{array}{l} P_2 = 1MPa \\ u_2 = 3051.6 \end{array} \right. \longrightarrow T_2 = 456.1°C$

EXAMPLE 4

An insulated 8-m^3 rigid tank contains air at 600 kPa and 400 K. A valve connected to the tank is now opened, and air is allowed to escape until the pressure inside drops to 200 kPa. The air temperature during the process is maintained constant by an electric resistance heater placed in the tank. Determine the electrical energy supplied to air during this process.

$m_{in} - m_{out} = \Delta m_{system}$

$-m_{out} = m_2 - m_1$

$E_{in} - E_{out} = \Delta E_{system} \Rightarrow W_{e,in} - m_e h_e = m_2 u_2 - m_1 u_1$

$m_1 = \dfrac{P_1 V_1}{T_1 R_1} = \dfrac{(600)(8)}{(0.287)(400)} = 41.81\ kg$,

* هوا همیشه از قانون گاز ایده آل تبعیت می‌کند

$m_2 = \dfrac{P_2 V_2}{T_2 R_2} = \dfrac{(200)(8)}{(0.287)(400)} = 13.94\ kg$,

* گاز باید فشار کمتر از 10kPa باشد

* در گاز ایده آل انرژی داخلی فقط به دما بستگی دارد

$m_e = m_1 - m_2 = 41.81 - 13.94 = 27.87\ kg$

$T = 400k \longrightarrow u_1 = u_2 = 286.16\ kJ/kg$

$h_e = 400.98$

$W_{e,in} = 3200\ kJ$

Today's lecture:

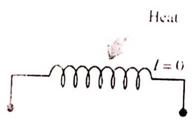
- Introduction to the second law
- Thermal energy reservoirs
- Heat engines
- Vapor power cycles
- Refrigeration cycles
- Kelvin-Planck statement
- Clausius statement

THE SECOND LAW OF THERMODYNAMICS

In this chapter, we introduce the second law of thermodynamics, which asserts that processes occur in a certain direction and that energy has quality as well as quantity. A process cannot take place unless it satisfies both the first and second laws of thermodynamics.

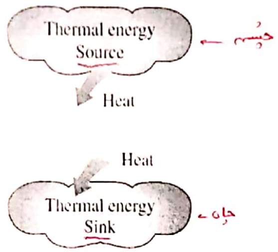
INTRODUCTION TO THE SECOND LAW

فرایندها فقط در یک جهت خاص رخ می دهند.

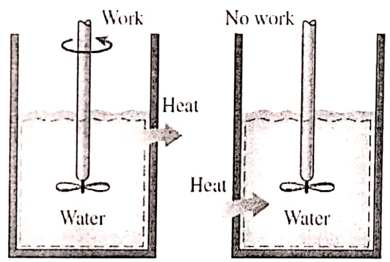


THERMAL ENERGY RESERVOIRS منبع انرژی گرمایی

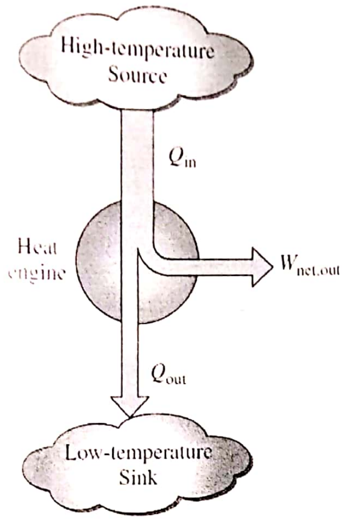
یک توده جسم فرضی با ظرفیت انرژی گرمایی (mc) بسیار بزرگ که با جذب یا دفع انرژی دمایش تغییر را محسوس نشود



HEAT ENGINES



- کار را می‌توان مستقیماً به طور کامل به گرما تبدیل کنیم
اما تبدیل گرما به کار نیازمند دستگاه‌های خاصی است
که به آن‌ها موتورهای گرمایی می‌گویند

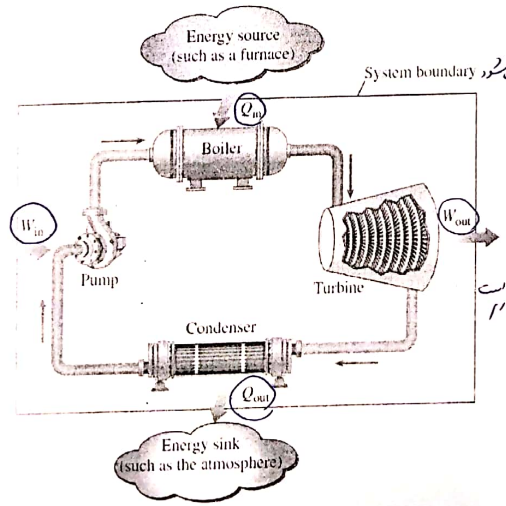


۱. از یک چشمه دما بالا گرما دریافت می‌کند
۲. بخشی از انرژی را به کار تبدیل می‌کند
۳. بقیه انرژی دریافتی را به یک چاه دما پایین منتقل می‌کند
۴. در یک سیکل کار می‌کند.

Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the **working fluid**.

سیال عامل

Steam Power Plant

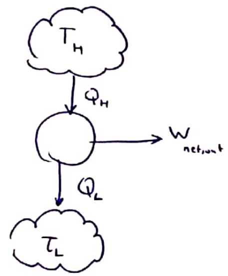


• Q_{in}: مقدار گرمایی است که در بویلر از چشمه دما بالا به آب داده می‌شود
• Q_{out}: گرمایی که در کندانسور از بخار به چاه دما پایین داده می‌شود
• W_{out}: کاری که توسط بخار در توربین انجام می‌شود و از سیکل خارج می‌شود
• W_{in}: کاری که برای تراکم مایع (آب) و بالا بردن فشار آن تا فشار بویلر لازم است

- $W_{net,out} = W_{out} - W_{in}$ (kJ)
- $E_{in} - E_{out} = \Delta E_{system}$
- $Q_{in} - W_{in} - Q_{out} - W_{out} = 0$
- $W_{net,out} = W_{out} - W_{in} = Q_{in} - Q_{out}$

Thermal Efficiency بازده گرمایی

- $\eta_{th} = \frac{\text{Desired output}}{\text{Required input}}$
- $\eta_{th} = \frac{W_{net,out}}{Q_{in}} < 1 \Rightarrow \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$
- $W_{net,out} = Q_H - Q_L$
- $\eta_{th} = \frac{W_{net,out}}{Q_H} = 1 - \frac{Q_L}{Q_H}$



Can we save Q_{out}?

EXAMPLE 1

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

$$\dot{Q}_H = 80MW, \quad \dot{Q}_L = 50MW,$$

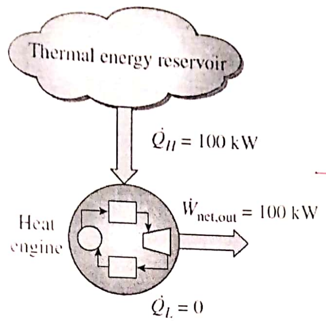
$$\dot{W}_{net,out} = \dot{Q}_H - \dot{Q}_L = 80 - 50 = 30MW$$

$$\eta = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_L}{\dot{Q}_H} = \frac{30}{80} = \frac{3}{8}$$

The Second Law of Thermodynamics:

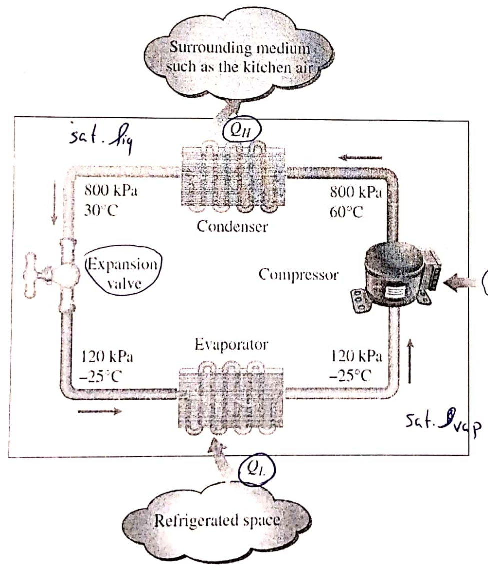
Kelvin–Planck Statement

هیچ دستگاهی وجود ندارد که در یک سیکل کار کند و تنها از یک منبع گرما بگیرد و به همان اندازه کار خالص انجام دهد.



→ هیچ دستگاهی وجود ندارد •

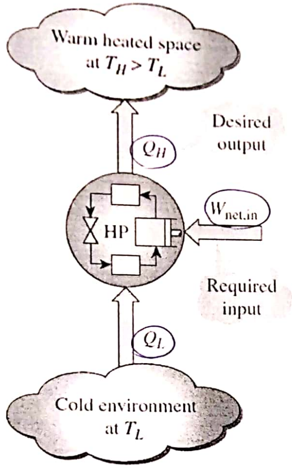
Refrigerators and heat pumps



- $E_{in} - E_{out} = \Delta E_{system}$
- $Q_L + W_{net,in} = Q_H$
- $W_{net,in} = Q_H - Q_L$

- $COP_R = \dfrac{\text{Desired output}}{\text{Required input}} = \dfrac{Q_L}{W_{net,in}} = \dfrac{Q_L}{Q_H - Q_L} = \dfrac{1}{\frac{Q_H}{Q_L} - 1}$

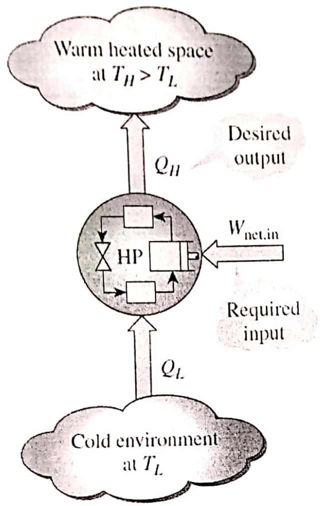
می‌تواند مقدارش بیشتر از ۱ باشد •



Coefficient of performance

- $COP_R = \frac{Q_L}{W_{net,in}}$
- $COP_{HP} = \frac{Q_H}{W_{net,in}}$ Heat pump
- $COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$
- $\underbrace{COP_R}_{>0} + 1 = \frac{Q_L}{W_{net,in}} + \frac{W_{net,in}}{W_{net,in}} = \frac{Q_H}{W_{net,in}} = COP_{HP}$
- $COP_{HP} > 1$

Heat pumps


Warm heated space
at $T_H > T_L$
Q_H
Desired
output
HP
$W_{net,in}$
Required
input
Q_L
Cold environment
at T_L

EXAMPLE 2

The food compartment of a refrigerator is maintained at 4°C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine (*a*) the coefficient of performance of the refrigerator and (*b*) the rate of heat rejection to the room that houses the refrigerator.

a) $\dot{Q}_L = 360 \frac{kJ}{min}$, $\dot{W}_{net,in} = 2 kW$,

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{360}{2 \cdot 60} = 3$$

b) $\dot{Q}_H = \dot{Q}_L + \dot{W}_{in} = 360 + (2)(60) = 480 \frac{kJ}{min}$

EXAMPLE 3

A heat pump is used to meet the heating requirements of a house and maintain it at 20°C. On a day when the outdoor air temperature drops to -2°C, the house is estimated to lose heat at a rate of 80,000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine (*a*) the power consumed by the heat pump and (*b*) the rate at which heat is absorbed from the cold outdoor air.

a) $COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} \longrightarrow \dot{W}_{net,in} = \frac{80000}{2.5} = 32000 \frac{kJ}{h}$

b) $\dot{Q}_L = \dot{Q}_H - \dot{W}_{net,in} = 80000 - 32000 = 48000 \frac{kJ}{h}$

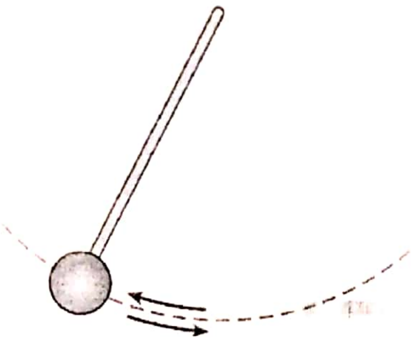
The Second Law of Thermodynamics:

Clausius Statement

امکان ندارد بتوان دستگاهی ساخت که در یک سیکل کار کند و هیچ اثر دیگری غیر از انتقال گرما از جسم دما پایین به جسم دما بالا ایجاد کند

REVERSIBLE AND IRREVERSIBLE PROCESSES

فرایند های برگشت پذیر و برگشت ناپذیر



(a) Frictionless pendulum

(b) Quasi-equilibrium expansion and compression of a gas

فرایند های برگشت پذیر

فرایندی که می‌توان جهت آن را عوض کرد بدون آنکه هیچ اثری روی محیط بگذارد

در پایان فرایند برگشت هم سیستم و هم محیط به حالت اولیه‌شان برمی‌گردند

Irreversibilities

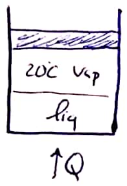
فرایند های برگشت ناپذیر

- اصطکاک
- انبساط آزاد یک گاز
- انتقال گرما از طریق یک اختلاف دمای محدود Δt (finite)
- مقاومت الکتریکی
- اختلاط مواد
- واکنش های شیمیایی

Internally and Externally Reversible Processes

برگشت پذیر درونی: هیچ عامل برگشت ناپذیری داخل مرزهای سیستم وجود نداشته باشد

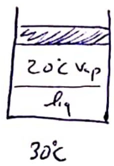
کاملاً برگشت پذیر: وقتی هم از داخل و هم از خارج برگشت پذیر باشد.



20.001°C

بخاطر اختلاف دمای کم

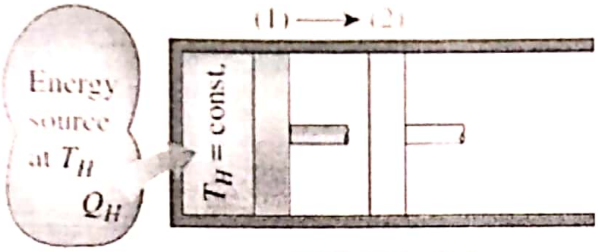
کاملاً برگشت پذیر



برگشت پذیر داخلی

The Carnot Cycle

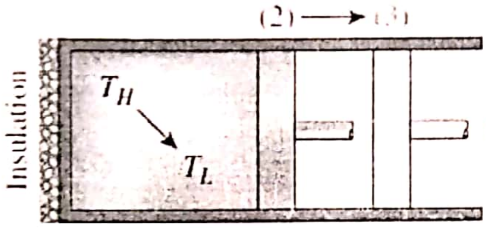
* فرایندهای برگشت‌پذیر بیشترین تولید کار و کمترین مصرف کار را دارند



(*a*) Process 1-2

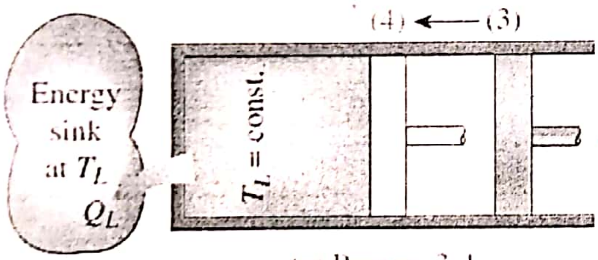
* انبساط دما ثابت برگشت‌پذیر $1 \rightarrow 2$

* Q_H



(*b*) Process 2-3

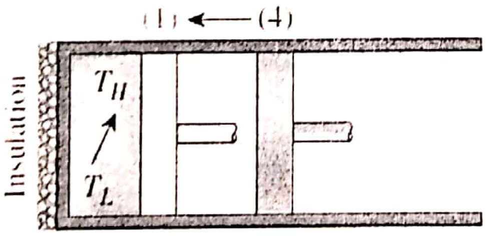
* انبساط آدیاباتیک (انتالپی کاهش) برگشت‌پذیر $2 \rightarrow 3$



(*c*) Process 3-4

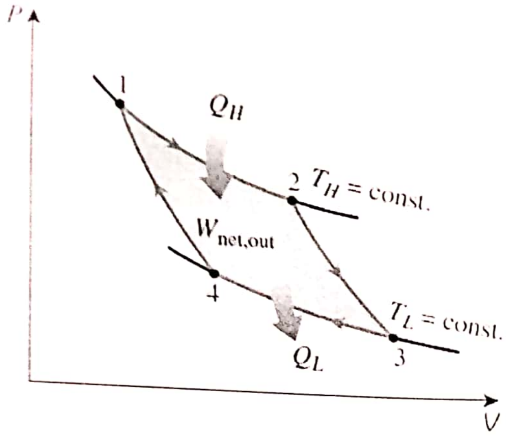
* تراکم دما ثابت برگشت‌پذیر $3 \rightarrow 4$

* Q_L



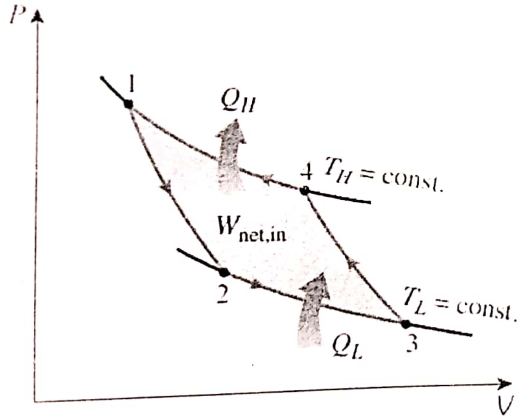
(*d*) Process 4-1

* تراکم آدیاباتیک (انتالپی افزایش) برگشت‌پذیر $4 \rightarrow 1$



The Reversed Carnot Cycle

سیکل معکوس کارنو در حالت ایده‌آل برای سیکل تبرید است



THE CARNOT PRINCIPLES

۱) بازده یک موتور گرمایی برگشت ناپذیر همیشه از بازده یک موتور برگشت پذیر که بین دو منبع کار می‌کند کمتر است

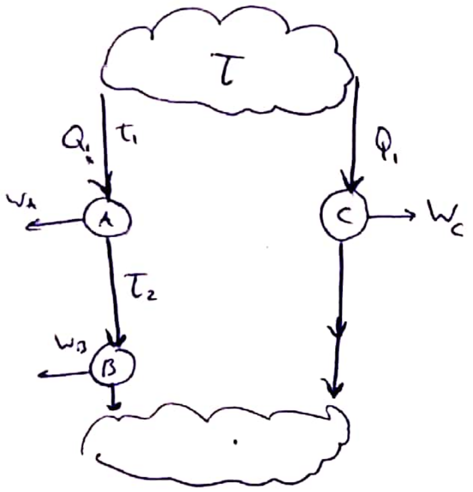
2) بازده همه موتورهای گرمایی برگشت پذیر بین دو منبع گرمایی یکسان کار می‌کنند، یکسان هستند.

THERMODYNAMIC TEMPERATURE SCALE

مقیاس دمای ترمودینامیک

مقیاس دمایی که از جنس و خواص ماده‌ای که از آن برای اندازه‌گیری دما استفاده می‌شود، مستقل است

$$\eta_{th,rev} = f(T_H, T_L) \quad , \quad \eta_{th} = 1 - \frac{Q_L}{Q_H} \rightarrow \overset{\text{تابع}}{g}(T_H, T_L)$$



$$\frac{Q_1}{Q_2} = f(T_1,T_2) \quad , \quad \frac{Q_2}{Q_3} = f(T_2,T_3) \quad , \quad \frac{Q_1}{Q_3} = f(T_1,T_3)$$

$$\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2} \times \frac{Q_2}{Q_3}$$

$$f(T_1,T_3) = f(T_1,T_2) \cdot f(T_2,T_3)$$

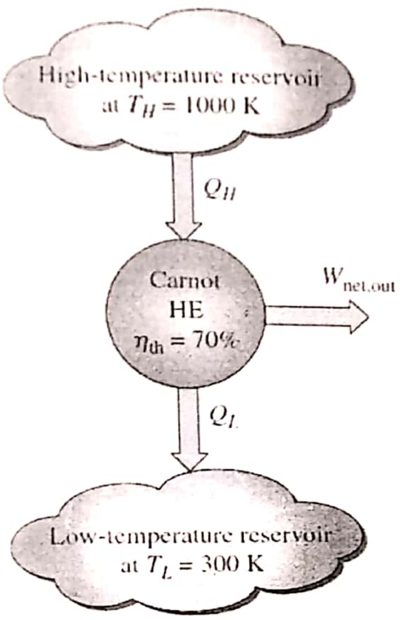
$$f(T_1,T_2) = \frac{\phi(T_1)}{\phi(T_2)} \quad , \quad f(T_2,T_3) = \frac{\phi(T_2)}{\phi(T_3)} \quad , \quad f(T_1,T_3) = \frac{\phi(T_1)}{\phi(T_3)}$$

$$\frac{Q_H}{Q_L} = \boxed{\frac{\phi[T_H]}{\phi[T_L]} = \left(\frac{Q_H}{Q_L}\right)_{rev}}$$

مقیاس کلوین

$$\phi[T] = T$$

THE CARNOT HEAT ENGINE



$$\eta_{th} = \frac{W_{net,out}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

$$\eta_{th,carnot} = 1 - \frac{T_L}{T_H}$$ کلوین

$\eta_{th} < \eta_{th,carnot}$ — موتور حرارتی برگشت ناپذیر +

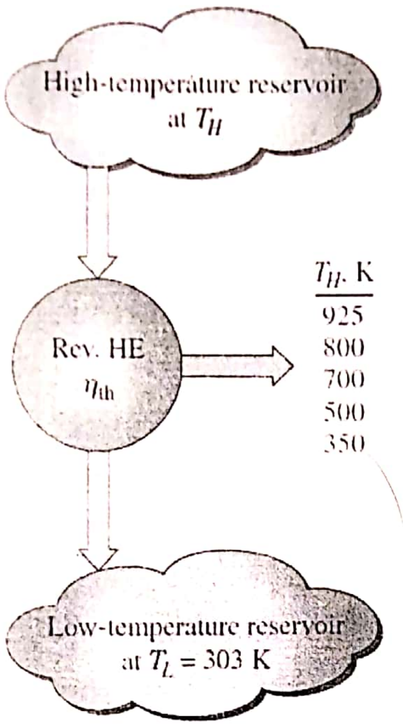
$\eta_{th} = \eta_{th,carnot}$ — موتور برگشت پذیر +

$\eta_{th} > \eta_{th,carnot}$ — غیرممکن +

EXAMPLE 1

The Quality of Energy

* هرچی دمای منبع انرژی بیشتر باشد ، می‌توان مقدار بیشتری از آن را به کار تبدیل کرد یعنی کیفیت بیشتر است .



T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

THE CARNOT REFRIGERATOR AND HEAT PUMP

* $COP_R = \frac{Q_L}{W_{in}} = \frac{1}{\frac{Q_H}{Q_L} - 1}$, * $COP_{HP} = \frac{Q_H}{W_{in}} = \frac{1}{1 - \frac{Q_L}{Q_H}}$

* $COP_{R,Rev} = \frac{1}{\frac{T_H}{T_L} - 1}$, * $COP_{Rev,HP} = \frac{1}{1 - \frac{T_L}{T_H}}$

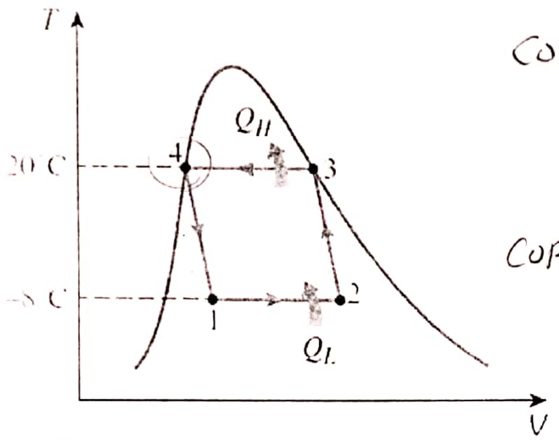
COP_R برگشت‌پذیر $= COP_{R,Rev}$

برگشت‌ناپذیر $< COP_{R,Rev}$

غیرممکن $> COP_{R,Rev}$

EXAMPLE 2 برگشت پذیر

A Carnot refrigeration cycle is executed in a closed system in the saturated liquid–vapor mixture region using 0.8 kg of refrigerant-134a as the working fluid. The maximum and the minimum temperatures in the cycle are 20 and -8°C, respectively. It is known that the refrigerant is saturated liquid at the end of the heat rejection process, and the net work input to the cycle is 15 kJ. Determine the fraction of the mass of the refrigerant that vaporizes during the heat addition process, and the pressure at the end of the heat rejection process.



$$COP_{R,rev} = \frac{1}{\frac{T_H}{T_L} - 1} = \frac{1}{\frac{20+273}{-8+273} - 1} = 9.464$$

$$COP = \frac{Q_L}{W_{in,net}} \Rightarrow Q_L = (9.464)(15) = 142 \text{ kJ}$$

R-134a

$$T_1 = T_2 = -8°C \longrightarrow h_{fg} = 204.59 \text{ kJ/kg} \quad , \quad Q_L = m_v h_{fg} = \frac{142}{204.59} = 0.694 \text{ kg}$$

$$\frac{m_v}{m_{total}} = \frac{0.694}{0.8} = 0.868$$

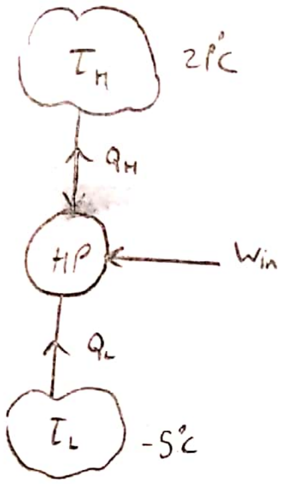
$$P_4 = P_{sat @ 20°C} \xrightarrow{Table} 572.1 \text{ kPa}$$

Scanned by CamScanner

EXAMPLE 3

A heat pump is to be used to heat a house during the winter. The house is to be maintained at 21°C at all times. The house is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to -5°C. Determine the minimum power required to drive this heat pump.

کمترین کار وقتی است که فرایند برگشت‌پذیر باشد



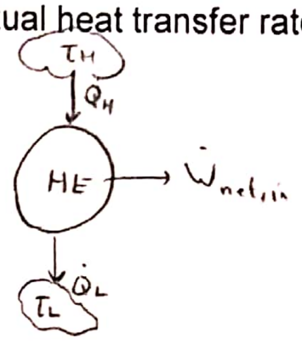
$$Q_H = 135000\ \frac{kJ}{h} = 37.5\ kW$$

$$COP_{Rev,max} = \frac{1}{1 - \frac{T_H}{T_L}} = 11.3$$

$$W_{in} = \frac{Q_H}{COP} \Rightarrow 3.32\ kW$$

EXAMPLE 1

A 600-MW steam power plant, which is cooled by a nearby river, has a thermal efficiency of 40 percent. Determine the rate of heat transfer to the river water. Will the actual heat transfer rate be higher or lower than this value? Why?



$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} \longrightarrow \dot{Q}_H = \frac{600}{0.4} = 1500\,MW$$

$$\dot{E}_{in} - \dot{E}_{out} = 0 \rightarrow \dot{E}_{in} = \dot{E}_{out} \rightarrow \dot{Q}_H = \dot{Q}_L + \dot{W}_{out}$$

$$\dot{Q}_L = 1500MW - 600MW = 900MW$$

کمتر است زیرا بازده ما در حقیقت کمتر است پس مقدار کمتری از انرژی به کار تبدیل می‌شود پس $\dot{Q}_L$ بیشتر می‌شود.

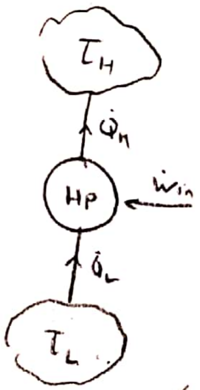
EXAMPLE 2

A heat pump is used to maintain a house at a constant temperature of 23°C. The house is losing heat to the outside air through the walls and the windows at a rate of 85,000 kJ/h while the energy generated within the house from people, lights, and appliances amounts to 4000 kJ/h. For a COP of 3.2, determine the required power input to the heat pump.

$$\dot{Q}_H = 85{,}000 - 4000 = 81000\,\frac{kJ}{h}$$

$$\dot{W}_{in} = \frac{\dot{Q}_H}{COP} = \frac{81000}{3.2} \times \frac{1}{3600} = 7.03\,kW$$

تبدیل به kW

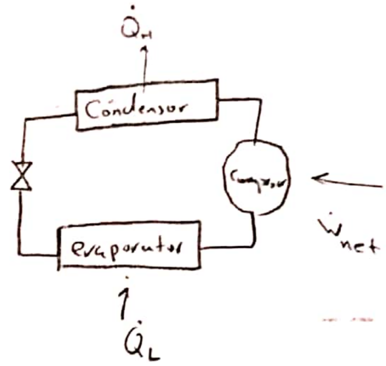


• وقتی می‌توان از رابطه‌ها استفاده کنیم که سیکل ما ریورسیبل باشد یا فرایند برگشت‌پذیر باشد.

EXAMPLE 3

Refrigerant-134a enters the condenser of a residential heat pump at 800 kPa and 35°C at a rate of 0.018 kg/s and leaves at 800 kPa as a saturated liquid. If the compressor consumes 1.2 kW of power, determine (a) the COP of the heat pump and (b) the rate of heat absorption from the outside air.

$\begin{cases} P_1 = 800\,kPa \\ T_1 = 35^\circ C \end{cases} \longrightarrow h_1 = 271.24\ kJ/kg$



$\begin{cases} P_2 = 800\,kPa \\ \text{sat. liq} \end{cases} \longrightarrow h_2 = 95.48\ kJ/kg$

$\dot{m}h_1 = \dot{Q}_H + \dot{m}h_2 \rightarrow \dot{Q}_H = \dot{m}(h_1 - h_2) = (0.018)(271.24 - 95.48)$

* خروجی کندانسور همیشه مایع اشباع است

$= 3.164\ kJ/kg$

$COP_{HP} = \dfrac{\dot{Q}_H}{\dot{W}_{in}} = \dfrac{3.164}{1.2} = 2.64$

b)

$\dot{Q}_L + \dot{W}_{net,in} = \dot{Q}_H \longrightarrow \dot{Q}_L = 1.96\ kW$

$T_H = ?$
$T_L = ?$

EXAMPLE 4

A commercial refrigerator with refrigerant-134a as the working fluid is used to keep the refrigerated space at -35°C by rejecting waste heat to cooling water that enters the condenser at 18°C at a rate of 0.25 kg/s and leaves at 26°C. The refrigerant enters the condenser at 1.2 MPa and 50°C and leaves at the same pressure subcooled by 5°C. If the compressor consumes 3.3 kW of power, determine (a) the mass flow rate of the refrigerant, (b) the refrigeration load, (c) the COP, and (d) the minimum power input to the compressor for the same refrigeration load.

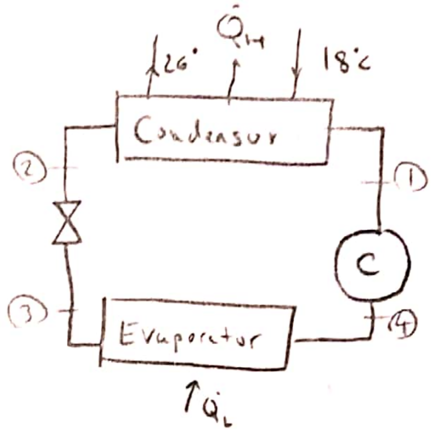
$\dot{Q}_L$

زیر دمای اشباع

۵ درجه زیر دمای اشباع می‌آید

a)

① $\begin{cases} P = 1.2\,\text{MPa} \\ T = 50^\circ C \end{cases} \longrightarrow h_1 = 278.28\ \text{kJ/kg}$



② $\begin{cases} P_2 = 1.2\,\text{MPa} \\ T_2 = T_{2\,@\,1.2\,\text{MPa}} - 5 \end{cases} \longrightarrow = T = 41.3^\circ C$

$T_{w,1} = 18^\circ C \rightarrow h_{w,1} = 75.54\ \text{kJ/kg}$

$T_{w,2} = +26^\circ C \rightarrow h_{w,2} = 109.01\ \text{kJ/kg}$

درکاندنسور فشار ثابت درنظرگرفته می‌شود ←

$\dot{Q}_H = \dot{m}_w (h_{w_2} - h_{w_1}) = (0.25)(109.01 - 75.54) = 8.367\ \text{kW}$

$\dot{Q}_H = \dot{m}_R (h_2 - h_1) \longrightarrow \dot{m}_R = 0.0498\ \text{kg/s}$

b) $\dot{Q}_L = \dot{Q}_H - \dot{W}_{net,in} \Rightarrow 5.07\,\text{kW} = \dot{Q}_L$

c) $COP_R = \dfrac{\dot{Q}_L}{\dot{W}_{net,in}} = 1.54$

d) $COP_{R,Rev} = \dfrac{1}{\dfrac{T_H}{T_L} - 1} = 4.49 \longrightarrow \dot{W}_{net,in,min} = \dfrac{\dot{Q}_L}{COP} = 1.13\,\text{kW}$

$T_H = 18^\circ$

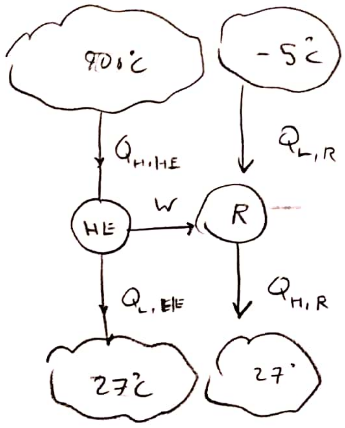
$T_L = -35^\circ$

EXAMPLE 5

A Carnot heat engine receives heat from a reservoir at 900°C at a rate of 800 kJ/min and rejects the waste heat to the ambient air at 27°C. The entire work output of the heat engine is used to drive a refrigerator that removes heat from the refrigerated space at -5°C and transfers it to the same ambient air at 27°C. Determine (a) the maximum rate of heat removal from the refrigerated space and (b) the total rate of heat rejection to the ambient air.

a)

$$COP_{R,Rev,max} = \frac{1}{\frac{T_H}{T_L} - 1} = 8.37$$



$$Q_{L,R} = COP_{R,rev} \cdot \dot{W}_{net,in}$$

$$\eta_{th,carnot} = 1 - \frac{T_L}{T_H} = 0.744$$

$$\dot{W}_{net,in} = \eta_{th} \cdot \dot{Q}_H = 595.2 \ \mathrm{kJ/min}$$

$$\dot{Q}_{L,R} = (8.37) \times (595.2) = 4982 \ \mathrm{kJ/min}$$

b)

$$\dot{Q}_{L,HE} + \dot{Q}_{H,R}$$

$$\dot{Q}_{L,HE} = \dot{Q}_H - \dot{W}_{out} = 204.8 \ \mathrm{kJ/min}$$

$$\dot{Q}_{H,R} = \dot{Q}_{L,R} + \dot{W}_{in,net} = 5577.2 \ \mathrm{kJ/kJ}$$

$$\dot{Q}_{L,HE} + \dot{Q}_{H,R} = 5782 \ \mathrm{kJ/kJ}$$

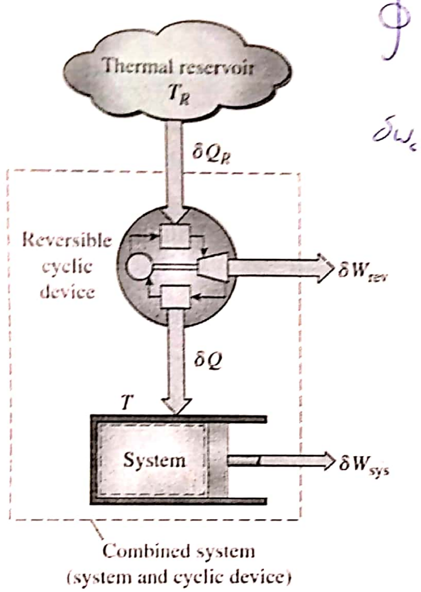
ENTROPY

Clausius inequality

نکته: در فرآیند برگشت‌پذیر نسبت دماها با انتگرال‌ها برابر است

$$\oint \frac{\delta Q}{T} \leq 0$$

$$\delta W_c \leq 0$$



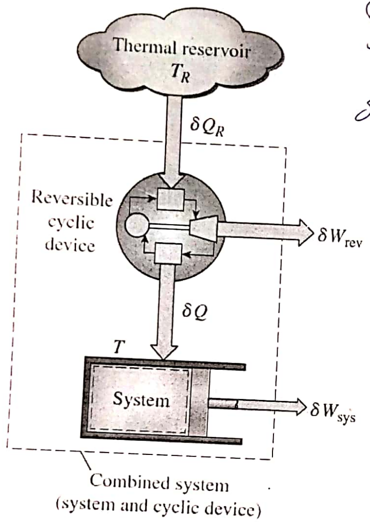
ENTROPY

Clausius inequality

نکته: در فرایند برگشت پذیر نسبت دماها با نسبت گرماها برابر است

$$\oint \frac{\delta Q}{T} \leq 0$$

$\delta W_c \leq 0$



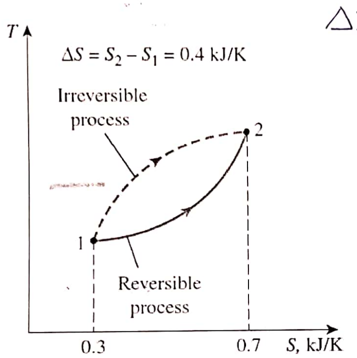
Entropy

* چه برگشت پذیر باشد چه نباشد باید فرض کنیم که برگشت پذیر است

$$dS = \left(\frac{\delta Q}{T}\right)_{int,rev} \quad \left(\frac{kJ}{K}\right)$$

کلوین

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{int,rev}$$



به حالت اول و ثانویه بستگی دارد به مسیر بستگی ندارد

Even for irreversible processes, the entropy change should be determined by carrying out the integration along some convenient *imaginary* internally reversible path between the specified states.

A Special Case: Internally Reversible Isothermal Heat Transfer Processes

انتقال گرما در یک زمانه ثابت پیرامون

$$\Delta S = \int_1^2 \left(\frac{\delta Q}{T}\right)_{int,rev} = \frac{1}{T_0}\int_1^2 (\delta Q)_{int,rev} = \frac{Q}{T_0} = \Delta S$$

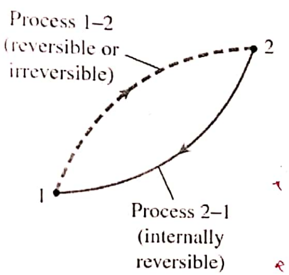
EXAMPLE 1

A piston–cylinder device contains a liquid–vapor mixture of water at 300 K. During a constant-pressure process, 750 kJ of heat is transferred to the water. As a result, part of the liquid in the cylinder vaporizes. Determine the entropy change of the water during this process.

$$\Delta S = \int \frac{\delta Q}{T} \xrightarrow{\text{isothermal}} \frac{Q}{T} = \frac{750}{300} = 2.5\,\mathrm{kJ/K}$$

سوال نگفته اما هم رها دست نزنید.

The increase of entropy principle



$$\oint \frac{\delta Q}{T} \leq 0 \Rightarrow \int_1^2 \frac{\delta Q}{T} + \int_2^1 \left(\frac{\delta Q}{T}\right)_{\text{int,rev}} \leq 0$$

$$\int_1^2 \frac{\delta Q}{T} + S_1 - S_2 \leq 0 \longrightarrow \Delta S = S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

تغییرات آنتروپی سیستم

انتگرال

آنتروپی توسط انتگرال را

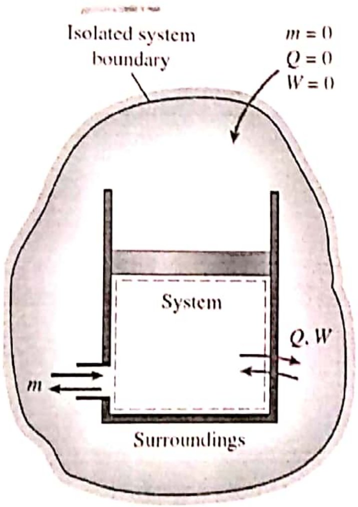
$$dS \geq \frac{\delta Q}{T}$$

Entropy generation S_{gen}

$$\Delta S_{system} = \int_1^2 \frac{\delta Q}{T} + S_{gen} \quad , \quad S_{gen} \geq 0$$

سیستم منزوی : $\Delta S_{system} \geq 0$

* انتروپی یک سیستم منزوی (یک سیستم با محیط اطراف آن) در طی یک فرایند همواره افزایش می‌یابد



* $S_{gen} = \Delta S_{tot} = \Delta S_{sys} + \Delta S_{sur} \geq 0$ (sur: محیط)

$$S_{gen} \begin{cases} > 0 & \text{فرایندهای برگشت ناپذیر} \\ = 0 & \text{فرایند برگشت پذیر} \\ < 0 & \text{impossible} \end{cases}$$

* فرایندها در جهتی خاص رخ می‌دهند که با اصل افزایش آنتروپی سازگار است $S_{gen} \geq 0$

* آنتروپی بقا ناپذیر است . در فرایندهای واقعی رو به افزایش است

* تولید انتروپی یک معیار کمّی برای نشان دادن مقدار برگشت ناپذیری‌ها . هرچه فرایند برگشت ناپذیرتر باشد انتروپی تولیدی بیشتر است

EXAMPLE 2

A heat source at 800 K loses 2000 kJ of heat to a sink at (a) 500 K and (b) 750 K. Determine which heat transfer process is more irreversible.

$$\Delta S_{source} = \frac{Q}{T_{source}} = \frac{-2000}{800} = -2.5 \ \text{kJ/K}$$

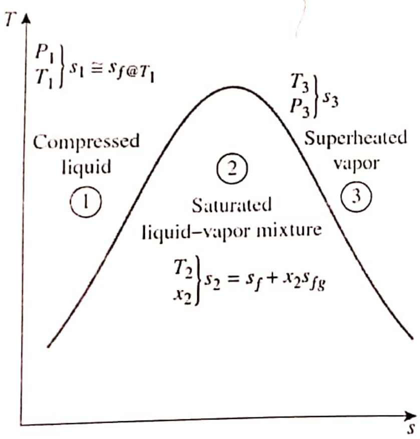
a) $\Delta S_{sink_I} = \frac{Q}{T_{sink}} = \frac{2000}{500} = 4 \ \text{kJ/K}$, $\Delta S_{gen_I} = \Delta S_{tot} = \Delta S_{source} + \Delta S_{sink_I} = 1.5 \ \text{kJ/K}$

b) $\Delta S_{sink_{II}} = \frac{Q}{T_{sink}} = \frac{2000}{750} = 2.7 \ \text{kJ/K}$, $\Delta S_{gen_{II}} = \Delta S_{tot} = \Delta S_{source} + \Delta S_{sink} = 0.2$,

$\Delta S_{gen_{II}} < \Delta S_{gen_I}$ $\Rightarrow$

فرایند دوم آنتروپی کمتر
تولید می‌کند پس برگشت پذیرتر است

ENTROPY CHANGE OF PURE SUBSTANCES



(1) Compressed liquid

P_1, T_1 : $S_1 = S_{f@T}$ $\rightarrow$

اگر جدول نداشته باشیم
می‌توانیم از $S_1 = S_{f@T}$
استفاده کنیم ولی اگر جدول
مایع متراکم را داشته باشیم حتماً باید از جدول استفاده کنیم

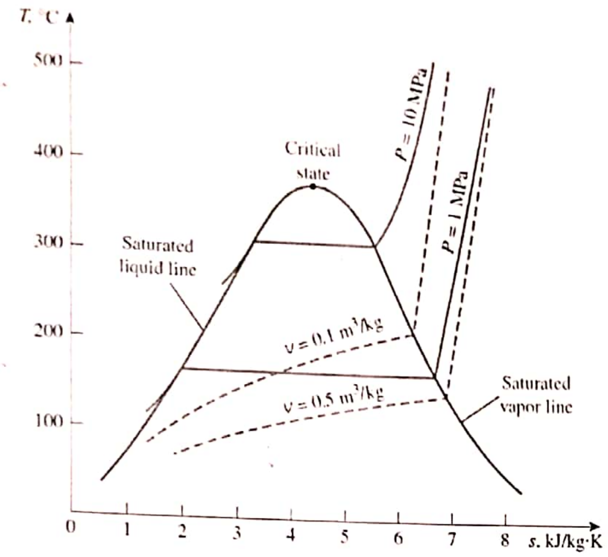
(2) mixture

T_1, x_1 , $S_1 = S_f + x S_{fg}$

(3) Superheated

$T_3, P_3 \xrightarrow{\text{جدول}} S_3$

$\Delta S = m \Delta s = m(s_2 - s_1) \ \text{kJ/K}$



EXAMPLE 3

A rigid tank contains 5 kg of refrigerant-134a initially at 20°C and 140 kPa. The refrigerant is now cooled while being stirred until its pressure drops to 100 kPa. Determine the entropy change of the refrigerant during this process.

① $\begin{cases} P = 140\,kPa \\ T = 20^\circ C \end{cases}$ ⟶ Superheated, $S_1 = 1.0625$

$V_1 = .016544$

② $\begin{cases} P = 100\,kPa \\ v_1 = v_2 = 0.16544 \end{cases}$ ⟶ mixture $v_f < v_2 < v_g$

$v_f = 0.0007259\ \frac{m^3}{kg}$, $v_g = 0.19255$

$v_2 = v_f + x v_{fg}$ ⟶ $x_2 = 0.859$

$S_f = 0.017188\ \frac{kJ}{K.kg}$, $S_{fg} = 0.87995\ \frac{kJ}{K.kg}$

$S_2 = S_f + x S_{fg} = 0.8278\ \frac{kJ}{kg\text{-}K}$, $\Delta S = m(S_2 - S_1) = -1.173\ \frac{kJ}{K}$

EXAMPLE 4

Refrigerant-134a at 320 kPa and 40°C undergoes an isothermal process in a closed system until its quality is 45 percent. On per unit mass basis, determine how much work and heat transfer are required.

$E_{in} - E_{out} = \Delta E_{system} \rightarrow W_{in} - Q_{out} = \Delta U$

① $\left\{ \begin{array}{l} P_1 = 320\,kPa \\ T_1 = 40^\circ C \end{array} \right. \longrightarrow$ superheated $\quad u_1 = 261.62\ \frac{kJ}{kg \cdot k} \quad s_1 = 1.0452\ \frac{kJ}{kg \cdot k}$

② $\left\{ \begin{array}{l} x = 45\% \\ T_1 = T_2 = 40^\circ C \end{array} \right. \longrightarrow$ mixture $\quad u_2 = u_f + x u_{fg} = 107.39 + 0.45(143.61) = 172.02\ \frac{kJ}{kg}$

$s_2 = s_f + x s_{fg} = 0.39493 + 0.45(0.52059) = 0.62920\ \frac{kJ}{kg \cdot k}$

ISENTROPIC PROCESSES

$\Delta S = 0$

آدیاباتیک و برگشت پذیر = isentropic

افزایش آنتروپی

① انتقال گرما

② برگشت ناپذیری ها

EXAMPLE 5

Steam enters an adiabatic turbine at 5 MPa and 450°C and leaves at a pressure of 1.4 MPa. Determine the work output of the turbine per unit mass of steam if the process is reversible.

$\dot{E}_{in} - \dot{E}_{out} = dE_{system}^{\nearrow 0\ steady}$, $\dot{E}_{in} = \dot{E}_{out} \Longrightarrow \dot{m}h_1 = \dot{W}_{out} + \dot{m}h_2$

$W_{out} = \dot{m}(h_1 - h_2)$

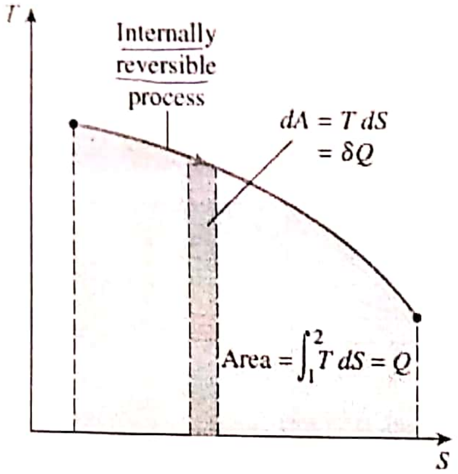
$\left\{ \begin{array}{l} P_1 = 5\,MPa \\ T_1 = 450^\circ C \end{array} \right. \longrightarrow$ superheated $\quad s_1 = 6.8210\ \frac{kJ}{kg \cdot k} \quad h_1 = 3317.2\ \frac{kJ}{kg \cdot k}$, $h_1 - h_2 = W$

$\left\{ \begin{array}{l} P_2 = 1.4\,MPa \\ s_1 = s_2 \end{array} \right. \longrightarrow$ superheated $\quad h_2 = 2967\ \frac{kJ}{kg \cdot k}$

isentropic

$\Longrightarrow 350\ \frac{kJ}{kg} = W$

PROPERTY DIAGRAMS INVOLVING ENTROPY



- $\delta Q_{int,rev} = T\,ds$

Total heat transfered

- $Q_{int,rev} = \int T\,ds$ (kJ)

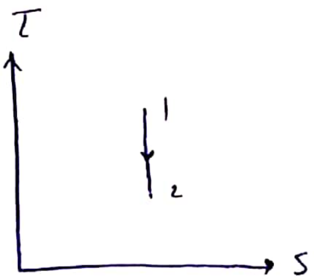
- $W_b = \int P\,dv$

unit-mass basis : $\delta q_{int,rev} = T\,ds \xrightarrow{\int} q_{int,rev} = \int T\,ds$ (kJ/kg)

- Internally reversible isothermal processes

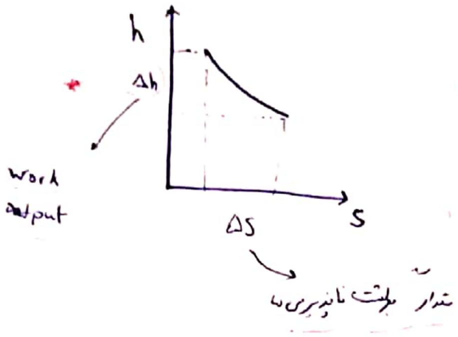
- $Q_{int,rev} = T_0\,\Delta S$ (kJ)

$q_{int,rev} = T_0\,\Delta s$ (kJ/kg)



← Isentropic process

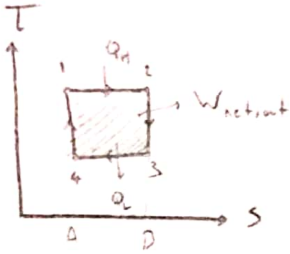
* Mollier diagram:



* Steady-flow

EXAMPLE 1

Show the Carnot cycle on a T-S diagram and indicate the areas that represent the heat supplied Q_H, heat rejected Q_L, and the net work output $W_{net,out}$ on this diagram.



1-2 Reversible isothermal

2-3 Isentropic

3-4 Reversible isothermal

4-1 Isentropic

$A12B = Q_H$

$A34B = Q_L$

$W_{net,out} = Q_H - Q_L = 1234$ سطح داخل الشكل

THE T ds RELATIONS

$$ds = \left(\frac{\delta Q}{T}\right)_{int,rev} \qquad \text{Isothermal} = \Delta S = \frac{\Delta Q}{T_0}$$

Energy Balance:

$$\delta Q_{int,rev} - \delta W_{int,rev,out} = du$$

$$\left\{\begin{array}{l} \delta Q_{int,rev} = Tds \\ \delta W_{int,rev} = Pdv \end{array}\right. \longrightarrow Tds - Pdv = du \longrightarrow$$

برحسب انرژی داخلی

$$\boxed{\begin{array}{ll} Tds = Pdv + du & (kJ/kg) \\ TdS = PdV + dU & (kJ) \end{array}} \quad \text{I}$$

Gibbs equation

$$h = u + pv \longrightarrow dh = \underbrace{du + pdv}_{} + vdp \longrightarrow dh - vdp = du + pdv$$

$$\boxed{Tds = dh - vdp} \quad \text{II}$$

برحسب آنتالپی

این روابط هم برای فرایندهای برگشت پذیر هم
برای فرایندهای برگشت ناپذیر صادق است

$$\text{I}: \; Tds = Pdv + du \longrightarrow ds = \frac{P}{T}dv + \frac{du}{T}$$

$$\text{II}: \; Tds = dh - vdp \longrightarrow ds = \frac{dh}{T} - \frac{v}{T}dp$$

ENTROPY CHANGE OF LIQUIDS AND SOLIDS

Incompressible (تراكم ناپذير) $dv = 0$

$C_p = C_v = C$, $du = c\,dT$, $dh = c\,dT$

$ds = \frac{du}{T} = \frac{c\,dT}{T} \xrightarrow{\int} s_2 - s_1 = \Delta s = \int_1^2 c(T)\,\frac{dT}{T}$

$\longrightarrow C_{avg} \int_1^2 \frac{dT}{T} = \boxed{C_{avg} \ln \frac{T_2}{T_1} \quad \frac{kJ}{kg.k}}$ For solids and liquids

Isentropic process:

$s_2 - s_1 = C_{avg} \ln \frac{T_2}{T_1} = 0 \longrightarrow T_1 = T_2$

EXAMPLE 2

The critical temperature of methane is 191 K, and thus methane must be maintained below 191 K to keep it in liquid phase. The properties of liquid methane at various temperatures and pressures are given. Determine the entropy change of liquid methane as it undergoes a process from 110 K and 1 MPa to 120 K and 5 MPa (a) using tabulated properties and (b) approximating liquid methane as an incompressible substance. What is the error involved in the latter case?

Properties of liquid methane

Temp., T, K	Pressure, P, MPa	Density, ρ, kg/m^3	Enthalpy, h, kJ/kg	Entropy, s, kJ/kg·K	Specific heat, c_p, kJ/kg·K
110	0.5	425.3	208.3	4.878	3.476
	1.0	425.8	209.0	4.875	3.471
	2.0	426.6	210.5	4.867	3.460
	5.0	429.1	215.0	4.844	3.432
120	0.5	410.4	243.4	5.185	3.551
	1.0	411.0	244.1	5.180	3.543
	2.0	412.0	245.4	5.171	3.528
	5.0	415.2	249.6	5.145	3.486

(1) $\begin{cases} T_1 = 110\,kPa \\ P_1 = 1MPa \end{cases} \longrightarrow S_1 = 4.875 \ \frac{kJ}{kg.k}$

$C_{p,1} = 3.471$

(2) $\begin{cases} T_2 = 120\,kPa \\ P_2 = 5MPa \end{cases} \longrightarrow S_2 = 5.145 \ \frac{kJ}{kg.k}$

$C_{p,2} = 3.486$

$\Delta s = S_2 - S_1 = 0.27 \ \frac{kJ}{kg\,k}$

b) $\Delta s = C_{avg} \ln \frac{T_2}{T_1} = \frac{C_{p_1} + C_{p_2}}{2} \ln \frac{T_2}{T_1} = 0.303 \ \frac{kJ}{kg.k}$

Error $= 0.122 = 12\%$

$\rho_{methan} = 425.8 - 415.2 \ \frac{kg}{m^3}$ —— هرچه تغییرات چگال در آن محدوده با دمای کمتر خطا کمتر.

THE ENTROPY CHANGE OF IDEAL GASES

$$Tds = du + pdv \longrightarrow ds = \frac{du}{T} + \frac{P}{T} dv$$

$$[du = C_v dT \quad , \quad Pv = RT]$$

برحسب حجم مخصوص

$$ds = \frac{C_v dT}{T} + \frac{R}{v} dv \xrightarrow{\int} s_2 - s_1 = \Delta s = \boxed{\int_1^2 C_v(T) \frac{dT}{T} + R \underbrace{\int_1^2 \frac{dv}{v}}_{\ln \frac{v_2}{v_1}}}$$

$$Tds = dh - vdp \longrightarrow ds = \frac{dh}{T} - \frac{v}{T} dp \quad , [dh = C_p dT \, , \, Pv = RT]$$

$$ds = \frac{C_p dT}{T} - \frac{R}{P} dP \xrightarrow{\int} s_2 - s_1 = \Delta s = \boxed{\int C_p(T) \frac{dT}{T} - R \ln \frac{P_2}{P_1}}$$

برحسب فشار

Constant Specific Heats (Approximate Analysis)

$$s_2 - s_1 = C_{v,avg} \int \frac{dT}{T} + R \ln \frac{v_2}{v_1} = C_{v,avg} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} \quad \left(\frac{kJ}{kg\,K}\right)$$

$$s_2 - s_1 = C_{p,avg} \int \frac{dT}{T} + R \ln \frac{P_2}{P_1} = C_{p,avg} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \quad \left(\frac{kJ}{kg \cdot K}\right)$$

On a unit-mole basis

$$\bar{s}_2 - \bar{s}_1 = \bar{C}_{v,avg} \ln \frac{T_2}{T_1} + R_u \ln \frac{v_2}{v_1} \quad \left(\frac{kJ}{kmol \cdot K}\right)$$

$$\bar{s}_2 - \bar{s}_1 = \bar{C}_{p,avg} \ln \frac{T_2}{T_1} - R_u \ln \frac{P_2}{P_1} \quad \left(\frac{kJ}{kmol \cdot K}\right)$$

Variable Specific Heats (Exact Analysis)

Reference temprature , 0 K دمای مرجع

$$s^\circ = \int_0^T c_p(T)\frac{dT}{T}$$ فقط تابع دما

$$\int_1^2 c_p(T)\frac{dT}{T} = s_2^\circ - s_1^\circ \longrightarrow s_2^\circ = s^\circ(T_2)\ ,\ s_1^\circ = s^\circ(T_1)$$

$$\boxed{s_2 - s_1 = s_2^\circ - s_1^\circ - R\ln\frac{P_2}{P_1}}\ \left(\frac{kJ}{kg.K}\right)\ ,\ \boxed{\bar{s}_2 - \bar{s}_1 = \bar{s}_2^\circ - \bar{s}_1^\circ - R_u\ln\frac{P_2}{P_1}}\ \left(\frac{kJ}{kmol.K}\right)$$

EXAMPLE 3

Air is compressed from an initial state of 100 kPa and 17°C to a final state of 600 kPa and 57°C. Determine the entropy change of air during this compression process by using (a) property values from the air table and (b) average specific heats.

a) $$s_2 - s_1 = s_2^\circ - s_1^\circ - R\ln\frac{P_2}{P_1} =$$

Table A-17

$$s_2 - s_1 = (1.79783 - 1.66802) - (0.287)\ln\frac{600}{100} = -0.3884\ \frac{kJ}{kg.K}$$

b) $c_{p,avg} = 1.006\ \frac{kJ}{K.kg}$ A-26

$$s_2 - s_1 = c_{p,avg}\ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1} = -0.3842\ \frac{kJ}{kg.K}$$

Isentropic Processes of Ideal Gases

$ds = 0 \quad \Delta s = 0$

Constant Specific Heats (Approximate Analysis)

$$s_2 - s_1 = c_{v,avg} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} = 0 \Rightarrow$$

$$c_{v,avg} \ln \frac{T_2}{T_1} = -R \ln \frac{v_2}{v_1} \rightarrow \ln \frac{T_2}{T_1} = -\frac{R}{c_{v,avg}} \ln \frac{v_2}{v_1} \Rightarrow \ln \frac{T_2}{T_1} = \ln \left(\frac{v_1}{v_2}\right)^{\frac{R}{c_{v,avg}}}$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\frac{R}{c_{v,avg}}} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

$$\boxed{\left(\frac{T_2}{T_1}\right)_{s=constant} = \left(\frac{v_1}{v_2}\right)^{k-1}} \qquad \boxed{\frac{R}{c_v} = k-1}$$

k نسبت گرمای ویژه $\frac{c_p}{c_v}$

$\longrightarrow$ 1st isentropic relation

$$s_2 - s_1 = c_{p,avg} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} = 0$$

$$\Rightarrow c_{p,avg} \ln \frac{T_2}{T_1} = R \ln \frac{P_2}{P_1} \Rightarrow \ln \frac{T_2}{T_1} = \frac{R}{c_p} \ln \frac{P_2}{P_1}$$

$$\Rightarrow \ln \frac{T_2}{T_1} = \ln \left(\frac{P_2}{P_1}\right)^{\frac{R}{c_p}} \Rightarrow \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{R}{c_p}}, \quad \frac{R}{c_p} = \frac{k-1}{k} = \frac{c_p - c_v}{c_p}$$

$$\boxed{\left(\frac{T_2}{T_1}\right)_{s=constant} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}}$$

2nd isentropic relation

k باید در دمای متوسط از جدول خوانده شود.

Subs 2nd in 1st : $\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_1}{v_2}\right)^{k-1}$

$$\Rightarrow \boxed{\left(\frac{P_2}{P_1}\right)_{s=constant} = \left(\frac{v_1}{v_2}\right)^{k}}$$

3rd isentropic relation

Variable Specific Heats (Exact Analysis)

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R\ln\frac{P_2}{P_1} = 0 \quad , \quad s_2^\circ = s_1^\circ + R\ln\frac{P_2}{P_1} \quad , \quad s_2^\circ = s^\circ(T_2)$$

$$\ln\frac{P_2}{P_1} = \frac{s_2^\circ - s_1^\circ}{R} \Rightarrow \frac{P_2}{P_1} = \exp\left(\frac{s_2^\circ - s_1^\circ}{R}\right) \Rightarrow \frac{P_2}{P_1} = \frac{\exp\left(\frac{s_2^\circ}{R}\right)}{\exp\left(\frac{s_1^\circ}{R}\right)}$$

Relative Pressure and Relative Specific Volume

$P_r = \exp\left(\frac{s^\circ}{R}\right)$ Relative pressure (dimensionless) $\rightarrow$ واحد ندارد

$$\boxed{\frac{P_2}{P_1} = \frac{P_{r_2}}{P_{r_1}}}$$

Given: P_1, T_1, P_2

Find: T_2

T ⋮ P_r

$T_1 \rightarrow P_{r_1}$

$T_2 \leftarrow P_{r_2} = P_{r_1} \cdot \frac{P_2}{P_1}$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \longrightarrow \frac{v_2}{v_1} = \frac{T_2}{T_1} \times \frac{P_1}{P_2} = \frac{T_2}{T_1} \times \frac{P_{r_1}}{P_{r_2}} = \frac{\frac{T_2}{P_{r_2}}}{\frac{T_1}{P_{r_1}}}$$

$v_r = \dfrac{T}{P_r}$ Relative specific volume

$$\boxed{\frac{v_2}{v_1} = \frac{v_{r_2}}{v_{r_1}} \quad s = \text{constant}}$$

$P_R = \dfrac{P}{P_{cr}} \longrightarrow$ اشتباه نشود با P_r

$T_1 \longrightarrow v_{r_1}$,

$T_2 \longleftarrow v_{r_2} = v_{r_1} \cdot \dfrac{v_2}{v_1}$

Scanned by CamScanner

EXAMPLE 1

isentropic

Air is compressed in a car engine from 22°C and 95 kPa in a reversible and adiabatic manner. If the compression ratio V_1/V_2 of this engine is 8, determine the final temperature of the air.

حجم نسبی

$$\frac{V_1}{V_2} = \frac{v_{r_1}}{v_{r_2}} = 8$$

فرض گرما ویژه متغیر با دما :

$$T_1 = 295\,k \xrightarrow{A-17} v_{r_1} = 647.9$$

$$\frac{v_{r_2}}{v_{r_1}} = \frac{V_2}{V_1} \Rightarrow v_{r_2} = \frac{v_{r_1}}{8} = \frac{647.9}{8} = 80.99 \xrightarrow{A-17} T_2 = 662.7\,k$$

فرض گرما ویژه ثابت :

$$\left(\frac{T_2}{T_1}\right)_{s=\text{constant}} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

k را باید در دمای متوسط T_2 و T_1 بخوانیم.

یکبار دمای متوسط را حدس بزنید و دوبار دمای متوسط گرفته. (در امتحان)

$$T_{avg} = 450\,k \xrightarrow{A-26} k = 1.391$$

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = (295)(8)^{(1.391-1)} = 665.2$$

$$T_{avg} = \frac{T_1 + T_2}{2} = 480.1\,k \longrightarrow$$ چون نزدیک دمای T_{avg} اولیه است پس حدس ما درست است.

REVERSIBLE STEADY-FLOW WORK

$W_b = \int_1^2 P\,dv$ Reversible boundary work for a closed system

Energy Balance:

$\delta Q_{rev} - \delta W_{rev} = dh + dke + dpe$

$\delta Q_{rev} = T ds$

$T ds = dh - v dp \longrightarrow \delta Q_{rev} = dh - v dp$

$dh - v dp - \delta W_{rev} = dh + dke + dpe$

$-\delta W_{rev} = dke + dpe + v dp$

$$\boxed{W_{rev,out} = -\int_1^2 v\,dp - \Delta KE - \Delta PE}$$

$W_{rev,out} = -\int_1^2 v\,dp$ Reversible work output if $\Delta KE = \Delta PE = 0$

$W_{rev,in} = \int_1^2 v\,dp + \Delta KE + \Delta PE$

$$\boxed{W_{rev,in} = \int_1^2 v\,dp \quad \text{if } \Delta KE = \Delta PE = 0}$$

Incompressible $v = \text{constant}$

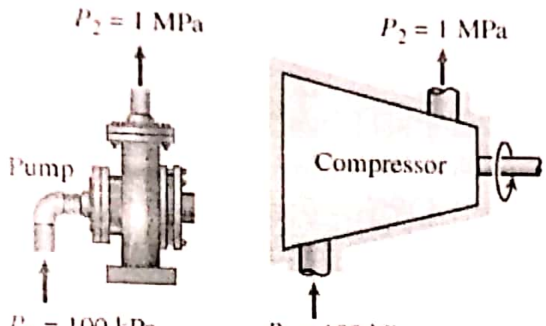
- $W_{rev,\,s.s} = -v(p_2 - p_1) - \Delta KE - \Delta PE$

- جریان پایا مایع بدون تبادل کار

- $v(p_2 - p_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) = 0$ (Bernoulli equation)

EXAMPLE 2

Determine the compressor work input required to compress steam isentropically from 100 kPa to 1 MPa, assuming that the steam exists as (a) saturated liquid and (b) saturated vapor at the inlet state.



(a) Compressing a liquid

(b) Compressing a vapor

a) $P_1 = 100\,kPa$, Sat. liq $\rightarrow v_1 = v_f = 0.001043\ m^3/kg$

$$w_{rev,in} = \int_1^2 v\,dp = v_1(P_2 - P_1) = 0.94\ kJ/kg$$

b) $T\,ds = dh - v\,dp = 0 \rightarrow v\,dp = dh \Rightarrow$

$$w_{rev,in} = \int_1^2 v\,dp = \int_1^2 dh = h_2 - h_1 \Rightarrow$$

① $P_1 = 100\,kPa$, Sat. vap $\rightarrow h_1 = 2675\ kJ/kg$, $s_1 = 7.3589\ kJ/kg.K$

① $P_2 = 1\,MPa$, isentropic $s_2 = s_1 = 7.3589$ $\xrightarrow{\text{Superheat}}$ $h_2 = 3194.5\ kJ/kg$

$$w_{rev,in} = h_2 - h_1 = 519.5\ kJ/kg$$

Reversible Steady-flow Work

$w_{rev,in} = \int_1^2 v\,dp \qquad w_{rev,out} = -\int_1^2 v\,dp$

Proof that Steady-Flow Devices Deliver the Most and Consume the Least Work When the Process is Reversible

Consider two steady-flow devices, one reversible and the other irreversible, operating between the same inlet and exit state

Energy Balance :

Actual, $\delta q_{act} - \delta w_{act} = dh + dke + dpe$

Reversible : $\delta q_{rev} - \delta w_{rev} = dh + dke + dpe$

$\delta q_{act} - \delta w_{act} = \delta q_{rev} - \delta w_{rev}$

$\delta w_{rev} - \delta w_{act} = \delta q_{rev} - \delta q_{act}$

$$\frac{\delta w_{rev} - \delta w_{act}}{T} = ds - \frac{\delta q_{act}}{T}$$

$$ds \geq \frac{\delta q_{act}}{T} \implies \frac{\delta w_{rev} - \delta w_{act}}{T} \geq 0 \longrightarrow \boxed{\delta w_{rev} \geq \delta w_{act}} \quad \text{work out}$$

$$\boxed{\delta w_{rev} \leq \delta w_{act}} \quad \text{work in}$$

MINIMIZING THE COMPRESSOR WORK

$$W_{rev,in} = \int_1^2 v\,dp$$

– Reversible – executing between the same pressure levels (P_1, P_2)

– Ideal gas behavior $(Pv = RT)$ with constant specific heat

(I) Isentropic process:

$$\left(\frac{P_2}{P_1}\right)_{s=const} = \left(\frac{V_1}{V_2}\right)^k \Rightarrow P_2V_2^k = P_1V_1^k \qquad PV^k = \text{constant } (c)$$

$$W_{comp,in} = \int_1^2 v\,dp = \int_1^2 \frac{c^{1/k}}{p^{1/k}}\,dp = c^{\frac{1}{k}}\left[\frac{p^{\frac{k-1}{k}}}{\frac{k-1}{k}}\right]_1^2$$

$$= c^{\frac{1}{k}} \cdot \frac{k}{k-1} \cdot \left(P_2^{\frac{k-1}{k}} - P_1^{\frac{k-1}{k}}\right)$$

$$\left[c^{\frac{1}{k}} = P_1^{\frac{1}{k}}v_1 = P_1^{\frac{1}{k}-1} \cdot P_1v_1 = P_1^{\frac{1-k}{k}}RT_1\right]$$

$$W_{comp,in} = P_1^{\frac{1-k}{k}}RT_1 \cdot \frac{k}{k-1}\left(P_2^{\frac{k-1}{k}} - P_1^{\frac{k-1}{k}}\right)$$

$$= \boxed{RT_1 \cdot \frac{k}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] = W_{comp,in}} \quad \text{if isentropic}$$

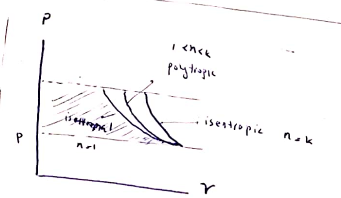
(II) Polytropic process $(PV^n = \text{constant})$

$$\boxed{W_{comp,in} = RT_1 \cdot \frac{n}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]} \quad \text{if polytropic}$$

(III) Isothermal process: $(PV = \text{constant})$

$$W_{comp,in} = \int_1^2 v\,dp = RT_1\int \frac{dp}{p}$$

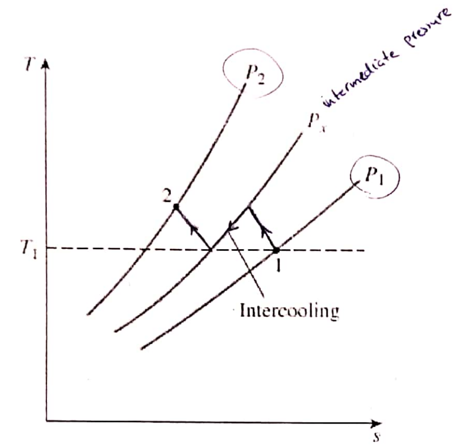
$$\boxed{= RT_1 \ln\frac{P_2}{P_1} = W_{comp,in}} \quad \text{if isothermal}$$



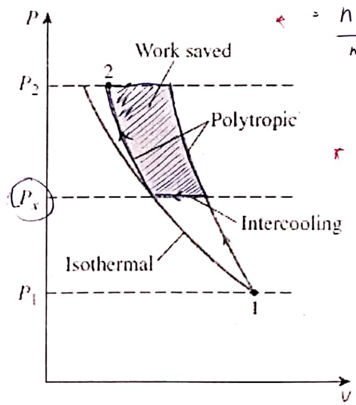
Multistage Compression with Intercooling تراکم چند مرحله‌ای همراه با سرمایش بین مرحله‌ای

+ فشار intercooler ثابت است

+ در هر مرحله تا دمای اولیه خنک می‌شود



+ $W_{comp,in} = W_{comp\,I,in} + W_{comp\,II,in}$



+ $= \frac{nRT_1}{n-1}\left[\left(\frac{P_x}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_x}\right)^{\frac{n-1}{n}} - 1\right]$ +

+ $\frac{dw_{comp,in}}{dP_x} = 0 \Rightarrow P_x = (P_1P_2)^{1/2} \Rightarrow$

$$\boxed{\frac{P_x}{P_1} = \frac{P_2}{P_x}}$$

$$\boxed{w_{comp\,I,in} = w_{comp\,II,in}}$$

EXAMPLE 1

Air is compressed steadily by a reversible compressor from an inlet state of 100 kPa and 300K to an exit pressure of 900 kPa. Determine the compressor work per unit mass for (a) isentropic compression with k =1.4, (b) polytropic compression with n =1.3, (c) isothermal compression, and (d) ideal two-stage compression with intercooling with a polytropic exponent of 1.3.

a) Isentropic

$$w_{comp,in} = \frac{kRT_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] = 263.2\ kJ/kg$$

b) Polytropic $n=1.3$

$$w_{comp,in} = \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] = 246.4\ kJ/kg$$

c) Isothermal

$$w_{comp,in} = RT_1 \ln\frac{P_2}{P_1} = 189.2\ kJ/kg$$

d)

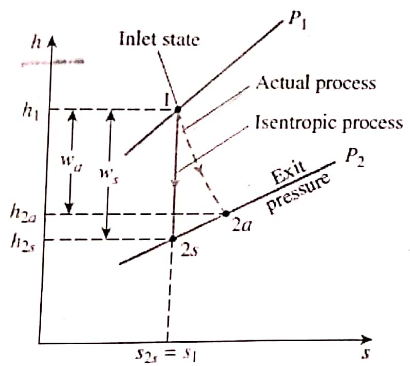
$$P_x = (P_1P_2)^{1/2} = 300k\ Pa$$

$$w_{comp,in} = 2\,w_{compI,in} = 2 \times \frac{nRT_1}{n-1}\left[\left(\frac{P_x}{P_1}\right)^{\frac{n-1}{n}} - 1\right] = 215.3\ kJ/kg$$

ISENTROPIC EFFICIENCIES OF STEADY-FLOW DEVICES

Isentropic Efficiencies of Turbines

$$\eta_{Turbine} = \frac{\text{actual turbine work}}{\text{Isentropic turbine work}} = \boxed{\frac{w_a}{w_s} \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}}}$$



EXAMPLE 2

Steam enters an adiabatic turbine steadily at 3 MPa and 400°C and leaves at 50 kPa and 100°C. If the power output of the turbine is 2 MW, determine (a) the isentropic efficiency of the turbine and (b) the mass flow rate of the steam flowing through the turbine.

State 1 $\begin{cases} P_1 = 3\,MPa \\ T = 400^\circ C \end{cases} \longrightarrow$ superheated $\longrightarrow h_1 = 3231.7\ kJ/kg$

$S_1 = 6.9235\ kJ/kg.K$

State 2a $\begin{cases} P_{2a} = 50\,kPa \\ T_{2a} = 100^\circ C \end{cases} \longrightarrow h_{2a} = 2682.4\ kJ/kg$

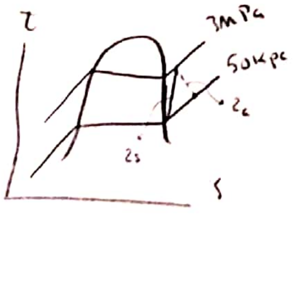
State 2s $\begin{cases} P_{2s} = 50\,kPa \\ S_{2s} = S_1 \end{cases} \longrightarrow$ $S_f = 1.0912\ kJ/kg.k$, $S_g = 7.5931\ kJ/kg.k$, $S_f < S < S_g \rightarrow$ mixture,

$x = \dfrac{S_{2s} - S_f}{S_{fg}} = 0.897$, $h_{2s} = h_f + x_{2s} h_{fg} = 340.54 + (0.877)(2304.7) = 2407.9\ kJ/kg$

$\eta_T = \dfrac{W_a}{W_s} = \dfrac{h_1 - h_{2a}}{h_1 - h_{2s}} = 0.667 = 66.7\%$

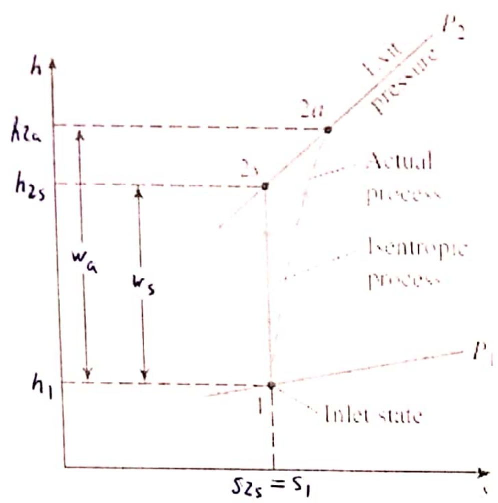
(b) $\dot{E}_{in} = \dot{E}_{out} \Rightarrow \dot{m} h_1 = \dot{W}_{a,out} + \dot{m} h_2$

$\dot{m} = \dfrac{W_{a,out}}{h_1 - h_{2a}} = \dfrac{2000}{3231.7 - 2682.4} = 3.64\ kg/s$



ISENTROPIC EFFICIENCIES OF STEADY-FLOW DEVICES

Isentropic Efficiencies of Compressors and Turbines



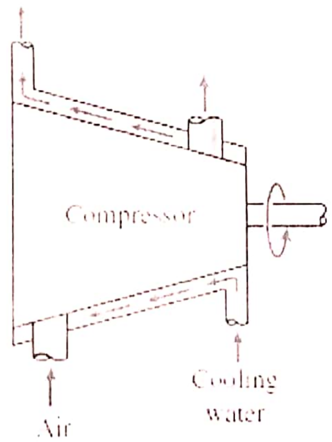
$$\eta_T = \frac{w_a}{w_s}$$

$$\eta_C = \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}} = \frac{w_s}{w_a}$$

$$\eta_C \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_P = \frac{w_s}{w_p} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} = \frac{v(P_2 - P_1)}{h_{2a} - h_1}$$

انتقال حرارت نداشته باشد ← adiabatic pump



Isothermal efficiency

$$\eta_C = \frac{w_t}{w_a} \rightarrow \text{reversible isothermal}$$

EXAMPLE 1

Air is compressed by an adiabatic compressor from 100 kPa and 12°C to a pressure of 800 kPa at a steady rate of 0.2 kg/s. If the isentropic efficiency of the compressor is 80 percent, determine (a) the exit temperature of air and (b) the required power input to the compressor.

$$\eta_c = 0.8 = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\left\{ \begin{array}{l} 100\,kPa \\ 12^\circ C \end{array} \right. \xrightarrow{A-17} h_1 = 285.14\ \frac{kJ}{kg}$$

$$\frac{P_{r_2}}{P_{r_1}} = \left(\frac{P_2}{P_1}\right)_{s=constant} \quad ; \quad P_{r_2} = (1.1584)\left(\frac{800}{100}\right) = 9.2672 \quad , \quad h_{2s} = 517.05$$

$$0.8 = \frac{517.05 - 285.14}{h_{2a} - 285.14} \longrightarrow h_{2a} = 575.03\ \frac{kJ}{kg}$$

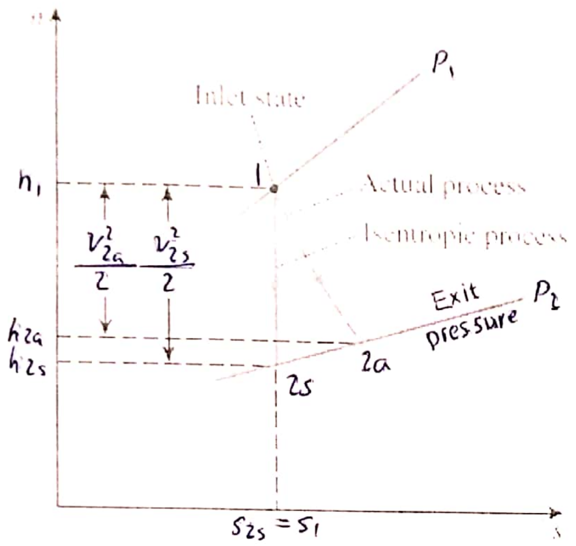
$$\longrightarrow T_{2a} = 569.5$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{a,in} + \dot{m}h_1 = \dot{m}h_{2a}$$

$$\dot{W}_{a,in} = \dot{m}(h_{2a} - h_1) = 58\,kW$$

Isentropic Efficiency of Nozzles



$$\eta_N = \frac{\text{Actual KE at nozzle exit}}{\text{Isentropic KE at nozzle exit}}$$

$$e_{in} = e_{out}$$

$$= \quad h_1 = h_{2a} + \frac{V_{2a}^2}{2}$$

$$\eta_N = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

EXAMPLE 2

Air at 200 kPa and 950 K enters an adiabatic nozzle at low velocity and is discharged at a pressure of 110 kPa. If the isentropic efficiency of the nozzle is 92 percent, determine (a) the maximum possible exit velocity, (b) the exit temperature, and (c) the actual exit velocity of the air. Assume constant specific heats for air.

$\eta_N = 0.2$, $T_{avg} = 850\,K \rightarrow C_{p,avg} = 1.11\ \frac{kJ}{kg} \rightarrow k = 1.349$

$$\frac{T_{2s}}{T_1} = \left(\frac{P_{2s}}{P_1}\right)^{\frac{k-1}{k}} \longrightarrow T_{2s} = (950)\left(\frac{110}{200}\right)^{\frac{k-1}{k}} = 814\,K$$

$T_{avg} = 882\,K \longrightarrow C_{p,avg} \longrightarrow T_{2s}$

$e_{in} = e_{out}$

$$h_1 + \cancel{\frac{V_1^2}{2}} = h_{2s} + \frac{V_{2s}^2}{2} \longrightarrow V_{2s} = \sqrt{2(h_1 - h_{2s})}$$

$$= \sqrt{2C_{p,avg}(T_1 - T_{2s})} = \sqrt{(2)(1.11)(950-814)}$$

(b) $$\eta_N = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} = \frac{\cancel{C_{p,avg}}(T_1 - T_{2s})}{\cancel{C_{p,avg}}(T_1 - T_{2a})} \Rightarrow T_{2a} = 825\,K$$

(c) $$\eta_N = \frac{V_{2a}^2}{V_{2s}^2} \longrightarrow V_{2a} = \sqrt{\eta_N} \cdot V_{2s} = 527\ \frac{m}{s}$$

ENTROPY BALANCE

$$\underbrace{S_{in} - S_{out}}_{\text{Net energy transfered through the system boundary}} + S_{gen} = \Delta S_{system}$$

Entropy Change of a System ΔS_{system}

$$\Delta S_{system} = \int_{final} - \int_{initial} = S_2 - S_1$$

Mechanisms of Entropy Transfer S_{in}, S_{out}

1. Heat transfer
2. Mass flow

3. Energy transfered by Heat: $S_{heat} = \frac{Q}{T}$

constant – usually boundary temprature

Mechanisms of Entropy Transfer S_{in}, S_{out}

1 Heat Transfer

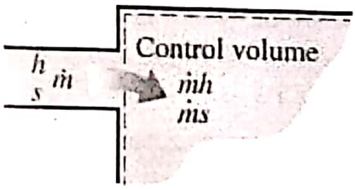
$$S_{heat} = \frac{Q}{T} \quad (T = \text{constant})$$

$$S_{heat} = \int_1^2 \frac{\delta Q}{T} \cong \sum \frac{Q_k}{T_k}$$

$$S_{work} = 0$$

کار با خود انتروپی منتقل نمی‌کند

2 Mass Flow



$$S_{mass} = ms$$ ← specific entropy

Entropy Generation

S_{gen}

Irreversibilities

Friction, chemical reaction, heat transfer

Internally reversible , $S_{gen} = 0$, $\Delta S_{tot} = \Delta S_{sys} + \Delta S_{sur}$

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system} \quad \left(\frac{kJ}{K}\right)$$

rate: $$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \frac{dS_{system}}{dt} \quad \left(\frac{kW}{K}\right)$$

$$\dot{S}_{heat} = \frac{\dot{Q}}{T}, \quad \dot{S}_{mass} = \dot{m}s$$

unit-mass

$$s_{in} - s_{out} + s_{gen} = \Delta s_{system}$$

Closed Systems ⟶ جریان جرم ندارد

$$\sum \frac{Q_k}{T_k} + S_{gen} = \Delta S_{system} = S_2 - S_1 \quad \left(\frac{kJ}{K}\right)$$

Adiabatic: $Q = 0$

$$S_{gen} = S_2 - S_1 = \Delta S_{system}$$

بالانس انتروپی برای سیستم و محیط اطراف آن:

$$S_{gen} = \sum \Delta S = \Delta S_{system} + \Delta S_{surr} = m(s_2 - s_1) + \frac{Q_{surr}}{T_{surr}}$$

به شرط دما ثابت بودن

Control Volumes

$$\sum \frac{Q_k}{T_k} + \sum m_i s_i - \sum m_e s_e + S_{gen} = (S_2 - S_1)_{cv} \quad \left(\frac{kJ}{K}\right)$$

$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \dot{S}_{gen} = \frac{dS_{system}}{dt} \quad \left(\frac{kW}{K}\right)$$

Steady flow process:

$$\dot{S}_{gen} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k}$$

steady flow, single stream:

$$\dot{S}_{gen} = \dot{m}(s_e - s_i) - \sum \frac{Q_k}{T_k}$$

Steady flow, single stream, adiabatic.

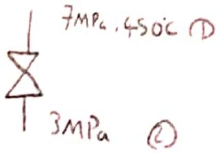
$$\dot{S}_{gen} = \dot{m}(s_e - s_i) \qquad s_e \geq s_i \text{ (adiabatic)}$$

reversible, adiabatic

$$s_e = s_i$$

EXAMPLE 1

Steam at 7 MPa and 450°C is throttled in a valve to a pressure of 3 MPa during a steady-flow process. Determine the entropy generated during this process and check if the increase of entropy principle is satisfied.



با فرض Q و W برابر صفر داریم:

$h_1 \cong h_2$, $\dot{m}_1 = \dot{m}_2 = m$

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \cancel{\frac{dS_{system}}{dt}}^{\,\text{steady}\; 0} = \dot{m}S_1 - \dot{m}S_2 + \dot{S}_{gen} = 0 \quad , \quad \dot{S}_{gen} = \dot{m}(S_2 - S_1)$$

چون $\dot{m}$ نداریم در واحد جرم می‌نویسیم.

$$S_{gen} = S_2 - S_1$$

$$(1)\begin{cases} P = 7\,MPa \\ T = 450 \end{cases} \longrightarrow S_1 = 6.6353 \ \frac{kJ}{kg.k} \qquad h_1 = 3288.3 \ \frac{kJ}{kg}$$

$$(2)\begin{cases} P = 3\,MPa \\ h_2 \cong h_1 = 3288.3 \ \frac{kJ}{kg} \end{cases} \longrightarrow S_2 = 7.0046 \ \frac{kJ}{kg.k}$$

$$\Rightarrow S_{gen} = S_2 - S_1 = 0.3698 \ \frac{kJ}{kg.k}$$

$S_{gen} \geq 0 \Longrightarrow$ Satisfies the Second law

EXAMPLE 2

A 50-kg block of iron casting at 500 K is thrown into a large lake that is at a temperature of 285 K. The iron block eventually reaches thermal equilibrium with the lake water. Assuming an average specific heat of 0.45 kJ/kg·K for the iron, determine (*a*) the entropy change of the iron block, (*b*) the entropy change of the lake water, and (*c*) the entropy generated during this process.

$T_2 = 285\,K$

(a) $\Delta S_{Iron} = m(S_2 - S_1) = mc_{avg} \ln \frac{T_2}{T_1} = (50)(0.45) \ln \frac{285}{500} = -12.65 \frac{kJ}{kg\,K}$

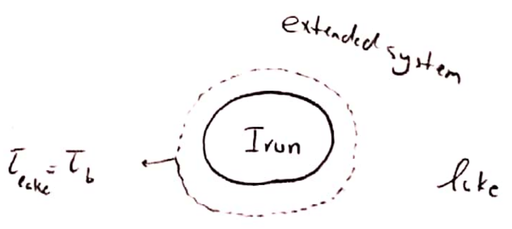
(b) Energy Balance : on the iron block

$E_{in} - E_{out} = \Delta E_{system} \longrightarrow -Q_{out} = \Delta U = mC_{avg}\Delta T \Rightarrow -Q_{out} = (50)(0.45)(500-285) = -4838\,kJ$

$\Delta S_{lake} = \frac{Q_{lake}}{T_{lake}} = \frac{4838}{285} = 16.97 \frac{kJ}{K}$

(c) $S_{in} - S_{out} + S_{gen} = \Delta S_{system}$

روش اول :

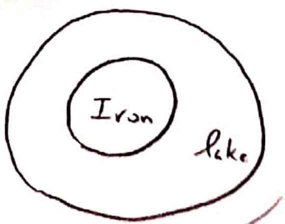


$-\frac{Q_{out}}{T_{lake}} + S_{gen} = \Delta S_{system}$, $S_{gen} = \frac{Q_{out}}{T_{lake}} + \Delta S_{system} = \frac{4838}{285} - 12.63 = 4.32 \frac{kJ}{K}$

چون تغییرات ΔS_{surr} بسیار کمتر از ΔS_{iron} است پس از آن صرف نظر می‌کنیم

* در این حالت کل سیستم adiabatic می‌شود.

روش دوم :



$S_{gen} = \Delta S_{tot} = \Delta S_{iron} + \Delta S_{lake} = -12.65 + 16.97 = 4.32 \frac{kJ}{K}$

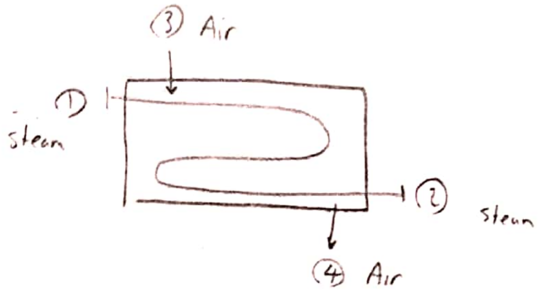
* در انتها سیستم را مشخص کنید.

EXAMPLE 3

101.325 kPa

Air in a large building is kept warm by heating it with steam in a heat exchanger. Saturated water vapor enters this unit at 35°C at a rate of 10,000 kg/h and leaves as saturated liquid at 32°C. Air at 1-atm pressure enters the unit at 20°C and leaves at 30°C at about the same pressure. Determine the rate of entropy generation associated with this process.

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \frac{dS_{system}}{dt} \overset{steady}{=} 0$$



$$\dot{m}_{steam} s_1 + \dot{m}_{air} s_3 - \dot{m}_{steam} s_2 - \dot{m}_{air} s_4 + \dot{S}_{gen} = 0$$

① $\begin{cases} T_1 = 35^\circ C \\ \text{sat vap} \end{cases} \longrightarrow s_1 = 8.3517 \ \frac{kJ}{kg\,K}, \ h_1 = 2564.6 \ \frac{kJ}{kg}$

② $\begin{cases} T_2 = 32^\circ C \\ \text{sat liq} \end{cases} \longrightarrow s_2 = 0.4641 \ \frac{kJ}{kg.K} \quad h_2 = 134.1 \ \frac{kJ}{kg}$

ثابت فرض شود

$$\dot{Q}_{steam} = \dot{m}_{steam}(h_1 - h_2) = 6751 \ kW = \dot{Q}_{air} = \dot{m}_{air}(h_4 - h_3) = \dot{m}_{air} C_p \Delta T$$

$$\longrightarrow \dot{m}_{air} = 671.7 \ \frac{kg}{s}$$

$$\dot{S}_{gen} = \dot{m}_{steam}(s_2 - s_1) + \dot{m}_{air} \underbrace{(s_4 - s_3)}_{C_p \ln \frac{T_4}{T_3}} = 0.74 \ \frac{kW}{k}$$

چون فشار ورودی و خروجی air برابر است پس ترم $R \ln \frac{P_2}{P_1}$ حذف می‌شود.

EXERGY: WORK POTENTIAL OF ENERGY

availability , available energy

* پتانسیل انجام کار مفید به مقدار همین انرژی در یک حالت معلوم : بیشترین کار مفید

Dead state

- تعادل ترمودینامیکی با محیط
- $T_0, P_0, h_0, u_0, \ldots$
- $T_0 = 25^\circ C$, $P = 1 atm$

* Work: f (initial state, process path, final state)

- حالت اولیه معلوم است
- فرایند باید برگشت پذیر باشد
- حالت نهایی حالت مرده

immediate surrounding

Surroundings

immediate surroundings → تحت تاثیر فرایند هست

Enviroment → تحت تاثیر فرایند قرار نگرد

* وقتی سیستم از یک حالت اولیه معلوم تا حالت محیط (حالت مرده) در یک فرایند برگشت پذیر میرسد ، حداکثر کار مفید ممکن را انجام می دهد.

که این پتانسیل انجام کار یا ~~[illegible]~~ ترمودینامیکی Exergy (انرژی)

خاصیت ترکیب محیط - سیستم است

Exergy (Work Potential) Associated with Kinetic and Potential Energy

$$x_{ke} = ke = \frac{V^2}{2} \quad \left(\frac{kJ}{kg}\right)$$

$$x_{pe} = pe = gz \quad \left(\frac{kJ}{kg}\right)$$

EXAMPLE 1

A wind turbine with a 12-m-diameter rotor is to be installed at a location where the wind is blowing steadily at an average velocity of 10 m/s. Determine the maximum power that can be generated by the wind turbine.

تبدیل واحد

$$ke = \frac{V^2}{2} = \frac{10^2}{2} \times 10^{-3} = 0.05 \ \frac{kJ}{kg}$$

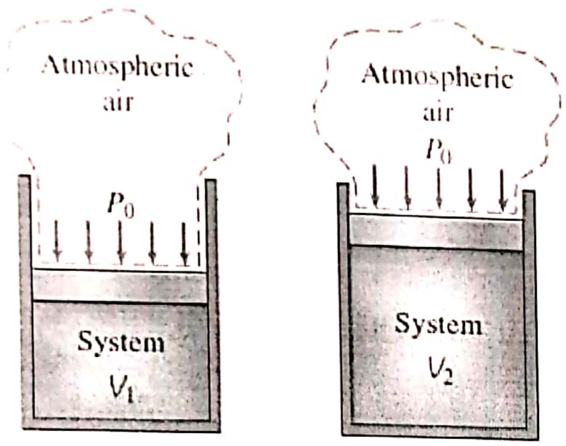
$$\dot{m} = \rho A V = \rho \frac{\pi D^2}{4} V = 1335 \ \frac{kg}{s} \longrightarrow \text{Maximum Power} = \dot{m} ke = 66.8 \text{ kW}$$

1 atm, 25°C $\longrightarrow \rho = 1.18 \ \frac{kg}{m^3}$

standard condition $\longrightarrow$

REVERSIBLE WORK AND IRREVERSIBILITY

surrounding work طرشيل



* $W_{surr} = P_0 (V_2 - V_1)$

* useful work $= W_u = W - W_{surr} = W - P_0 (V_2 - V_1)$

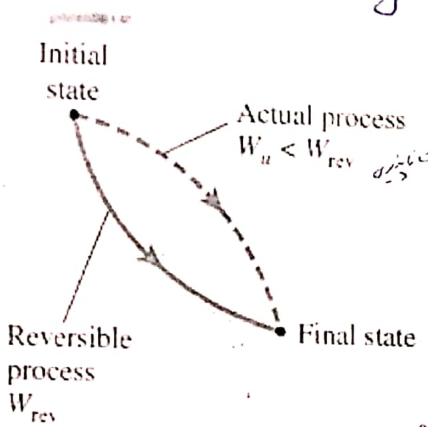
Reversible work

* در یک فرایند بین حالت اولیه و نهایی معلوم
* ماکزیمم کار مفیدی که سیستم می‌تواند انجام دهد. (کمترین مقدار کار ورودی نیاز سیستم)

اگر حالت نهایی Dead state باشد این کار برگشت‌پذیر همان اگزرژی است

Irreversibility

(Exergy destroyed)



برگشت ناپذیری

* $I = W_{rev,out} - W_{u,out}$
* $I = W_{u,in} - W_{rev,in}$

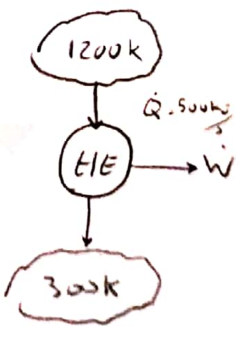
$I = W_{rev} - W_u$

* Actual Processes : $I > 0$
* $W_{rev} > W_u$ for work-producing devices
* $W_{rev} < W_u$ for work-consuming devices

EXAMPLE 2

A heat engine receives heat from a source at 1200 K at a rate of 500 kJ/s and rejects the waste heat to a medium at 300 K. The power output of the heat engine is 180 kW. Determine the reversible power and the irreversibility rate for this process.

$$\eta_{th,rev} = \frac{\dot{W}_{out}}{\dot{Q}_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H} =$$

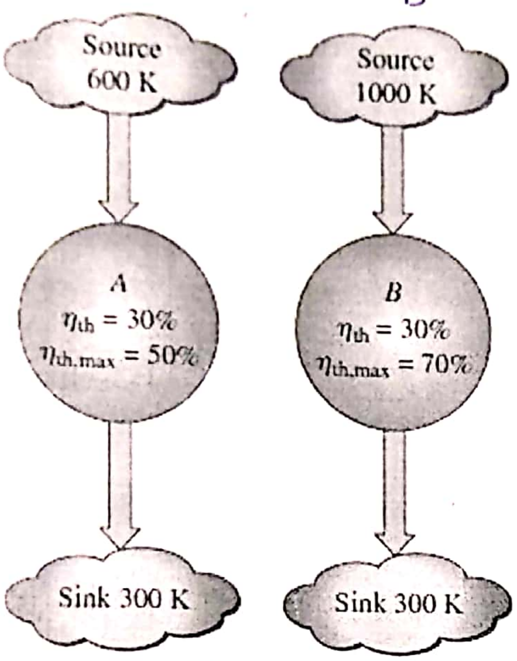


$$\dot{W}_{out} = \left(1 - \frac{T_{sink}}{T_{source}}\right)\dot{Q} = \left(1 - \frac{300}{1200}\right)500 = 375\text{ kW}$$ → توان برگشت پذیر

$$\dot{I} = \dot{W}_{rev,out} - \dot{W}_{u,out} = 375 - 180 = 195\text{ kW}$$

SECOND-LAW EFFICIENCY

A B



$$\eta_{th,rev,A} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{600} = 50\%$$

$$\eta_{th,rev,B} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{1000} = 70\%$$

$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}}$$ (Heat Engines)

$$\eta_{II,A} = 1 - \frac{0.3}{0.5} = \cancel{0.4} \; 0.6$$, $$\eta_{II,B} = 1 - \frac{0.3}{0.7} = 0.43$$

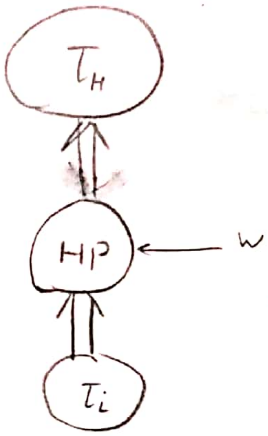
$$\eta_{II} = \frac{W_u}{W_{Rev}}$$ (Work-~~Consuming~~ Producing devices) , $$\eta_{th} = \frac{W_{rev}}{W_u}$$ (work-consuming devices)

$$\eta_{II} = \frac{COP}{COP_{rev}}$$ (refigerator and heat pumps)

EXAMPLE 3

A house that is losing heat at a rate of 50,000 kJ/h when the outside temperature drops to 4°C is to be heated by electric resistance heaters. If the house is to be maintained at 25°C at all times, determine the reversible work input for this process and the irreversibility.

$$COP_{HP,rev} = \frac{1}{1 - \frac{277.15}{298.15}} = 14.2$$



$$\dot{Q}_H = 50000 \frac{kJ}{h} = 13.89 kW = \dot{W}_{e,in}$$

$$\dot{W}_{rev} = \frac{\dot{Q}_H}{COP_{HP,rev}} = \frac{13.89}{14.2} = 0.987 kW$$

$$\dot{I} = \dot{W}_{u,in} - \dot{W}_{rev,in} = 13.89 - 0.987 = 12.91 kW$$