

Review of Engineering Thermodynamics

Universal Balance Equation for Any Extensive Property

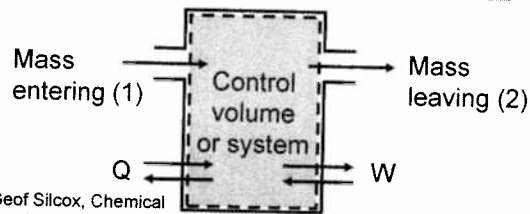
$$\text{Accumulation} = \text{transport} + \text{generation}$$

Integrated form for some period of time:

$$\left[\begin{array}{c} \text{final} \\ \text{amount} \end{array} \right] - \left[\begin{array}{c} \text{initial} \\ \text{amount} \end{array} \right] = \left[\begin{array}{c} \text{amount} \\ \text{entering} \end{array} \right] - \left[\begin{array}{c} \text{amount} \\ \text{leaving} \end{array} \right] + \left[\begin{array}{c} \text{amount} \\ \text{generated} \end{array} \right] - \left[\begin{array}{c} \text{amount} \\ \text{consumed} \end{array} \right]$$

Rate form:

$$\left[\begin{array}{c} \text{rate of} \\ \text{change} \end{array} \right] = \left[\begin{array}{c} \text{rate of} \\ \text{transport in} \end{array} \right] - \left[\begin{array}{c} \text{rate of} \\ \text{transport out} \end{array} \right] + \left[\begin{array}{c} \text{rate of} \\ \text{generation} \end{array} \right] - \left[\begin{array}{c} \text{rate of} \\ \text{consumption} \end{array} \right]$$



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Mass Balance

- Unsteady balance for CV

$$\frac{dm_{CV}}{dt} = \sum_{\text{inlets}} \dot{m}_i - \sum_{\text{exits}} \dot{m}_e$$

$$\Delta m_{CV} = m_2 - m_1 = \sum_{\text{inlets}} m_i - \sum_{\text{exits}} m_e$$

- Steady balance for CV

$$0 = \sum_{\text{inlets}} \dot{m}_i - \sum_{\text{exits}} \dot{m}_e$$

$$0 = \sum_{\text{inlets}} m_i - \sum_{\text{exits}} m_e$$

- Balance for closed system

$$\frac{dm_{sys}}{dt} = 0$$

$$\Delta m_{sys} = m_2 - m_1 = 0$$

- Averaged flow

$$\dot{m} = \rho_{av} V_{el_{av}} A = \frac{V_{el_{av}} A}{v_{av}} = \frac{\dot{V}}{v_{av}}$$

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Energy Balance

$$e = u + \frac{1}{2}Vel^2 + gz, \quad h = u + Pv$$

- Unsteady balance for CV

$$\frac{dE_{CV}}{dt} = \dot{Q}_{in,net} + \dot{W}_{in,net} + \sum_{inlets} \dot{m}_i \left(h + \frac{Vel^2}{2} + gz \right)_i - \sum_{exits} \dot{m}_e \left(h + \frac{Vel^2}{2} + gz \right)_e$$

- Steady balance for CV

$$0 = \dot{Q}_{in,net} + \dot{W}_{in,net} + \sum_{inlets} \dot{m}_i \left(h + \frac{Vel^2}{2} + gz \right)_i - \sum_{exits} \dot{m}_e \left(h + \frac{Vel^2}{2} + gz \right)_e$$

- Balance for closed system

$$\frac{dE_{sys}}{dt} = \dot{Q}_{in,net} + \dot{W}_{in,net}$$

$$\Delta E_{sys} = Q_{in,net} + W_{in,net}$$

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Entropy Balance

There is only one form of entropy.

- Unsteady balance for CV

$$\frac{dS_{CV}}{dt} = \sum_{j=1}^n \frac{\dot{Q}_{in,j}}{T_j} + \sum_{inlets} \dot{m}_i s_i - \sum_{exits} \dot{m}_e s_e + \dot{S}_{gen}$$

$$\dot{S}_{gen} > 0 \text{ irreversible process}$$

$$\dot{S}_{gen} = 0 \text{ reversible process}$$

$$\dot{S}_{gen} < 0 \text{ impossible process}$$

- Steady balance for CV

$$0 = \sum_{j=1}^n \frac{\dot{Q}_{in,j}}{T_j} + \sum_{inlets} \dot{m}_i s_i - \sum_{exits} \dot{m}_e s_e + \dot{S}_{gen}$$

- Balance for closed system

$$\frac{dS_{sys}}{dt} = \sum_{j=1}^n \frac{\dot{Q}_{in,j}}{T_j} + \dot{S}_{gen}$$

$$\Delta S_{sys} = m(s_2 - s_1) = \int_1^2 \frac{\delta Q_{in}}{T} + S_{gen}$$

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Combined Entropy and Energy Balance

$$du = \delta q + \delta w \qquad ds = \frac{\delta q}{T} + ds_{gen}$$

$$du = \delta q_{rev} + \delta w_{rev} \qquad ds = \frac{\delta q_{rev}}{T} \qquad \delta w_{rev} = -Pdv$$

$$\boxed{Tds = du + Pdv} \quad \text{or} \quad \boxed{ds = \frac{du}{T} + \frac{Pdv}{T}}$$

An alternate form follows from the relation

$$d(Pv) = Pdv + vdP$$

$$\boxed{Tds = dh - vdP} \quad \text{or} \quad \boxed{ds = \frac{dh}{T} - \frac{vdP}{T}}$$

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Combined Entropy and Energy Balance for Ideal Gases

$$\boxed{\Delta s = \int_1^2 c_v(T) \frac{dT}{T} + R \ln \frac{v_2}{v_1}}$$

$$\boxed{\Delta s = \int_1^2 c_p(T) \frac{dT}{T} - R \ln \frac{P_2}{P_1}}$$

For constant or averaged heat capacities,

$$\boxed{\Delta s = c_{v,av} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}}$$

$$\boxed{\Delta s = c_{p,av} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}}$$

where $T_{av} = \frac{T_1 + T_2}{2}$ and $c_{av} = c(T_{av})$

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Equations for Work

Reversible boundary work, closed system:

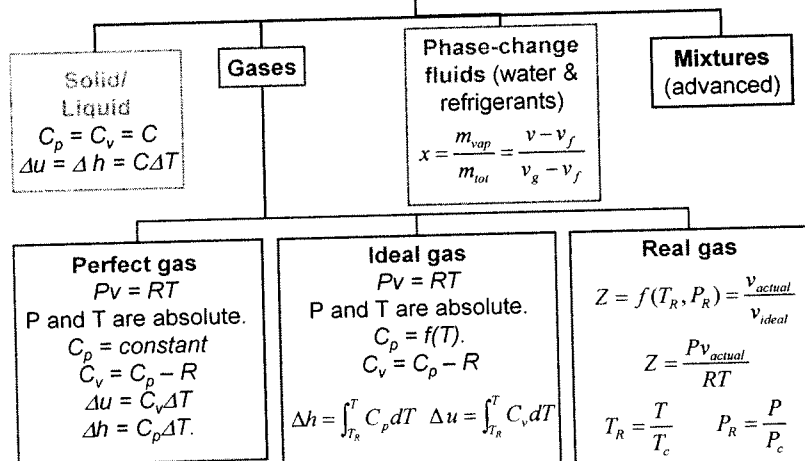
$$W_{rev,in} = - \int_{v_1}^{v_2} P dv$$

Steady-flow, reversible work, open system:

$$W_{rev,in} = \frac{\dot{W}}{\dot{m}} = \int_{P_1}^{P_2} v dP + \frac{Vel_2^2 - Vel_1^2}{2} + g(z_2 - z_1)$$

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Models of Working Substances



This chart was inspired by Subrata Bhattacharjee, *The Expert System for Thermodynamics*, Prentice Hall, Upper Saddle River, NJ, 2003. ISBN 0-13-009235-5. www.thermofluids.net.

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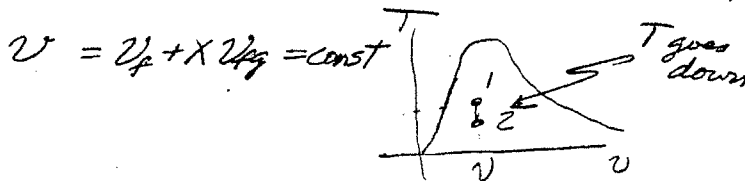
THERMO PROBLEMS

48. A system is at rest in a certain process, except that the boundaries of the system may expand or contract in accordance with the nature of the process that is occurring. The system undergoes a process in which heat Q is received from the surroundings and the change in internal energy, $\Delta U = U_{\text{final}} - U_{\text{initial}} = Q/2$. This process results in system boundaries that

$$\begin{aligned} 1^{\text{st}} \text{ Law: } Q_2 &= U_2 - U_1 + W_2 \\ Q_2 &= \frac{Q_2}{2} + W_2 \Rightarrow W_2 = \frac{Q_2}{2} \\ W_2 &= + \end{aligned}$$

- (A) remain stationary.
- (B) expand.
- (C) burst.
- (D) contract.
- (E) become rigid.

50. An insulated tank contains half liquid and half vapor by volume in equilibrium. The release of a small quantity of the vapor without the addition of heat will cause



- (A) cooling of the liquid in the tank.
- (B) superheating of the vapor in the tank.
- (C) an increase in internal energy of the remaining mixture.
- (D) a rise in temperature.
- (E) an increase in enthalpy.

51. The heat transfer during an adiabatic process is

definition of adiabatic is $Q_2 = 0$

- (A) reversible.
- (B) irreversible.
- (C) dependent on temperature.
- (D) dependent on pressure.
- (E) zero.

52. An isentropic process is one which

C is not really right, but only choice. All others are wrong -

- (A) is adiabatic but not reversible.
- (B) is reversible but not adiabatic.
- (C) is adiabatic and reversible.
- (D) occurs at constant pressure but not constant temperature.
- (E) occurs at constant pressure and temperature.

53. Pure water is boiling in an open pan at atmospheric pressure. Salt at a temperature equal to that of the boiling water is added. Immediately after the salt dissolves, which of the following will most likely occur?

Salt on ice \Rightarrow lower melting point. It's logical to assume that it also changes the boiling temp. All other answers are wrong

- (A) The boiling ceases.
- (B) The temperature of the solution drops by 10°C .
- (C) The water ionizes.
- (D) The entire mass becomes solid.
- (E) The salt vaporizes.

54. An inventor proposes to propel a ship by withdrawing heat from seawater and converting it all into work. Since the thermal energy of the sea is essentially unlimited, the ship could run almost forever without any fuel. This scheme fails because

can't do by 2nd Law

- (A) it violates the first law of thermodynamics.
- (B) it violates the second law of thermodynamics.
- (C) it violates the mechanical energy balance.
- (D) the temperature of seawater is too low.
- (E) there is too much friction between the ship's hull and the water.

55. When the pressure of an ideal gas is doubled while the absolute temperature is halved, the volume is

$$v_1 = \frac{mRT_1}{P_1} \quad v_2 = \frac{mRT_1/2}{2P_1} = \frac{v_1}{4}$$

- (A) quadrupled.
- (B) doubled.
- (C) constant.
- (D) halved.
- (E) quartered.

56. All of the following statements about the Carnot cycle are true EXCEPT:

Carnot Cycle is reversible. All other answers are true for Carnot

- (A) It is the most efficient cycle between any two temperatures.
- (B) It is irreversible.
- (C) It operates between two constant temperature reservoirs.
- (D) It is a cycle in which the heat is transferred isothermally.
- (E) It is a cycle in which the efficiency is independent of the working substance.

Select either problem.

57. (SI)
During a process in which 20 joules of positive work is done by a closed stationary system, the internal energy decreases by 50 joules. The heat transfer is most nearly:

- (A) 70 J extracted
- (B) 30 J extracted
- (C) 30 J added
- (D) 70 J added
- (E) 1,000 J added

57. (non-SI)
During a process in which 1556 foot-pounds of positive work is done by a closed stationary system, the internal energy decreases by 5 British thermal units. The heat transfer is most nearly:

- (A) 7 Btu extracted
- (B) 3 Btu extracted
- (C) 3 Btu added
- (D) 7 Btu added
- (E) 10 Btu added

1ST LAW
closed $\Rightarrow Q_2 = U_2 - U_1 + W_2$

$Q_2 = -50 + 20 = -30$

58. The heat liberated during the burning of a substance at constant pressure is equal to the negative of the

- (A) change in chemical potential.
- (B) change in Gibb's function.
- (C) entropy change.
- (D) enthalpy of combustion.
- (E) enthalpy of formation.

definition

59. The net entropy change in the universe during a process in an open system is

- (A) undefined.
- (B) indeterminate.
- (C) zero.
- (D) equal to or greater than zero.
- (E) equal to or less than zero.

2nd Law

60. Let G =Gibbs free energy
 A =Helmholtz free energy
 H =enthalpy
 T =absolute temperature
 S =entropy
 U =internal energy
 P =pressure
 V =volume

All of the following relationships are correct EXCEPT:

- (A) $A = U - TS$
- (B) $A = H - PV - TS$
- (C) $G = U + PV - TS = H - TS$
- (D) $G = H - TS$
- (E) $G = A + PV$

? GUESS! from D & C
From B: $A = H - TS - PV = G - PV$
 $\therefore G = A + PV$

61. All of the following statements about work done on or by a gas are true EXCEPT:

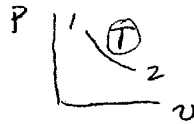
- (A) Work is transitory in nature.
- (B) The differential of work is exact.
- (C) Work is the area under a curve on a P - V plane.
- (D) Work is a path-function.
- (E) Work is zero for a constant volume process.

defn $\delta W \Rightarrow$ inexact differential
ie, path function

Note: Must be closed system

62. A cylinder fitted with a frictionless piston contains an ideal gas at temperature T and pressure P . If the gas expands reversibly and isothermally until the pressure is $P/5$, the work done by the gas is

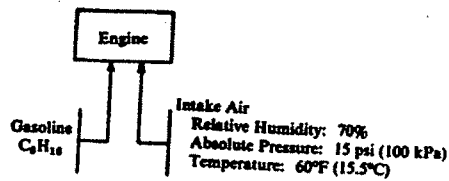
- (A) equal to the heat absorbed by the gas.
- (B) equal to the internal energy change of the gas.
- (C) equal to the enthalpy change of the gas.
- (D) equal to 5 P times the volume change in the gas.
- (E) greater than the heat absorbed by the gas.



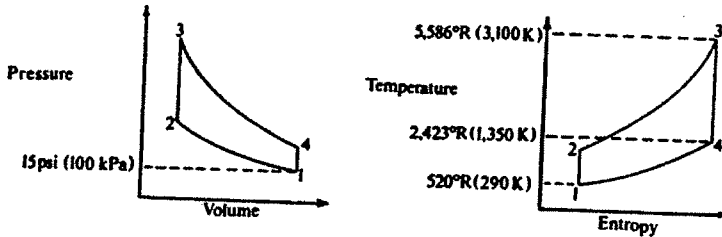
$W = \int P dV = RT \ln\left(\frac{P_1}{P_2}\right) = RT \ln(5)$

$Q_2 = U_2 - U_1 + W_2$
 \Rightarrow since $U = U(T)$

Questions 66-70 relate to a spark-ignition engine that receives fuel and air as shown below.



Assume that the operating medium is an ideal gas and that the engine operates according to the cycle shown on the pressure-volume and temperature-entropy diagrams below.



The compression ratio of the cycle is 8, and the heat added during the process of going from state 2 to state 3 is 750 Btu/lb_m (1,740 kJ/kg).

66. The temperature at state 2 is most nearly:

- (A) 3,250°R (1,800 K)
- (B) 1,250°R (690 K)
- (C) 1,200°R (670 K)
- (D) 820°R (460 K)
- (E) 520°R (290 K)

$$\textcircled{5} \Rightarrow \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = \left(\frac{V_4}{V_3}\right)^{k-1} = \frac{T_3}{T_4}$$

$$T_2 = \frac{T_1 T_3}{T_4} = \frac{290(3100)}{1350} = \underline{\underline{666 \text{ K}}}$$

67. The pressure at state 2 is most nearly:

- (A) 34.4 psi (240 kPa)
- (B) 98.8 psi (680 kPa)
- (C) 174 psi (1,200 kPa)
- (D) 276 psi (1,840 kPa)
- (E) 394 psi (2,700 kPa)

$$P_2 = P_1 \left(\frac{V_1}{V_2}\right)^k = 100(8)^{1.4} = \underline{\underline{1838 \text{ kPa}}}$$

68. The specific volume at intake (state 1) is most nearly:

- (A) 1850 ft³/lbm (115 m³/kg)
- (B) 1210 ft³/lbm (75 m³/kg)
- (C) 143 ft³/lbm (8.9 m³/kg)
- (D) 12.8 ft³/lbm (0.83 m³/kg)
- (E) 1.32 ft³/lbm (0.082 m³/kg)

$$v_1 = \frac{RT_1}{P_1} = \frac{8314(290)}{29 \cdot 100000} = \underline{\underline{0.8314 \frac{\text{m}^3}{\text{kg}}}}$$

69. The thermal efficiency of the cycle is most nearly:

- (A) 0.298
- (B) 0.383
- (C) 0.437
- (D) 0.565
- (E) 0.917

$$\eta = 1 - \frac{1}{r^{k-1}} = 1 - \frac{1}{8^{(1.4-1)}} = \underline{\underline{56.5\%}}$$

70. The heat rejected by the cycle is most nearly:

- (A) 560 Btu/lbm (1300 kJ/kg)
- (B) 457 Btu/lbm (1060 kJ/kg)
- (C) 435 Btu/lbm (1010 kJ/kg)
- (D) 325 Btu/lbm (755 kJ/kg)
- (E) 288 Btu/lbm (670 kJ/kg)

$$Q_H = 1740$$

$$Q_L = 0.565 = 1 - \frac{Q_L}{Q_H}$$

$$Q_L = (1 - 0.565) 1740 = \underline{\underline{757}}$$

