Review of Engineering Thermodynamics

Universal Balance Equation for Any Extensive Property

Accumulation = transport + generation

Integrated form for some period of time:

\[
\begin{align*}
\text{final amount} - \text{initial amount} &= \text{amount entering} - \text{amount leaving} + \text{amount generated} - \text{amount consumed} \\
\end{align*}
\]

Rate form:

\[
\text{rate of change} = \text{rate of transport in} - \text{rate of transport out} + \text{rate of generation} - \text{rate of consumption}
\]

Mass entering (1) \hspace{1cm} Control volume or system \hspace{1cm} Mass leaving (2)

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Mass Balance

- Unsteady balance for CV

\[
\frac{dm_{CV}}{dt} = \sum_{\text{mass}} \dot{m}_i - \sum_{\text{exit}} \dot{m}_i \\
\Delta m_{CV} = m_2 - m_1 = \sum_{\text{inlets}} m_i - \sum_{\text{exits}} m_i
\]

- Steady balance for CV

\[
0 = \sum_{\text{inlets}} m_i - \sum_{\text{exits}} m_i
\]

- Balance for closed system

\[
\frac{dm_{sys}}{dt} = 0 \\
\Delta m_{sys} = m_2 - m_1 = 0
\]

- Averaged flow

\[
m = \rho \omega V e l \omega A = \frac{V e l \omega A}{v_x} = \frac{V}{v_x}
\]

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Energy Balance

\[ e = u + \frac{1}{2} V e l^2 + g z, \ h = u + P v \]

- Unsteady balance for CV

\[ \frac{dE_{cv}}{dt} = \dot{Q}_{in, net} + \dot{W}_{in, net} + \sum_{inlet} m_i \left( h + \frac{Ve l^2}{2} + gz \right) - \sum_{exit} m_e \left( h + \frac{Ve l^2}{2} + gz \right) \]

- Steady balance for CV

\[ 0 = \dot{Q}_{in, net} + \dot{W}_{in, net} + \sum_{inlet} m_i \left( h + \frac{Ve l^2}{2} + gz \right) - \sum_{exit} m_e \left( h + \frac{Ve l^2}{2} + gz \right) \]

- Balance for closed system

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

\[ \Delta E_{sys} = \dot{Q}_{in, net} + \dot{W}_{in, net} \]

Entropy Balance

There is only one form of entropy.

- Unsteady balance for CV

\[ \frac{dS_{cv}}{dt} = \sum_{j=1}^{n} \frac{\dot{Q}_{in, j}}{T_j} + \sum_{inlet} m_i s_i - \sum_{exit} m_e s_e + \dot{S}_{gen} \]

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

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

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

- Steady balance for CV

\[ 0 = \sum_{j=1}^{n} \frac{\dot{Q}_{in, j}}{T_j} + \sum_{inlet} m_i s_i - \sum_{exit} m_e s_e + \dot{S}_{gen} \]

- Balance for closed system

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

\[ \Delta S_{sys} = m(s_i - s_e) = \int \frac{\dot{Q}_{in}}{T} + s_{gen} \]

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Combined Entropy and Energy Balance

\[ du = \delta q + \delta w \quad ds = \frac{\delta q}{T} + ds_{gen} \]

\[ du = \delta q_{rev} + \delta w_{rev} \quad ds = \frac{\delta q_{rev}}{T} \quad \delta w_{rev} = -Pdv \]

\[ Tds = du + Pdv \quad \text{or} \quad ds = \frac{du}{T} + \frac{Pdv}{T} \]

An alternate form follows from the relation

\[ d(Pv) = Pdv + vdP \]

\[ Tds = dh - vdP \quad \text{or} \quad ds = \frac{dh}{T} - \frac{vdP}{T} \]

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Combined Entropy and Energy Balance for Ideal Gases

\[ \Delta S = \int_{T_1}^{T_2} c_v(T) \frac{dT}{T} + R \ln \frac{V_2}{V_1} \]

\[ \Delta S = \int_{T_1}^{T_2} c_p(T) \frac{dT}{T} - R \ln \frac{P_2}{P_1} \]

For constant or averaged heat capacities,

\[ \Delta S = c_{v,av} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \]

\[ \Delta S = c_{p,av} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \]

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:

\[ w_{\text{rev,bs}} = -\int_{v_i}^{v_f} P\, dv \]

Steady-flow, reversible work, open system:

\[ W_{\text{rev,os}} = \frac{\dot{W}}{m} = \int_{v_i}^{v_f} v\, dP + \frac{V e_tv^2 - V e_tv_i^2}{2} + g(z_f - z_i) \]

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Models of Working Substances

- **Solid/Liquid**
  \[ C_p = C_v = C \]
  \[ \Delta u = \Delta h = C \Delta T \]

- **Gases**
  \[ PV = RT \]
  \[ C_p = \text{constant} \]
  \[ C_v = C_p - R \]
  \[ \Delta u = C_p \Delta T \]

- **Phase-change fluids (water & refrigerants)**
  \[ x = \frac{m_{\text{water}}}{m_{\text{water}}} \]
  \[ x = \frac{v - v_f}{v_s - v_f} \]

- **Mixtures (advanced)**

**Perfect gas**
\[ PV = RT \]
\[ C_p = \text{constant} \]
\[ C_v = C_p - R \]
\[ \Delta u = \int_{v_i}^{v_f} C_v\, dT \]

**Ideal gas**
\[ PV = RT \]
\[ C_p = f(T) \]
\[ C_v = C_p - R \]
\[ \Delta u = \int_{v_i}^{v_f} C_v\, dT \]

**Real gas**
\[ Z = f(T_s, P_s) - \frac{v_{\text{actual}}}{v_{\text{ideal}}} \]
\[ Z = \frac{PV_{\text{actual}}}{RT} \]
\[ T_s = \frac{T}{T_c} \]
\[ P_s = \frac{P}{P_c} \]

P and T are absolute.


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40. 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 \(\Delta U\) is zero. This process results in system boundaries that:
(A) remain stationary.
(B) expand.
(C) burst.
(D) contract.
(E) become rigid.

40. 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) an increase 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:
(A) reversible.
(B) irreversible.
(C) dependent on temperature.
(D) dependent on pressure.
(E) zero.

52. An isentropic process is one which:
(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?
(A) The boiling ceases.
(B) The temperature of the solution drops by 10°C.
(C) The water boils.
(D) The entire mass becomes solid.
(E) The salt vaporizes.

54. An inventor proposes to cause 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:
(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:
(A) quadrupled.
(B) doubled.
(C) constant.
(D) halved.
(E) quartered.

56. All of the following statements about the Carnot cycle are true EXCEPT:
(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.
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 1500 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

58. The heat liberated during the burning of a substance 
at constant pressure is equal to the negative of the 
change in chemical potential. (A) change in chemical potential. 
(B) change in Gibb's function. (C) entropy change. 
(D) enthalpy of combustion. (E) enthalpy of formation.

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.

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=H-PV=U-TS
(D) G=U-TS
(E) 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.

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 0.5P, 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 0.5 times the volume change in the gas. 
(E) greater than the heat absorbed by the gas.

\[ \Delta U = Q - W \]

\[ Q = W + \Delta U \]

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

\[ Q = U_2 - U_1 + W_2 \]

\[ Q = -50 + 20 = 30 \]
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 6, and the heat added during the process of going from state 2 to state 3 is 750 Btu/lbm (1,740 kJ/kg).

66. The temperature at state 2 is most nearly:
   (A) 3,250°F (1,800 K)
   (B) 1,250°F (800 K)
   (C) 1,250°F (670 K)
   (D) 220°F (450 K)
   (E) 520°F (290 K)

   \[ T_2 = \frac{T_1}{n-1} = \left(\frac{V_2}{V_1}\right)^{k-1} \]

   \[ T_2 = \frac{2,423(1,350)}{520} = \frac{290(3,000)}{1350} = 666 K \]

67. The pressure at state 2 is most nearly:
   (A) 84.4 psi (580 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)

   \[ P_2 = P_1 \left(\frac{V_1}{V_2}\right)^k = 100 \left(\frac{8}{5}\right)^{1.4} = 1838 kPa \]

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) 145 ft³/lbm (8.9 m³/kg)
   (D) 25 ft³/lbm (0.83 m³/kg)
   (E) 1.92 ft³/lbm (0.092 m³/kg)

   \[ V_1 = \frac{RT_1}{P_1} = \frac{8314(290)}{29 \cdot 100000} = 0.8314 \text{ m}^3/\text{kg} \]

69. The thermal efficiency of the cycle is most nearly:
   (A) 0.298
   (B) 0.333
   (C) 0.437
   (D) 0.560
   (E) 0.617

   \[ \eta = 1 - \frac{L}{Q_0} = 1 - \frac{L}{Q_{in}} = \frac{56.57}{56.57} = 56.57\% \]

70. The heat rejected by the cycle is most nearly:
   (A) 660 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) 388 Btu/lbm (670 kJ/kg)

   \[ Q_L = 0.565 = 1 - \frac{Q_L}{Q_{in}} \]

   \[ Q_L = (1 - 0.565) \cdot 1740 = 757 \]