MAE 320 – Thermodynamics
HW 2 Assignment

This assignment is due Monday, September 12th, 2016. Each problem is worth the points indicated. Copying of the solution from another is not acceptable.

(1) (16 points) Multiple choice questions (there maybe more than one correct answer)

(1a) (2p) Circle the extensive property
(A) Total Mass
(B) Temperature
(C) Pressure
(D) Density
(E) Total kinetic energy

(1b) (2p) 10 kWh is equal to
(A) $3.6 \times 10^7 J$
(B) $3.6 \times 10^7 W$
(C) 10,000 W
(D) $10^{-8} TWh$ (terawatt-hours)
(E) None of above

(1c) (2p) Circle the one which is NOT a state property of a thermodynamic system?
(A) Specific volume
(B) Boundary work
(C) Heat transfer
(D) Thermal energy
(E) Specific internal energy

(1d) (2p) The unit of specific kinetic energy is (are)
(A) J/kg
(B) $J^2/kg^2$
(C) W
(D) W/kg
(E) m$^2$/s$^2$

(1e) (2p) For closed systems, energy is transferred across the system boundary by means of
(A) Heat Transfer
(B) Work
(C) Mass transfer
(D) Phase transition
(E) None of above

(1f) (2p) The thermal energy of a system includes
(A) Nuclear energy
(B) Chemical energy
(C) Latent energy
(D) Sensible energy
(E) Kinetic energy

(1g) (2p) The least number of independent intensive properties needed to specify a state of a simple compressible system is
(A) 0
(B) 1
(C) 3
(D) 6
(E) None of above (2)

(1h) (2p) circle the one which is conserved during a process:

(A) Energy
(B) Heat
(C) Work
(D) Volume
(E) None of above
(2) (24 points) Simple calculation questions

(2a) (6p) The normal temperature of a healthy human body is 36.6°C. A patient measures his temperature by means of three thermometers, with three different temperature scales. Specifically, the readings are: 103.5°F on Monday, 311.6 K on Tuesday, and 558.3 R on Wednesday. Please check if the patient is recovering and elucidate your answer by converting the values above into °C.

Solution: Let us convert all temperature readings into the Celsius scale, namely,

Mon: 103.5°F = [(103.5 - 32) / 1.8]°C ≈ 39.7°C;
Tue: 311.6 K = (311.6 - 273.15)°C ≈ 38.5°C;
Wed: 558.3 R = (558.3 - 459.67)°F ≈ 98.6°F = [(98.6 - 32) / 1.8]°C ≈ 37°C

It is seen that patient’s temperature (though elevated!) decreases monotonically tending to a “healthy” level of 36.6°C. Consequently, we can conclude that the patient is recovering.

(2b) (6p) The absolute pressure on the bottom of a river is three times higher than that ambient pressure. Please determine the depth of the river if the density of water is 1000 kg/m³ and the atmospheric pressure is 1 bar.

Solution: Absolute pressure at the river bank equals to the atmospheric pressure, \( P_{\text{atm}} = 1 \text{ bar} \), while that on the river bottom is given by \( P_{\text{bottom}} = P_{\text{atm}} + P_{\text{H}_2\text{O}} = P_{\text{atm}} + \rho g z \), where \( \rho = 1000 \text{ kg/m}^3 \), \( g = 9.81 \text{ N/kg} \), and \( z \) is the river depth (to be determined). It is stated that \( P_{\text{bottom}} = 4 P_{\text{bank}} = 4 P_{\text{atm}} \). Consequently, \( z = \frac{P_{\text{bottom}} - P_{\text{atm}}}{\rho g} = \frac{3 P_{\text{atm}}}{\rho g} = \frac{3 \times 10^5 \text{ Pa}}{10^3 (\text{kg/m}^3) \times 9.81 (\text{N/kg})} \approx 30.58 \text{ m} \).

(2c) (6p) Oil with a density of 800 kg/m³ is flowing at a velocity of 20 m/s at the atmospheric pressure in a horizontal tube elevated at 20 m above the sea level. Please determine the diameter of the tube if the rate of mechanical energy (KE, PE and flow work) for oil is \( 6 \times 10^4 \text{ J/s} \).

Solution:

Note: The density of oil was changed from 850 to 800 kg/m³. The students who solved this question using density of 850 kg/m³ may copied answers from homework solution in the past years.

For each mass of oil \( m \) transferred through the system, the total mechanical energy reads

\[ E = m \left( \frac{P}{\rho} + gZ + \frac{V^2}{2} \right), \]

such that the equation for the energy rate is given by

\[ \dot{E} = 6 \times 10^4 \text{ J/s} = \dot{m} \left( \frac{P}{\rho} + gZ + \frac{V^2}{2} \right). \] (1)

The mass flow rate

\[ \dot{m} = \rho \dot{V} = \rho V A = \rho V \pi D^2 / 4, \] (2)
where $D$ is the diameter that has to be determined. Combining Eqs (1) and (2), we find

$$
\dot{E} = \left( gZ + \frac{V^2}{2} \right) \rho V \pi D^2 \quad \Rightarrow \quad D = 2 \sqrt[3]{\frac{\dot{E}}{\pi \rho V \left( \frac{P}{\rho} + gZ + \frac{V^2}{2} \right)}} = 
$$

$$
= 2 \sqrt{\frac{6 \times 10^4 \text{J/s}}{3.14 \times 800 \text{ kg/m}^3 \times 20 \text{ m/s} \times \left( \frac{101.3 \text{kPa} \times \frac{1000 \text{Pa}}{\text{kPa}}}{800 \text{ kg/m}^3} + 9.8 \text{ m/s}^2 \times 20 \text{ m} + \frac{1}{2} \times 400 \text{ m}^2 \text{s}^2 \right)}} = 0.0956 \text{ m} = 9.56 \text{ cm}
$$

**Note:** Please double check the density of oil used in this question.

(2d) (6p) Instructor’s house is maintained at a comfortable temperature by means of an electrical resistor heater during winter. The heater is operated at a constant current ($I$) under an applied voltage of 110 V. Please find $I$ if the instructor pays $8.00/day for heating, with the electricity cost of $0.10/kWh. Also, please calculate the heat produced by such a heater hourly. For simplicity, assume that the heater operates uniformly all the time, with 95% of conversion efficiency from the electrical energy to the internal energy of air in the house.

**Note: the instructor paid each day has been revised from $8.4/day to $8.0/day.**

**Solution:** The electrical energy consumption rate in Instructor’s house is given by

$$
\dot{W}_{\text{electric}} = \frac{\$8.00/\text{day}}{\$0.10/\text{kWh}} = 80 \text{kWh/day} = 80 \text{kW} \times \text{hour/24 hours} = 3.333 \text{kW}.
$$

On the other hand, $\dot{W}_{\text{electric}} = I \times U \Rightarrow I = \frac{\dot{W}_{\text{electric}}}{U} = \frac{3.333 \text{kW}}{110 \text{V}} \approx 30.3 \text{ A}.$

The conversion efficiency coefficient relates the heat release and the electrical energy consumption:

$$
\eta_{\text{heater}} = \frac{\text{Benefit}}{\text{Cost}} = \frac{\dot{Q}_{\text{heater}}}{\dot{W}_{\text{electricity}}} \Rightarrow \dot{Q}_{\text{heater}} = \eta_{\text{heater}} \times \dot{W}_{\text{electricity}} = 0.95 \times 3.333 \text{kW} = 3.17 \text{kW}.
$$

Then the hourly heat production is $Q = \dot{Q}_{\text{heater}} \times t = 3.17 \text{kWh} \approx 11.4 \text{ MJ}$ (hourly).
(3) (20 points) An electric fan is used to accelerate the initially quiescent air up to a velocity of 20 m/s with a mass flow rate of 9.6 kg/s. The density of the air is 1.2 kg/m³. The electricity consumption rate is 2.25 kW. The efficiency of the fan in transferring the mechanical work into the kinetic energy of the gas is 87%. Ignoring the change in the potential energy of the gas,

(A) (3p) Draw a schematic diagram of this system showing the conversion of the electrical work to the kinetic energy of the gas.

Solution: The system consists of two major components as illustrated in the schematic below. Specifically, the so-called “motor” converts the electrical power into the mechanical work, which in turn is converted into the kinetic energy of the gas exiting the “fan” itself.

![Schematic Diagram](image)

(B) (3p) Determine the volumetric flow rate of the gas.

Solution: The mass flow rate is coupled to the volumetric flow rate through

\[ \dot{V}_{\text{gas}} = \frac{\dot{m}_{\text{gas}}}{\rho_{\text{gas}}} = \frac{9.6 \text{ kg/s}}{1.2 \text{ kg/m}^3} = 8 \text{ m}^3/\text{s} . \]

(C) (3p) Determine the specific kinetic energy (J/kg) of the gas entering and exiting the fan.

Solution: The gas entering the fan is quiescent; hence its specific kinetic energy is zero. Indeed:

\[ ke_{\text{inlet}} = \frac{1}{2} V_{\text{in}}^2 = \frac{1}{2} (0 \text{ m/s})^2 = 0 \text{ m}^2/\text{s}^2 = 0 \text{ J/kg} . \]

In contrast, for the gas exiting the fan we find

\[ ke_{\text{exit}} = \frac{1}{2} V_{\text{exit}}^2 = \frac{1}{2} (20 \text{ m/s})^2 = 200 \text{ m}^2/\text{s}^2 = 200 \text{ J/kg} . \]

(D) (3p) Determine the rate of kinetic energy (J/s) of the gas exiting the fan.

Solution: The rate of kinetic energy of the gas exiting the fan can be found as a product of the specific kinetic energy and the associated mass flow rate, namely,

\[ KE_{\text{exit}} = \dot{m}_{\text{gas}} \times ke_{\text{exit}} = 9.6 (\text{kg/s}) \times 200 (\text{J/kg}) = 1920 \text{ J/s} = 1.92 \text{ kW} . \]

(E) (4p) Determine the power output of the fan.

Solution: It is stated that the efficiency of the fan in transferring the mechanical work into the kinetic energy of the gas is \( \eta_{\text{fan}} = 87\% \). This means that

\[ \eta_{\text{fan}} = \frac{KE_{\text{exit}}}{W_{\text{fan}}} = 0.87 . \]
Consequently, the power output of the fan is given by
\[ \dot{W}_{\text{fan}} = \frac{\dot{K}E_{\text{exit}}}{0.87} = \frac{1.92 \text{ kW}}{0.87} \approx 2.21 \text{ kW}. \]

(F) (4p) Determine the efficiency of the electrical to mechanical work conversion by the fan.

**Solution:** Similar to (E), the electrical to mechanical work conversion efficiency is given by
\[ \eta_{\text{motor}} = \frac{\dot{W}_{\text{fan}}}{\dot{W}_{\text{electrical}}} = \frac{2.21 \text{ kW}}{2.25 \text{ kW}} = 98\%. \]

**Note:** It is also interesting to determine the total efficiency of the setup:
\[ \eta_{\text{tot}} = \frac{\dot{K}E_{\text{exit}}}{\dot{W}_{\text{electricity}}} = \frac{1.92 \text{ kW}}{2.25 \text{ kW}} \approx 85.3\%. \]

One can readily check that \( \eta_{\text{tot}} \approx \eta_{\text{motor}} \times \eta_{\text{fan}} \). Indeed, \(0.98 \times 0.87 = 0.853\).

(G) the efficiency of the electrical to mechanical work conversion by the fan.
(4) (20 points) A power generator consists of an internal combustion (IC) engine connected to an electricity producer. Specifically, the engine converts the chemical energy of a combustible fuel into the mechanical work which, in turn, is converted to electricity by the producer. Obviously, the engine efficiency is defined as the ratio of the mechanical power to the consumption rate chemical energy; while the producer efficiency is defined as the ratio of the output of electrical power to mechanical power. Please determine

(A) (4p) The power output of the generator if the output current is 30 A at a voltage of 110 V.

Solution: The power output of the is \( \hat{W}_{\text{electricity}} = U \times I = 110V \times 30A = 3300 \text{ W} = 3.3 \text{ kW} \).

(B) (4p) The power output of the IC engine given the efficiency of the generator of 85%.

Solution: \( \eta_{\text{Gen}} = 0.85 = \frac{W_{\text{electricity}}}{W_{\text{engine}}} = \frac{\hat{W}_{\text{electricity}}}{\hat{W}_{\text{engine}}} \Rightarrow \hat{W}_{\text{engine}} = \frac{\hat{W}_{\text{electricity}}}{\eta_{\text{Gen}}} = \frac{3.3 \text{ kW}}{0.85} \approx 3.88 \text{ kW} \).

(C) (3p) The total mechanical work produced by this engine if it operates continuously for 1 year.

Solution: This work is given by the product of the engine power output and the associated time:
\[ W_{\text{engine}} = \hat{W}_{\text{engine}} \times t = 3.88 \text{ kW} \times 1 \text{ year} = 3.88 \text{ kW} \times 365 \text{ (days/year)} \times 24 \text{ (hr/day)} \approx 34 \text{ MWh} \approx 12.2 \times 10^{10} \text{ J} \).

(D) (6p) The total rate of chemical energy consumed (J/s) and the efficiency of the engine when it operates with gasoline and consumes the fuel at a rate of 10 g/min. The specific heat of burning gasoline is \( 4.3 \times 10^7 \text{ J/kg} \).

Solution: The rate of chemical energy consumption is found as the product of the fuel mass flow rate, \( \dot{m}_{\text{gasoline}} = 10 \text{ g/min} \), and the specific heat of burning gasoline, \( e_{\text{gasoline}} = 4.3 \times 10^7 \text{ J/kg} \).

Therefore, \( \dot{E}_{\text{chem}} = \dot{m}_{\text{gasoline}} \times e_{\text{gasoline}} = \frac{0.01 \text{ kg}}{60s} \times 4.3 \times 10^7 \frac{\text{ J}}{\text{ kg}} \approx 7.17 \frac{\text{ kJ}}{\text{ s}} = 7.17 \text{ kW} \).

Then the efficiency of the engine is given by
\[ \eta_{\text{Engine}} = \frac{W_{\text{engine}}}{E_{\text{chem}}} = \frac{\hat{W}_{\text{engine}}}{\dot{E}_{\text{chem}}} = \frac{3.88 \text{ kW}}{7.17 \text{ kW}} \approx 54\% . \)

(E) (3p) The total efficiency of the power generator.

Solution: \( \eta_{\text{PowerGen}} = \frac{W_{\text{electricity}}}{E_{\text{chem}}} = \frac{\hat{W}_{\text{electricity}}}{\dot{E}_{\text{chem}}} = \frac{3.3 \text{ kW}}{7.17 \text{ kW}} \approx 46\% . \)

Alternatively, \( \eta_{\text{PowerGen}} = \frac{\hat{W}_{\text{electricity}}}{\dot{E}_{\text{chem}}} = \frac{\hat{W}_{\text{electricity}}}{W_{\text{engine}}} \times \frac{W_{\text{engine}}}{\dot{E}_{\text{chem}}} = \eta_{\text{Gen}} \times \eta_{\text{Engine}} = 0.85 \times 0.54 \approx 0.46 . \)
5) (20 points) A rigid tank, filled partly with water, is heated by a burner as illustrated in the figure (right). During this process, the system is being stirred by a paddle wheel for mixing of water. The initial internal energy of water was 1000 kJ. The mechanical work transferred into water by the paddle during the heating process is 200 kJ, the heat loss to the surrounding is 500 kJ, and the heat transfer from the burner to water is 1500 kJ. Please

Note: $Q_{out} = 500 \text{ kJ}$ and $W_{in} = 200 \text{ kJ}$ in this question. If student used $Q_{out} = 515 \text{ kJ}$ and/or $W_{in} = 200 \text{ kJ}$, they may have copied the solution from past years.

(A) (4p) List the forms of energy transfer involved in the process.

Solution: Heat transfer and work transfer are involved.

(B) (4p) Is this a closed system or a control volume system? Explain.

Solution: Mass transfer is not involved; hence we deal with a closed system.

(C) (5p) Write down the First Law of Thermodynamics for this system.

Solution: The 1st Law of Thermodynamics is actually a form of the energy balance law. The closed system under the consideration incorporates both heat and work transfer. Consequently, the 1st Law for it yields

$$\Delta E = U_2 - U_1 = Q_{12} - W_{12} = (Q_{in} - Q_{out}) - (W_{out} - W_{in}).$$

In our case, $U_1 = 1000 \text{ kJ}$, $Q_{in} = 1500 \text{ kJ}$, $Q_{out} = 500 \text{ kJ}$, $W_{in} = 200 \text{ kJ}$, $W_{out} = 0$.

(D) (5p) Calculate the final internal energy of water.

Solution: From the equation above we find

$$U_2 = U_1 + (Q_{in} - Q_{out}) - (W_{out} - W_{in}) = 1000 \text{ kJ} + (1500 \text{ kJ} - 500 \text{ kJ}) - (0 \text{ kJ} - 200 \text{ kJ}) = 2200 \text{ kJ}.$$

(6). (20 Points) The issue of global warming is receiving considerable attention these days. Write an essay (no less than 1 page, single-line space, times new roman font, 11 point) with at least three references on the subject of global warming. Explain what is meant by the term global warming and discuss objectively the scientific evidence that is cited as the basis for the argument that global warming is occurring. Determine the respective contributions to the electric power provided to customers by the electric utility serving your locale attributable to coal, natural gas, oil, biomass, nuclear power, wind power and solar power, and summarize your findings in a pie chart. For each type of contribution to the electric power, evaluate its effect on global warming.

Optional Question: # 24, 26, 57, 63, 72 in text book.