Exercises: things engineers think about

1. When you hear the term “energy crisis” used by the news media, do the media really mean exergy crisis? Explain.
2. A convenience store sells gasoline and bottled drinking water at nearly the same price per gallon. Comment.
3. For each case illustrated in Fig. 5.1 (Sec. 5.1), identify the relevant intensive property difference between the system and its surroundings that underlies the potential for work. For cases (a) and (b) discuss whether work could be developed if the particular intensive property value for the system were less than for the surroundings.
4. Is it possible for exergy to be negative? For exergy change to be negative? For exergy destruction to be negative?
5. Do those helium-filled blimps flying over stadiums on game days have exergy? Explain.
6. Does a system consisting of an evacuated space of volume \( V \) have exergy? Explain.
7. When an automobile brakes to rest, what happens to the exergy associated with its motion?
8. A block of ice melts when left in a sunny location. Does its exergy increase or decrease? Explain.
9. When evaluating exergy destruction, is it necessary to use an exergy balance? Explain.
10. Referring to the heat exchanger of Fig. 7.10, if both the hot and cold streams are at temperatures less than \( T_0 \), what form would the energetic efficiency take?
11. Apart from the well-to-wheel efficiency, what other considerations are used to compare different options for powering vehicles?
12. A gasoline-fueled generator is claimed by its inventor to produce electricity at a lower unit cost than the unit cost of the fuel used, where each cost is based on exergy. Comment.

Problems: developing engineering skills

Exploring Energy Concepts

7.1 By inspection of Fig. P7.1 giving a \( T-v \) diagram for water, indicate whether exergy would increase, decrease, or remain the same in (a) Process 1-2, (b) Process 3-4, (c) Process 5-6. Explain.

![Fig. P7.1](image)

7.2 An ideal gas is stored in a closed vessel at pressure \( p \) and temperature \( T \).

(a) If \( T = T_0 \), derive an expression for the specific exergy in terms of \( p, p_0, T_0, \) and the gas constant \( R \).

(b) If \( p = p_0 \), derive an expression for the specific exergy in terms of \( T, T_0, \) and the specific heat \( c_p \), which can be taken as constant.

Ignore the effects of motion and gravity.

7.3 Consider an evacuated tank of volume \( V \). For the space inside the tank as the system, show that the exergy given by \( E = p_0 V \). Discuss.

7.4 Equal molar amounts of carbon dioxide and helium are maintained at the same temperature and pressure. Which has the greater value for exergy relative to the same reference environment? Assume the ideal gas model with constant \( c_v \) for each gas. There are no significant effects of motion and gravity.

7.5 Two solid blocks, each having mass \( m \) and specific heat \( c \), and initially at temperatures \( T_1 \) and \( T_2 \), respectively, are brought into contact, insulated on their outer surfaces, and allowed to come into thermal equilibrium.

(a) Derive an expression for the exergy destruction in terms of \( m, c, T_1, T_2, \) and the temperature of the environment, \( T_0 \).

(b) Demonstrate that the exergy destruction cannot be negative.

(c) What is the source of exergy destruction in this case?

7.6 A system undergoes a refrigeration cycle while receiving \( Q_C \) by heat transfer at temperature \( T_C \) and discharging energy \( Q_H \) by heat transfer at a higher temperature \( T_H \). There are no other heat transfers.

(a) Using energy and exergy balances, show that the net work input to the cycle cannot be zero.

(b) Show that the coefficient of performance of the cycle can be expressed as

\[
\beta = \left( \frac{T_C}{T_H - T_C} \right) \left( 1 - \frac{T_H E_d}{T_B (Q_H - Q_C)} \right)
\]

where \( E_d \) is the exergy destruction and \( T_0 \) is the temperature of the exergy reference environment.

(c) Using the result of part (b), obtain an expression for the maximum theoretical value for the coefficient of performance.
7.7 When matter flows across the boundary of a control volume, an energy transfer by work, called flow work, occurs. The rate is \( \dot{m}(p_0 v) \) where \( \dot{m} \), \( p \), and \( v \) denote the mass flow rate, pressure, and specific volume, respectively, of the matter crossing the boundary (see Sec. 4.4.2). Show that the energy transfer accompanying flow work is given by \( \dot{m}(p_0 \rho_0 v) \), where \( p_0 \) is the pressure at the dead state.

7.8 When matter flows across the boundary of a control volume, an exergy transfer accompanying mass flow occurs, which is given by \( \dot{m} e_s \), where \( e_s \) is the specific exergy (Eq. 7.2) and \( \dot{m} \) is the mass flow rate. An exergy transfer accompanying flow work, which is given by the result of Problem 7.7, also occurs at the boundary. Show that the sum of these exergy transfers is given by \( \dot{m} e_s \), where \( e_s \) is the specific flow exergy (Eq. 7.14).

7.9 For an ideal gas with constant specific heat ratio \( k \), show that in the absence of significant effects of motion and gravity the specific flow exergy can be expressed as

\[
\frac{e_s}{c_p T_0} = \frac{T}{T_0} - 1 - \frac{T}{T_0} \ln \left( \frac{T}{T_0} \right) + \ln \left( \frac{p}{p_0} \right)^{(k-1)/k}
\]

(a) For \( k = 1.2 \) develop plots of \( e_s/c_p T_0 \) versus \( T/T_0 \) for \( p/p_0 = 0.25, 0.5, 1, 2, 4 \). Repeat for \( k = 1.3 \) and 1.4.

(b) The specific flow exergy can take on negative values when \( p/p_0 < 1 \). What does a negative value mean physically?

7.10 An ideal gas with constant specific heat ratio \( k \) enters a turbine operating at steady state at \( T_1 \) and \( p_1 \) and expands adiabatically to \( T_2 \) and \( p_2 \). When would the value of the exergetic turbine efficiency exceed the value of the isentropic turbine efficiency? Discuss. Ignore the effects of motion and gravity.

Evaluating Exergy

7.11 A system consists of 5 kg of water at 10°C and 1 bar. Determine the exergy, in kJ, if the system is at rest and zero elevation relative to an exergy reference environment for which \( T_0 = 20°C \), \( p_0 = 1 \) bar.

7.12 Determine the exergy, in kJ, at 0.7 bar, 90°C for 1 kg of (a) water, (b) Refrigerant 134a, (c) air as an ideal gas with \( c_p \) constant. In each case, the mass is at rest and zero evaluation relative to an exergy reference environment for which \( T_0 = 20°C \), \( p_0 = 1 \) bar.

7.13 Determine the specific exergy, in kJ/kg, at 0.01°C of water as a (a) saturated vapor, (b) saturated liquid, (c) saturated solid. In each case, consider a fixed mass at rest and zero elevation relative to an exergy reference environment for which \( T_0 = 20°C \), \( p_0 = 1 \) bar.

7.14 Determine the specific exergy, in Btu, of one pound mass of (a) saturated water vapor at 212°F, (b) saturated liquid water at 40°F. (c) ammonia at −40°F, 6 lb/ft². In each case, consider a fixed mass at rest and zero elevation relative to an exergy reference environment for which \( T_0 = 70°F \), \( p_0 = 14.7 \) lb/ft².

7.15 A balloon filled with helium at 20°C, 1 bar and a volume of 0.5 m³ is moving with a velocity of 15 m/s at an elevation of 0.5 km relative to an exergy reference environment for which \( T_0 = 20°C \), \( p_0 = 1 \) bar. Using the ideal gas model, determine the specific exergy of the helium, in kJ.

7.16 A vessel contains carbon dioxide. Using the ideal gas model (a) determine the specific exergy of the gas, in Btu/lb, at \( p = 90 \) lb/ft² and \( T = 200°F \). (b) plot the specific exergy of the gas, in Btu/lb, versus pressure ranging from 15 to 90 lb/ft², for \( T = 80°F \). (c) plot the specific exergy of the gas, in Btu/lb, versus temperature ranging from 80 to 200°F, for \( p = 15 \) lb/ft².

The gas is at rest and zero elevation relative to an exergy reference environment for which \( T_0 = 80°F \), \( p_0 = 15 \) lb/ft².

7.17 Oxygen \((O_2)\) at temperature \( T \) and 1 atm fills a balloon at rest on the surface of the earth at a location where the ambient temperature is 40°F and the ambient pressure is 1 atm. Using the ideal gas model with \( c_p = 0.22 \) Btu/lb°F, plot the specific exergy of the oxygen, in Btu/lb, relative to the earth and its atmosphere at this location versus \( T \) ranging from 500 to 600°F.

7.18 A vessel contains 1 lb of air at pressure \( p \) and 200°F. Using the ideal gas model, plot the specific exergy of the air, in Btu/lb, for \( p \) ranging from 0.5 to 2 atm. The air is at rest and negligible elevation relative to an exergy reference environment for which \( T_0 = 60°F \), \( p_0 = 1 \) atm.

7.19 Determine the specific exergy, in kJ/kg, at 0.6 bar, −10°C of (a) ammonia, (b) Refrigerant 22, (c) Refrigerant 134a. Let \( T_0 = 0°C \), \( p_0 = 1 \) bar and ignore the effects of motion and gravity.

7.20 Consider a two-phase solid–vapor mixture of water at −10°C. Each phase present has the same mass. Determine the specific exergy, in kJ/kg, if \( T_0 = 20°C \), \( p_0 = 1 \) atm, and there are no significant effects of motion or gravity.

7.21 Determine the exergy, in kJ, of the contents of a 2-m³ storage tank, if the tank is filled with (a) air as an ideal gas at 400°C and 0.35 bar, (b) water vapor at 400°C and 0.35 bar. Ignore the effects of motion and gravity and let \( T_0 = 17°C \), \( p_0 = 1 \) atm.

7.22 Refrigerant 134a vapor initially at 1 bar and 20°C fills a rigid vessel. The vapor is cooled until the temperature becomes −32°C. There is no work during the process. For the refrigerant, determine the heat transfer per unit mass and the change in specific exergy, each in kJ/kg. Comment. Let \( T_0 = 20°C \), \( p_0 = 0.1 \) MPa and ignore the effects of motion and gravity.

7.23 As shown in Fig. P7.23, two kilograms of water undergo a process from an initial state where the water is saturated vapor at 120°F, the velocity is 30 m/s, and the elevation is 6 m to a final state where the water is saturated liquid at 10°C, the velocity is 25 m/s, and the elevation is 3 m. Determine in kJ, (a) the exergy at the initial state, (b) the exergy at the final state, and (c) the change in exergy. Let \( T_0 = 25°C \), \( p_0 = 1 \) atm, and \( g = 9.8 \) m/s².

7.24 Two pounds of air initially at 200°F and 50 lb/ft² undergo two processes in series:

Process 1–2: Isothermal to \( p_2 = 10 \) lb/ft²

Process 2–3: Constant pressure to \( T_3 = −10°F \)
(c) the change in exergy of the ammonia.
(d) the amount of exergy destruction.

Ignore the effects of motion and gravity and let \( T_0 = 60^\circ\text{F}, p_0 = 1\ \text{atm}. \)

**Fig. P7.31**

7.36 As shown in Fig. P7.36, a 0.8-lb metal bar initially at 1900°F is removed from an oven and quenched by immersing it in a closed tank containing 20 lb of water initially at 530°F. Each substance can be modeled as incompressible. An appropriate constant specific heat for the water is \( c_w = 1.0\ \text{Btu/lb} \cdot \text{°F}, \) and an appropriate value for the metal is \( c_m = 0.1\ \text{Btu/lb} \cdot \text{°F}. \) Heat transfer from the tank contents can be neglected. Determine the exergy destruction, in Btu. Let \( T_0 = 77^\circ\text{F}. \)

**Fig. P7.36**

7.32 One pound of air is contained in a closed, rigid, insulated tank. Initially the temperature is 500°F and the pressure is 1 atm. The air is stirred by a paddle wheel until its temperature is 700°F. Using the ideal gas model, determine for the air the change in exergy, the transfer of exergy accompanying work, and the exergy destruction, all in Btu. Ignore the effects of motion and gravity and let \( T_0 = 500^\circ\text{F}, p_0 = 1\ \text{atm}. \)

7.33 One kilogram of helium initially at 20°C and 1 bar is contained within a rigid, insulated tank. The helium is stirred by a paddle wheel until its pressure is 1.45 bar. Employing the ideal gas model with \( k = 1.67, \) determine the work and the exergy destruction for the helium, each in kJ. Ignore the effects of motion and gravity and let \( T_0 = 20^\circ\text{C}, p_0 = 1\ \text{bar}. \)

7.34 One lb mol of carbon dioxide gas is contained in a 100-ft³ rigid, insulated vessel initially at 4 atm. An electric resistor of negligible mass transfers energy to the gas at a constant rate of 12 Btu/s for 1 min. Employing the ideal gas model and ignoring the effects of motion and gravity, determine (a) the change in exergy of the gas, (b) the electrical work, and (c) the exergy destruction, each in Btu. Let \( T_0 = 70^\circ\text{F}, p_0 = 1\ \text{atm}. \)

7.35 A rigid, well-insulated tank consists of two compartments, each having the same volume, separated by a valve. Initially, one of the compartments is evacuated and the other contains 0.25 lb mol of nitrogen gas at 50 lb/in² and 100°F. The valve is opened and the gas expands to fill the total volume, eventually achieving an equilibrium state. Using the ideal gas model for the nitrogen
(a) determine the final temperature, in °F, and final pressure, in lb/in².
(b) evaluate the exergy destruction, in Btu.
(c) What is the cause of exergy destruction in this case?
Let \( T_0 = 70^\circ\text{F}, p_0 = 1\ \text{atm}. \)

7.37 Figure P7.37 provides steady-state data for a composite of a hot plate and two solid layers. Perform a full exergy accounting, in kW, of the electrical power provided to the composite, including the exergy transfer accompanying heat transfer from the composite and the destruction of exergy in the hot plate and each of the two layers. Let \( T_0 = 300\ \text{K}. \)

**Fig. P7.37**

7.38 As shown in Fig. P7.38, heat transfer at a rate of 500 Btu/h takes place through the inner surface of a wall. Measurements made during steady-state operation reveal temperatures of \( T_1 = 2500^\circ\text{F}, T_2 = 1000^\circ\text{F} \) at the inner and outer surfaces, respectively. Determine, in Btu/h
(a) the rates of exergy transfer accompanying heat at the inner and outer surfaces of the wall.
(b) the rate of exergy destruction.
(c) What is the cause of exergy destruction in this case?
Let \( T_0 = 500^\circ\text{R}. \)
7.39 Figure P7.39 provides steady-state data for the outer wall of a dwelling on a day when the indoor temperature is maintained at 20°C and the outdoor temperature is 0°C. The heat transfer rate through the wall is 1100 W. Determine, in W, the rate of exergy destruction (a) within the wall, and (b) within the enlarged system shown on the figure by the dashed line. Comment. Let $T_0 = 0°C$.

7.40 A gearbox operating at steady state receives 2 hp along the input shaft and delivers 1.89 hp along the output shaft. The outer surface of the gearbox is at 110°F. For the gearbox, (a) determine, in Btu/s, the rate of heat transfer and (b) perform a full exergy accounting, in Btu/h, of the input power. Let $T_0 = 70°F$.

7.41 A gearbox operating at steady state receives 20 horsepower along its input shaft, delivers power along its output shaft, and is cooled on its outer surface according to $hA(T_b - T_0)$, where $T_b = 110°F$ is the temperature of the outer surface and $T_0 = 40°F$ is the temperature of the surroundings far from the gearbox. The product of the heat transfer coefficient $h$ and outer surface area $A$ is 35 Btu/h · R. For the gearbox, determine, in hp, a full exergy accounting of the input power. Let $T_0 = 40°F$.

7.42 At steady state, an electric motor develops power along its output shaft of 0.5 hp while drawing 4 amps at 120 V. The outer surface of the motor is at 120°F. For the motor, (a) determine, in Btu/h, the rate of heat transfer and (b) perform a full exergy accounting, in Btu/h, of the electrical power input. Let $T_0 = 60°F$.

7.43 For the curling iron of Problem 6.55, perform a full exergy accounting, in Btu/h, of the electrical power supplied. Let $T_0 = 70°F$.

7.44 As shown in Fig. P7.44, a silicon chip measuring 5 mm on a side and 1 mm in thickness is embedded in a ceramic substrate. At steady state, the chip has an electrical power input of 0.225 W. The top surface of the chip is exposed to a coolant whose temperature is 20°C. The heat transfer coefficient for convection between the chip and the coolant is 150 W/m² · K. Heat transfer by conduction between the chip and the substrate is negligible. Determine (a) the surface temperature of the chip, in °C, and (b) the rate of exergy destruction within the chip, in W. What causes the exergy destruction in this case? Let $T_0 = 293 K$.

7.45 An electric water heater having a 200 liter capacity heats water from 23 to 55°C. Heat transfer from the outside of the water heater is negligible, and the states of the electrical heating element and the tank holding the water do not change significantly. Perform a full exergy accounting, in kJ, of the electricity supplied to the water heater. Model the water as incompressible with a specific heat $c = 4.18$ kJ/kg · K. Let $T_0 = 23°C$. 

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**Fig. P7.38**

**Fig. P7.44**

**Fig. P7.39**
accounting in kW, based on the compressor power input and comment.

**7.92** Refrigerant 134a enters a water-jacketed compressor operating at steady state at 10°C, 3.2 bar and exits at 70°C, 10 bar. Cooling water enters as a separate stream at 20°C and exits at 32°C with no significant change in pressure. The refrigerant mass flow rate is 1.63 kg/s, and the power input to the compressor is 55.2 kJ per kg of refrigerant flowing. Assuming no heat transfer between the outer surface of the water jacket and the surroundings, and neglecting the effects of motion and gravity

(a) determine the mass flow rate of cooling water, in kg/s, and
(b) perform a full exergy accounting, in kW, based on the compressor power input and comment.

Let \( T_0 = 20^\circ\text{C}, p_0 = 1 \text{ bar}. \)

**7.93** For the compressor and heat exchanger of Problem 6.114, perform a full exergy accounting, in kW, based on the compressor power input. Let \( T_0 = 300 \text{ K}, p_0 = 96 \text{ kPa}. \)

**7.94** Figure P7.94 shows liquid water at 80 lb/in.\(^2\), 300°F entering a flash chamber through a valve at the rate of 22 lbs. At the valve exit, the pressure is 42 lb/in.\(^2\). Saturated liquid at 40 lb/in.\(^2\) exits from the bottom of the flash chamber and saturated vapor at 40 lb/in.\(^2\) exits from the top. The vapor stream is led to a steam turbine having an isentropic efficiency of 90% and an exit pressure of 2 lb/in.\(^2\). For steady-state operation, negligible heat transfer with the surroundings, and no significant effects of motion and gravity, perform a full exergy accounting, in Btu/s, of the net rate at which exergy is supplied: \( (E_{11} - E_{13} - E_{13}). \) Let \( T_0 = 500^\circ\text{R}, p_0 = 1 \text{ atm}. \)

**Fig. P7.94**

**7.95** Figure P7.95 provides steady-state operating data for a throttling valve in parallel with a steam turbine having an isentropic turbine efficiency of 90%. The streams exiting the valve and the turbine mix in a mixing chamber. Heat transfer with the surroundings and the effects of motion and gravity can be neglected. Determine

(a) the power developed by the turbine, in Btu/s.
(b) the mass flow rates through the turbine and valve, each in lbm.
(c) a full exergy accounting, in Btu/s, of the net rate at which exergy is supplied: \( (E_{11} - E_{13} - E_{13}). \)

Let \( T_0 = 500^\circ\text{R}, p_0 = 1 \text{ atm}. \)

**Fig. P7.95**

**Using Exergetic Efficiencies**

**7.96** For the water heater of Problem 7.45, devise and evaluate an exergetic efficiency.

**7.97** Plot the exergetic efficiency given by Eq. 7.21b versus \( T_0/T_0 \) for \( T_0/T_0 \) of 7.0 and \( \eta = 0.4, 0.6, 0.8, 1.0. \) What can be learned from the plot when \( T_0/T_0 \) is fixed? When \( \eta \) is fixed? Discuss.

**7.98** From an input of electricity, an electric resistance furnace operating at steady state delivers energy by heat transfer to a process at the rate \( Q_0 \) at a use temperature \( T_0 \). There are no other significant energy transfers.

(a) Devise an exergetic efficiency for the furnace.
(b) Plot the efficiency obtained in part (a) versus the use temperature ranging from 300 to 900 K. Let \( T_0 = 20^\circ\text{C}. \)

**7.99** Steam enters a turbine operating at steady state at \( p_1 = 12 \text{ MPa}, T_1 = 700^\circ\text{C} \) and exits at \( p_2 = 0.6 \text{ MPa}. \) The isentropic turbine efficiency is 88%. Property data are provided in the accompanying table. Stray heat transfer and the effects of motion and gravity are negligible. Let \( T_0 = 300 \text{ K}, p_0 = 100 \text{ kPa}. \) Determine (a) the power developed and the rate of exergy destruction, each in kJ per kg of steam flowing, and (b) the exergetic turbine efficiency.

<table>
<thead>
<tr>
<th>State</th>
<th>( p ) (MPa)</th>
<th>( T ) (°C)</th>
<th>( h ) (kJ/kg)</th>
<th>( s ) (kJ/kg · K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine inlet</td>
<td>12</td>
<td>700</td>
<td>3858.4</td>
<td>7.0749</td>
</tr>
<tr>
<td>Turbine exit</td>
<td>0.6 ( (\eta = 88%) )</td>
<td>3017.5</td>
<td>7.2938</td>
<td></td>
</tr>
</tbody>
</table>

**7.100** Saturated liquid water at 0.01 MPa enters a power plant pump operating at a steady state. Liquid water exits the pump at 10 MPa. The isentropic pump efficiency is 90%. Property data are provided in the accompanying table. Stray heat transfer and the effects of motion and gravity are negligible. Let \( T_0 = 300 \text{ K}, p_0 = 100 \text{ kPa}. \) Determine (a) the power required by the pump and the rate of exergy destruction, each in kJ per kg of water flowing, and (b) the exergetic pump efficiency.

<table>
<thead>
<tr>
<th>State</th>
<th>( p ) (MPa)</th>
<th>( h ) (kJ/kg)</th>
<th>( s ) (kJ/kg · K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump inlet</td>
<td>0.01</td>
<td>191.8</td>
<td>0.6493</td>
</tr>
<tr>
<td>Pump exit</td>
<td>10</td>
<td>204.5</td>
<td>0.6531</td>
</tr>
</tbody>
</table>
7.101 At steady state, an insulated steam turbine develops work at a rate of 338 Btu per lb of steam flowing through the turbine. Steam enters at 800 lbf/in.² and 1000°F and exits at 14.7 lbf/in.². Evaluate the isentropic turbine efficiency and the exergetic turbine efficiency. Ignore the effects of motion and gravity. Let $T_0 = 60^\circ\text{F}$, $p_0 = 14.7$ lbf/in.².

7.102 Hydrogen at 25 bar, 450°C enters a turbine and expands to 2 bar, 160°C with a mass flow rate of 0.2 kg/s. The turbine operates at steady state with negligible heat transfer with its surroundings. Assuming the ideal gas model with $k = 1.37$ and ignoring the effects of motion and gravity, determine

(a) the isentropic turbine efficiency.
(b) the exergetic turbine efficiency.

Let $T_0 = 25^\circ\text{C}$, $p_0 = 1$ atm.

7.103 Steam enters a turbine operating at steady state at 5 MPa, 600°C and exits at 50 kPa. Stray heat transfer and the effects of motion and gravity can be ignored. If the rate of exergy destruction is 95.4 kJ per kg of steam flowing, determine (a) the isentropic turbine efficiency and (b) the exergetic turbine efficiency. Let $T_0 = 293$ K, $p_0 = 1$ bar.

7.104 Air enters an insulated turbine operating at steady state with a pressure of 4 bar, a temperature of 450 K, and a volumetric flow rate of 5 m³/s. At the exit, the pressure is 1 bar. The isentropic turbine efficiency is 84%. Assuming the ideal gas model and ignoring the effects of motion and gravity, determine

(a) the power developed and the exergy destruction rate, each in kW.
(b) the exergetic turbine efficiency.

Let $T_0 = 20^\circ\text{C}$, $p_0 = 1$ bar.

7.105 Steam at 200 lbf/in.², 660°F enters a turbine operating at steady state with a mass flow rate of 16.5 lb/min and exits at 14.7 lbf/in.², 238°F. Stray heat transfer and the effects of motion and gravity can be ignored. Let $T_0 = 537^\circ\text{R}$, $p_0 = 14.7$ lbf/in.². Determine for the turbine (a) the power developed and the rate of exergy destruction, each in Btu/min, and (b) the isentropic and exergetic turbine efficiencies.

7.106 Figure P7.106 shows a turbine operating at steady state with steam entering at $p_1 = 30$ bar, $T_1 = 350^\circ\text{C}$ and a mass flow rate of 30 kg/s. Process steam is extracted at $p_3 = 5$ bar, $T_2 = 200^\circ\text{C}$. The remaining steam exits at $p_2 = 0.15$ bar, $x = 90\%$, and a mass flow rate of 25 kg/s. Stray heat transfer and the effects of motion and gravity are negligible. Let $T_0 = 25^\circ\text{C}$, $p_0 = 1$ bar. The accompanying table provides property data at key states. For the turbine, determine the power developed and rate of exergy destruction, each in MW. Also devise and evaluate an exergetic efficiency for the turbine.

<table>
<thead>
<tr>
<th>State</th>
<th>$p$ (bar)</th>
<th>$T$ (°C)</th>
<th>$h$ (kJ/kg)</th>
<th>$s$ (kJ/kg · K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>350</td>
<td>3115.3</td>
<td>6.7428</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>200</td>
<td>2855.4</td>
<td>7.0992</td>
</tr>
<tr>
<td>3</td>
<td>0.15 (x = 90%)</td>
<td></td>
<td>2361.7</td>
<td>7.2831</td>
</tr>
</tbody>
</table>

7.107 For the turbine and heat exchanger arrangement of Problem 6.116, evaluate an exergetic efficiency for (a) each turbine, (b) the heat exchanger, and (c) an overall control volume enclosing the turbines and heat exchanger. Comment. Let $T_0 = 300$ K, $p_0 = 1$ bar.

7.108 Determine the exergetic efficiency for the turbine of
(a) Problem 6.130. Let $T_0 = 300$ K.
(b) Problem 6.131. Let $T_0 = 500^\circ\text{R}$.
(c) Problem 6.132. Let $T_0 = 295$ K.
(d) Problem 6.133. Let $T_0 = 530^\circ\text{R}$.

7.109 Steam at 400 lbf/in.², 600°F enters a well-insulated turbine operating at steady state and exits as saturated vapor at a pressure $p$.

(a) For $p = 50$ lbf/in.², determine the exergy destruction rate, in Btu per lb of steam expanding through the turbine, and the turbine exergetic and isentropic efficiencies.
(b) Plot the exergy destruction rate, in Btu per lb of steam flowing, and the exergetic efficiency and isentropic efficiency, each versus pressure $p$ ranging from 1 to 50 lbf/in.².

Ignore the effects of motion and gravity and let $T_0 = 60^\circ\text{F}$, $p_0 = 1$ atm.

7.110 Saturated water vapor at 400 lbf/in.² enters an insulated turbine operating at steady state. A two-phase liquid–vapor mixture exits at 0.6 lbf/in.². Plot each of the following versus the steam quality at the turbine exit ranging from 75 to 100%

(a) the power developed and the rate of exergy destruction, each in Btu per lb of steam flowing.
(b) the isentropic turbine efficiency.
(c) the exergetic turbine efficiency.

Let $T_0 = 60^\circ\text{F}$, $p_0 = 1$ atm. Ignore the effects of motion and gravity.

7.111 Argon enters an insulated turbine operating at steady state at 1000°C and 2 MPa and exhausts at 350 kPa. The mass flow rate is 0.5 kg/s. Plot each of the following versus the turbine exit temperature, in °C

(a) the power developed, in kW.
(b) the rate of exergy destruction in the turbine, in kW.
(c) the exergetic turbine efficiency.

For argon, use the ideal gas model with $k = 1.67$. Ignore the effects of motion and gravity. Let $T_0 = 20°C$, $p_0 = 1$ bar.

7.112 An insulated steam turbine at steady state can be operated at part-load conditions by throttling the steam to a lower pressure before it enters the turbine. Before throttling, the steam is at 200 lbf/in.², 600°F. After throttling, the