

11 Thermodynamics

Robert Michel

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This chapter reviews the basic knowledge and working tools required to pass the thermodynamics portion of the Fundamentals of Engineering (FE/EIT) exam. It excludes areas of thermodynamics not normally included on the exam.

Typical solved problems are grouped at the end of this chapter and are referred to in the text section of the review material.

FIRST LAW OF THERMODYNAMICS

Except for nuclear physics, involving the conversion of mass into energy, mass is conserved in a process. In thermodynamics, the mass in a closed system (such as a piston-cylinder) is constant. In an open system, where mass is flowing in and out, the sum of the mass flowing into the system equals the mass flowing out if there is no accumulation of mass within the system. This is called conservation of mass.

Energy is also conserved and must be accounted for. The types of energy that are important in thermodynamics are the following:

- Internal energy
- Flow energy
- Kinetic energy
- Potential energy
- Heat
- Work

The first four energy types are a function of the state or condition of the substance. Heat and work are forms of energy which cross the boundary of systems and are not a function of the state

The first law of thermodynamics is a bookkeeping system to keep track of these energies

Closed System

For a typical closed thermodynamic system (Fig. 11-1), the kinetic and potential energy are not important, and since there is no flow, the bookkeeping is simple and reduces to

$$u_1 + q = u_2 + w \quad \Delta E = Q - W = \Delta U + \Delta KE + \Delta PE$$

Open System

For an open system (Fig. 11-2), the bookkeeping system yields

$$u_1 + p_1 v_1 + \frac{V_1^2}{2g_c} + Z_1 g/g_c + q = u_2 + p_2 v_2 + \frac{V_2^2}{2g_c} + Z_2 g/g_c + w$$

In many common open-system processes, the kinetic energy ($V^2/2g_c$) and the potential energy (Zg/g_c) are not important. For convenience, u and pv are combined into h (enthalpy), and the equation then reduces to

$$h_1 + q = h_2 + w$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W}_s + \dot{m}(h_{in} - h_{out}) + \dot{m}(KE_{in} - KE_{out}) \dots$$

Thermodynamics

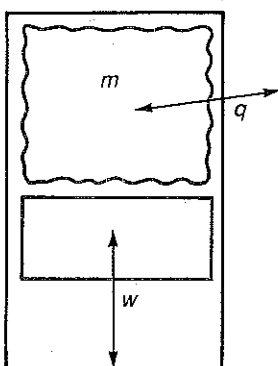


Fig. 11-1

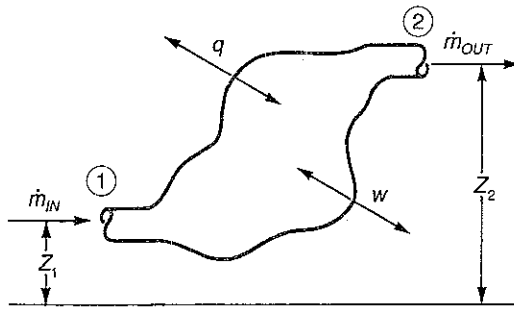


Fig 11-2

The thermodynamic sign convention for heat and work is that q_{in} is positive and w_{out} is positive. This is the normal flow of heat and work in an engine or power plant.

Care must be taken to keep the units consistent. For example, the normal units for internal energy, heat and work are kJ/kg or BTU/lbm. In the S I. system, $V^2/2g_c$ and Zg/g_c must be divided by 1000—in the U S. system by 778. Remember that g_c in the S I system has a value of 1 but is 32.2 in the U.S. system.

The first law is the most popular one by far in solving thermodynamics problems!

Example 1

A piston-cylinder contains 5 kg of air. During a compression process 100 kJ of heat is removed while 250 kJ of work is done on the air. Find the change in internal energy of the air.

Solution

The system is a closed system since the mass is fixed. So

$$u_1 + q = u_2 + w$$

Here, $q = -100$ kJ, since heat leaving a system is negative, and $w = -250$ kJ, since work done on a system is negative. Thus

$$u_2 - u_1 = -100 - (-250) = 150 \text{ kJ, or } \frac{150}{5} = 30 \text{ kJ/kg}$$

Example 2

Heated air enters a turbine at a flow rate of 5 kg/s. The entering and leaving conditions are shown in the table below. The heat loss from the turbine is 50 kW. Find the power produced.

	Inlet	Exit
Pressure, kPa	1000	100
Temperature, °K	800	500
Velocity, m/s	100	200
Specific internal energy, kJ/kg	137	85
Specific volume, m ³ /kg	0.23	1.44
Elevation, m	3	10



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Solution

The system has mass flowing across the boundaries so it is an open system

$$\begin{aligned}u_1 + p_1 v_1 + \frac{Z_1 g}{g_c} + \frac{V_1^2}{2g_c} + q &= u_2 + p_2 v_2 + \frac{Z_2 g}{g_c} + \frac{V_2^2}{2g_c} + w \\w &= (u_1 - u_2) + (p_1 v_1 - p_2 v_2) + \frac{(Z_1 - Z_2)g}{g_c} + \frac{V_1^2 - V_2^2}{2g_c} + q \\&= (137 - 85) + (1000 \times 0.23 - 100 \times 1.44) + \frac{(3 - 10) \times 9.81}{1000} + \frac{100^2 - 200^2}{2 \times 1 \times 1000} \\&= 52 + 86 - 0.069 - 15 = 122.9 \frac{\text{kJ}}{\text{kg}}\end{aligned}$$

$$\dot{w} = w \times \dot{m} = 122.9 \times 5 = 615 \text{ kW}$$

PROPERTIES OF PURE SUBSTANCES

Use of Steam Tables

Property tables for substances that go through a phase change during normal thermodynamic processes, such as H₂O, R-12 and NH₃, are divided into three groups:

- **Saturated Tables.** These show the properties (v , u , h , s) of the saturated liquid and saturated vapor. For convenience, there are usually two sets; one using T as the entering argument and one using P . The highest temperature/pressure entry is usually the critical point. The quality x is needed to define properties in the mixture region.
- **Superheated Tables.** These show the properties (v , u , h , s) as a function of T and P in the superheated area to the right of the saturated vapor curve and are usually grouped by pressure. Any two properties (v , u , h , s , T , P) may be used to define the state. The saturated state is usually noted. At moderate pressures and temperatures well away from saturation, perfect gas relationships may be used as an approximation.
- **Subcooled or Compressed Liquid Tables.** These tables show properties (v , u , h , and s) as a function of T and P in the area to the left of the saturated liquid curve and are usually grouped by pressure. As with the Superheated Tables, any two properties may be used to define the state, and the saturated state is usually noted. For points in the region that are below the tabulated pressures, the properties are approximated as those of the saturated liquid at the same temperature (v , u , h and s are weak functions of pressure).

The procedure for finding the state-point properties for given data where the condition of the substances is not defined is best done in a structured manner:

1. Always look at the saturation tables first to determine whether the state point is liquid, vapor, or "wet" (Fig. 11-3).

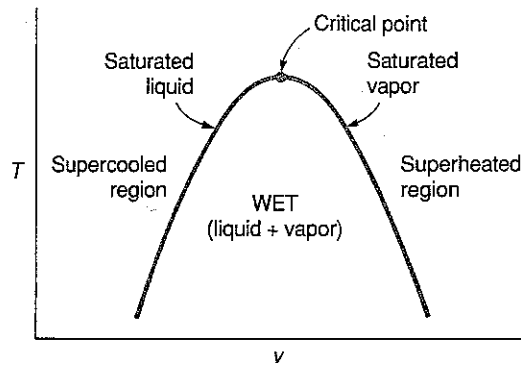


Fig 11-3

2. When one is given T or P and h , v , or u ,
 - a. If h , v , or u are between f and g , the point is in the wet region (inside the dome). Calculate the quality x using saturation properties and given properties. For example,

$$x = \frac{u - u_f}{u_{fg}}$$

- b. If h , v , or u are greater than the saturated-vapor value, the point is in the superheated region. Locate the properties in the superheated tables.
- c. If h , v , or u are less than the saturated-liquid value, the point is in the subcooled liquid region. Locate the properties in the liquid tables and/or calculate from the saturated-liquid properties.

3. Given T or P and x ,

Go directly to the saturated tables since an intermediate value of x implies it is in the "wet" region.

4. Given T and P ,

Compare the saturation temperature with the given temperature. The saturation temperature is read at the given pressure.

If T is greater than T_{sat} , the point is superheated vapor.

If T is less than T_{sat} , the point is subcooled liquid.

Example 3

Fill in the following table for steam (water) using the extracted tabulations as well as the Mollier chart where it is applicable

	$T, ^\circ\text{C}$	P, kPa	$x, \%$	$h, \text{kJ/kg}$	$u, \text{kJ/kg}$	$v, \text{m}^3/\text{kg}$
a)	200	—	—	852.45	—	—
b)	—	150	—	—	1000	—
c)	300	800	—	—	—	—
d)	200	5000	—	—	—	—
e)	—	300	—	—	—	0.85
f)	300	—	80	—	—	—
g)	—	1000	90	—	—	—

Properties of Saturated Water (SI units): Temperature Table

$v, \text{cm}^3/\text{g}; u, \text{kJ/kg}; h, \text{kJ/kg}; s, \text{kJ}/(\text{kg})(^\circ\text{K})$

Temp., $^\circ\text{C}$ T	Press., bars P	Specific volume		Internal energy		Enthalpy		Entropy		
		Sat liquid v_f	Sat vapor v_g	Sat liquid u_f	Sat vapor u_g	Sat liquid h_f	Evap h_{fg}	Sat vapor h_g	Sat liquid s_f	Sat vapor s_g
110	1.433	1.0516	1210	461.14	2518.1	461.30	2230.2	2691.5	1.4185	7.2387
120	1.985	1.0603	891.9	503.50	2529.3	503.71	2202.6	2706.3	1.5276	7.1296
170	7.917	1.1143	242.8	718.33	2576.5	719.21	2049.5	2768.7	2.0419	6.6663
180	10.02	1.1274	194.1	762.09	2583.7	763.22	2015.0	2778.2	2.1396	6.5857
200	15.54	1.1565	127.4	850.65	2595.3	852.45	1940.7	2793.2	2.3309	6.4323
300	85.81	1.4036	21.67	1332.0	2563.0	1344.0	1404.9	2749.0	3.2534	5.7045

Thermodynamics

Properties of Saturated Water (SI units): Pressure Table

$v, \text{ft}^3/\text{lb}; u \text{ and } h, \text{BTU}/\text{lb}; s, \text{BTU}/(\text{lb})(^\circ\text{R})$

Press bars P	Temp $^\circ\text{C}$ T	Specific volume		Internal energy		Enthalpy		Entropy		
		Sat liquid v_f	Sat vapor v_g	Sat liquid u_f	Sat vapor u_g	Sat liquid h_f	Evap. h_{fg}	Sat vapor h_g	Sat liquid s_f	Sat vapor s_g
10.0	179.9	1.1273	194.4	761.68	2583.6	762.81	2015.3	2778.1	2.1387	6.5863

Properties of Water (SI units): Superheated-vapor Table

$v, \text{cm}^3/\text{g}; u, \text{kJ/kg}; h, \text{kJ/kg}; s, \text{kJ}/(\text{kg})(^\circ\text{K})$

Temp, $^\circ\text{C}$	v	u	h	s	v	u	h	s
5.0 bars (0.50 MPa) ($T_{\text{sat}} = 151.86^\circ\text{C}$)				7.0 bars (0.70 MPa) ($T_{\text{sat}} = 164.97^\circ\text{C}$)				
280	503.4	2771.2	3022.9	7.3865	357.4	2766.9	3017.1	7.2233
320	541.6	2834.7	3105.6	7.5308	385.2	2831.3	3100.9	7.3697
10.0 bars (01.0 MPa) ($T_{\text{sat}} = 179.91^\circ\text{C}$)								
280	248.0	2760.2	3008.2	7.0465				
320	267.8	2826.1	3093.9	7.1962				

Properties of Water (SI units): Superheated-vapor Table

$v, \text{cm}^3/\text{g}; u, \text{kJ}/\text{kg}; h, \text{kJ}/\text{kg}; s, \text{kJ}/(\text{kg})(^\circ\text{K})$								
Temp, $^\circ\text{C}$	v	u	h	s	v	u	h	s
1.5 bars (0.15 MPa) ($T_{\text{sat}} = 111.37^\circ\text{C}$)				3.0 bars (0.30 MPa) ($T_{\text{sat}} = 133.55^\circ\text{C}$)				
280	1695	2778.6	3032.8	7.9555	844	2775.4	3028.6	7.6299
320	1819	2840.6	3113.5	8.0964	907	2838.1	3110.1	7.7722

Solution

See the explanations in the list below the table

	$T, ^\circ\text{C}$	P, kPa	$x, \%$	$h, \text{kJ}/\text{kg}$	$u, \text{kJ}/\text{kg}$	$v, \text{m}^3/\text{kg}$
a)	200	1153.8	0	852.45	857.8	0.0012
b)	111.37	150	0.26	1045	1000	0.3018
c)	300	800	—	3056.5*	2797.2	0.3241
d)	200	5000	—	853.9	848.1	0.00012
e)	283.8*	300	—	3036.4*	2781.5	0.85
f)	300	8581	80	2467.9	2316.8	0.0176
g)	179.9	1000	90	2576.6	2401.5	0.1751

*Note that these values may be found also in the Mollier diagram

- This state falls directly on the saturated liquid line.
- The given value for internal energy falls between u_f and u_g , so the state is inside the vapor dome. Calculate x and use x to find h and v .
- The temperature of 300°C is higher than $T_{\text{sat}} = 170.4^\circ\text{C}$, so the state is superheated.
- The temperature of 200°C is less than $T_{\text{sat}} = 264^\circ\text{C}$, so the state is subcooled. Find the properties in the saturation tables for subcooled liquid at 200°C (good approximation)
- The specific volume is greater than $v_g = 0.6058$ at the saturation pressure of 300 kPa , so it is superheated.
- A quality value (x) is specified, so the state is obviously in the vapor dome. Use x to find h , u , and v .
- Same as line f.

Mollier Diagram

The Mollier chart shows a small but useful part of the steam tables in graphical form. It shows selected properties (h , s , T , P , and x) in the area where steam turbines operate, that is, superheated vapor and “wet” areas of high quality. The skeleton Mollier diagram (Fig. 11-4) shows the trend of property lines, and Fig. 11-A shows a representative Mollier diagram in S.I. units. A typical use of the diagram is to evaluate turbine expansion—the ideal (isentropic) change in enthalpy across the turbine. The turbine inlet T and P are usually specified, and they locate the point in the superheated region (Point 1 in the illustration for Example 4). The ideal expansion ($s = \text{constant}$) is taken to the specified turbine discharge pressure (Point 2 in Example 4). The turbine discharge h and x can be read and the Δh calculated. This chart will be used further in the section on the Rankine cycle

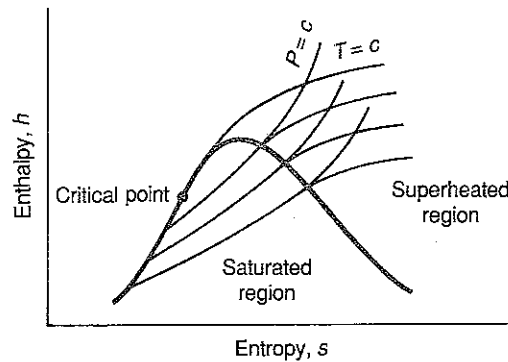
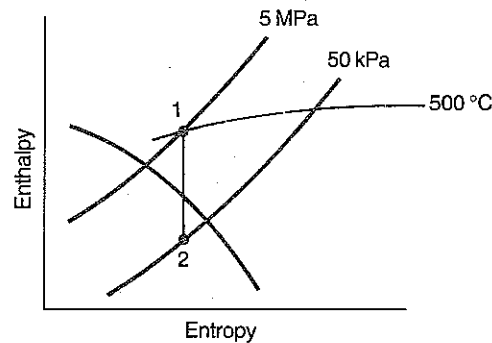


Fig 11-4

Example 4

Find the enthalpy change across an ideal (isentropic) steam turbine where the entering conditions are $P = 5 \text{ MPa}$ and $T = 500 \text{ }^\circ\text{C}$, and the exit condition is $P = 50 \text{ kPa}$.

Solution

On the accompanying illustration, read at the intercept of $P = 5 \text{ MPa}$ and $500 \text{ }^\circ\text{C}$:

$h_1 = 3433 \text{ kJ/kg}$, $s_1 = 6.97 \text{ kJ/kg} \cdot \text{K}$. Read at the intercept of $P = 50 \text{ kPa}$ and $s = 6.97$:
 $h_2 = 2427$, $x = 0.91$ Now, $h_1 - h_2 = 3433 - 2427 = 1006 \text{ kJ/kg}$

Use of R-12, NH_3 Tables, and P - h Diagrams

Typically, the four working fluids used in most thermodynamic texts and on the EIT exam are H_2O , R-12, NH_3 and Air. The refrigerant R-22 has similar characteristics to R-12, so it is not customarily tabled. The refrigerants R-12 and NH_3 exhibit the same phase-diagram characteristics as water, so they have the same type of tabled data, that is, subcooled liquid, saturated mixture, and superheated vapor. The guidelines given for finding one's way around the steam tables apply equally well to R-12 and NH_3 .

By tradition and for convenience, refrigerant properties are shown in a P - h diagram; this is especially useful when analyzing a vapor compression refrigeration cycle, since it operates at two basic pressure levels. A skeleton P - h chart is shown in Fig. 11-5 and will be used later in the section on the Vapor Compression Refrigeration cycle.

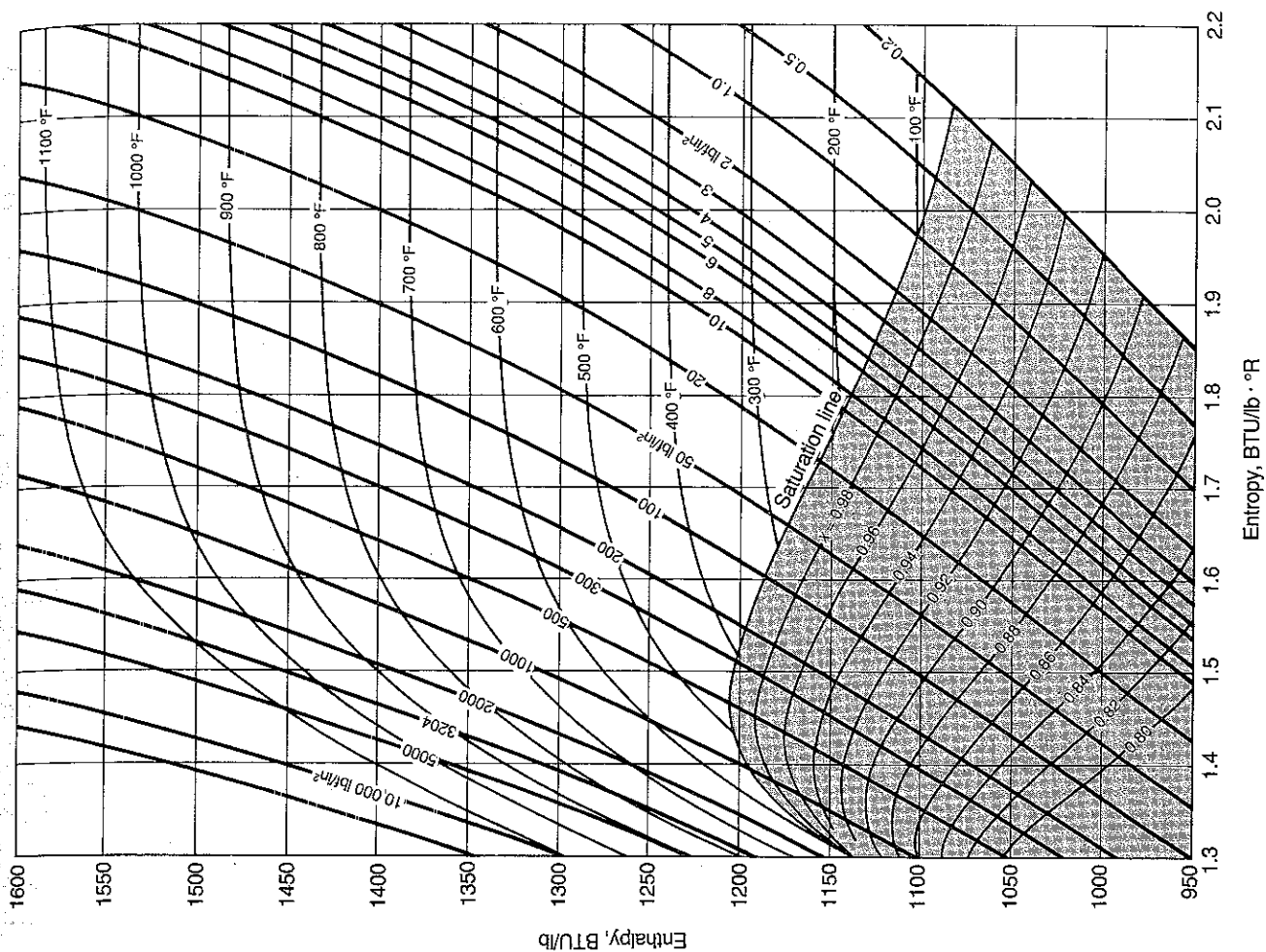


Fig. 11A

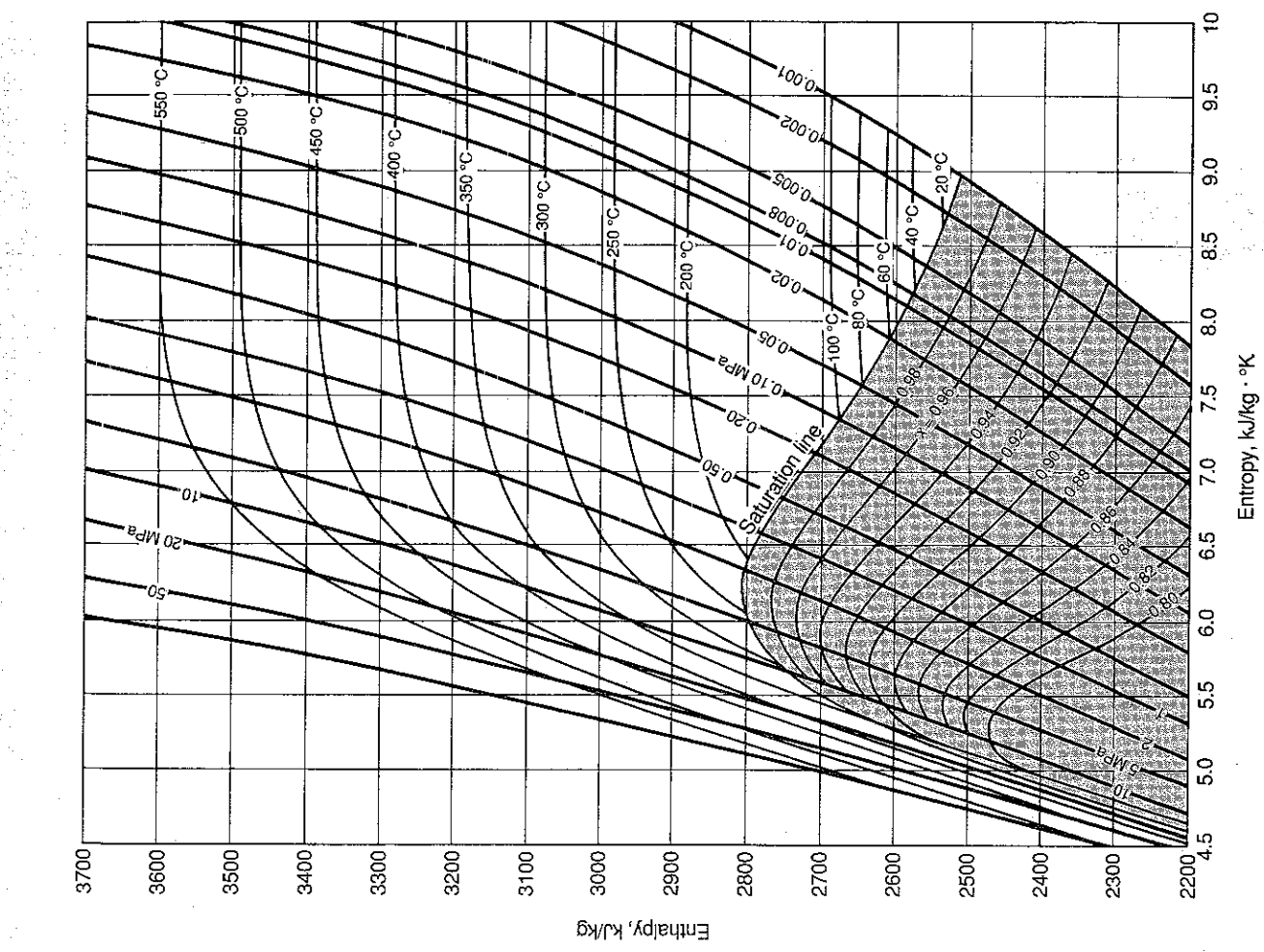


Fig. 11B

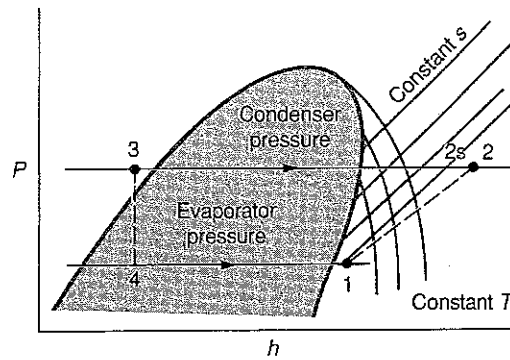


Fig. 11-5

Example 5

Saturated liquid R-12 at $P = 2$ bars is heated to 100°C at constant pressure. Find the original and final state point properties.

Properties of Saturated Refrigerant 12, CCl_2F_2 (SI units): Pressure Table

v , cm^3/g ; u , kJ/kg ; h , kJ/kg ; s , $\text{kJ}/(\text{kg})(^\circ\text{K})$

Press., bars P	Temp., $^\circ\text{C}$ T	Specific volume		Internal energy		Enthalpy		Entropy		
		Sat. liquid v_f	Sat. vapor v_g	Sat. liquid u_f	Sat. vapor u_g	Sat. liquid h_f	Evap h_{fg}	Sat. vapor h_g	Sat. liquid s_f	Sat. vapor s_g
2.0	-12.53	0.6962	83.54	24.43	165.36	24.57	157.50	182.07	0.0992	0.7035

Properties of Superheated Refrigerant 12, CCl_2F_2 (US units)

v , ft^3/lb ; u , BTU/lb ; h , BTU/lb ; s , $\text{BTU}/(\text{lb } ^\circ\text{R})$

Temp.,
 $^\circ\text{F}$

	v	u	h	s	v	u	h	s
	20 psia ($T_{\text{sat}} = -8.13^\circ\text{F}$)				30 psia ($T_{\text{sat}} = 11.11^\circ\text{F}$)			
200	2.8874	97.026	107.712	0.2265	1.9116	96.852	107.464	0.2196
220	2.9789	99.907	110.932	0.2313	1.9735	99.746	110.702	0.2244

Solution

At $P = 2$ bars

$$v_f = 0.6962 \text{ m}^3/\text{kg}$$

$$u_f = 24.43 \text{ kJ}/\text{kg}$$

$$h_f = 24.57 \text{ kJ}/\text{kg}$$

$$s_f = 0.0992 \text{ kJ}/\text{kg} \cdot ^\circ\text{K}$$

At $P = 2$ bars and 100°C , the R-12 is superheated.

$$v = 180.9 \text{ m}^3/\text{kg}$$

$$u = 229.67 \text{ kJ}/\text{kg}$$

$$h = 255 \text{ kJ}/\text{kg}$$

$$s = 0.9593 \text{ kJ}/\text{kg} \cdot ^\circ\text{K}$$

IDEAL GASES

Equations of State

There are many relationships that relate the state-point properties of gases with varying degrees of accuracy. In order of increasing accuracy they are as follows:

1. Ideal Gas
2. Van der Waals
3. Beattie-Bridgeman
4. Generalized Compressibility
5. Property tables such as H₂O, R-12, NH₃

When dealing with a wide range of temperature and pressure for gases that are far from their saturated vapor state, the ideal gas relationship is accurate for most engineering work. Several working expressions are:

$$Pv = RT$$

$$Pv = mRT = n\bar{R}T, \quad R = \frac{\bar{R}}{\text{m.w.}}$$

$$pv = \bar{R}T, \quad \text{where } v = \bar{v} = \frac{V}{m} = \frac{V}{\text{m.w.}}$$

The Van der Waals and Beattie-Bridgeman relationships are cumbersome. They require constants for each gas and are seldom used except perhaps in a computer simulation. Use of the Generalized Compressibility Chart(s) is sometimes required. The equation of state takes the form

$$\frac{PV}{RT} = z$$

where z can take on a value of 0.2 to 4.0. For most pressures and temperatures, z is in a narrow range around 1.0 (which, of course, is the ideal approximation). A skeletal chart is shown in Fig. 11-6 where $p_r = \frac{P}{P_c}$ and $t_r = \frac{T}{T_c}$ with P_c and T_c being evaluated at the critical point for the gas in question.

A typical application involves a given temperature and pressure for T and P and the calculation of v . Solution steps are:

1. Look up T_c , P_c , and R for the gas.
2. Calculate p_r and t_r .
3. Check the generalized compressibility chart and read z .
4. Calculate $v = z \times \frac{RT}{P}$.

If tables are available in the temperature and pressure range for the superheated gas in question, the specific volume can be read directly. This is the most accurate source of data, since the tables are based on experimental data.

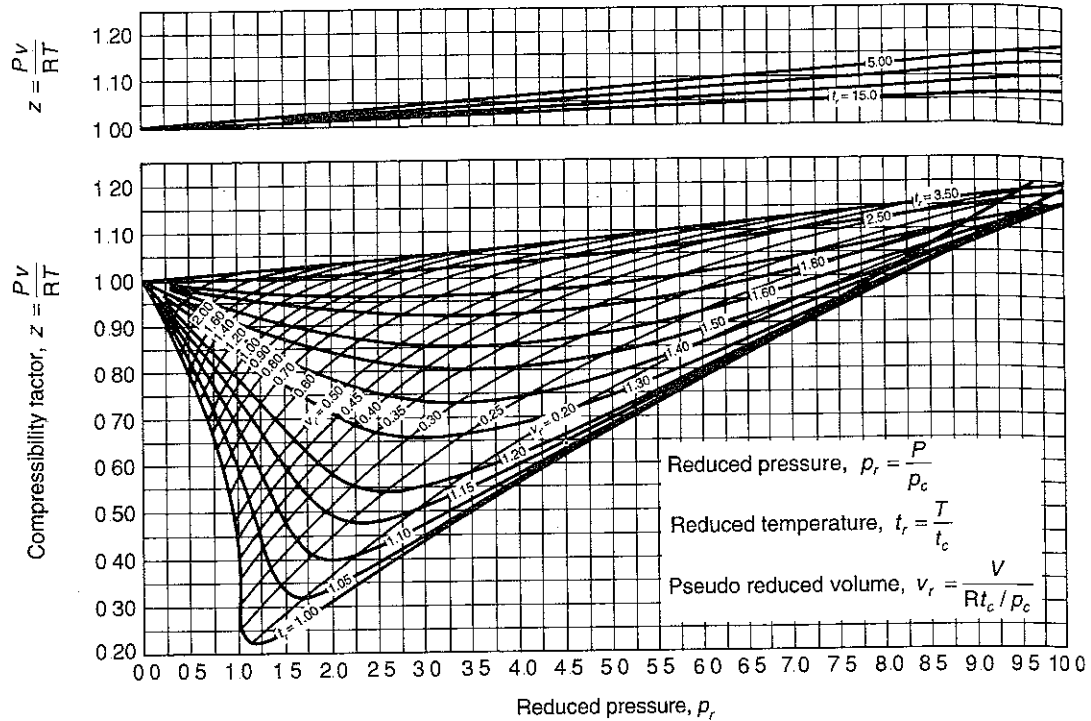


Fig. 11-6

Example 6

Calculate and compare the specific volumes of water (H_2O) at $P = 10$ MPa and $T = 400$ °C. The gas (steam) table value is $v = 0.02641$ m³/kg. For an ideal gas

$$R = \frac{8.31}{\text{m.w.}} = \frac{8.31}{18} = 0.462$$

$$v = \frac{RT}{P} = \frac{0.462(673)}{10,000} = 0.0311 \text{ m}^3/\text{kg}$$

Thermodynamics**Solution**

The critical P and T for water are

$$p_c = 22.09 \text{ MPa}, \quad t_c = 647.3 \text{ °K}$$

Therefore,

$$p_r = \frac{10}{22.09} = 0.453, \quad t_r = \frac{673}{647.3} = 1.04, \quad z = 0.83 \quad \left\{ \begin{array}{l} \text{read from com-} \\ \text{pressibility chart} \end{array} \right.$$

$$v = 0.0311 \times 0.83 = 0.0258 \text{ m}^3/\text{kg}$$

The steam table value is the most accurate, and the ideal gas value is the least accurate.

Enthalpy and Internal Energy Changes

The other condition which is usually considered to be part of the definition of ideal gas is that the specific heats (C_p and C_v) are constant. This allows a number of working relationships to be developed:

$$h_2 - h_1 = C_p (T_2 - T_1)$$

$$u_2 - u_1 = C_v (T_2 - T_1)$$

$$C_p = C_v + R \text{ (always true)}$$

$$k = \frac{C_p}{C_v} = \text{Constant}$$

$$C_p = \frac{kR}{k-1}$$

$$C_v = \frac{R}{k-1}$$

Use of Gas (Air) Tables

Tables of gas properties all use the same general format. Normally, examination questions use air tables only. The tables show T , h , and u as the primary properties of interest and, typically, three other variables such as p_r , v_r , or s_0 where the latter is defined as

$$\int_0^T C_p \frac{dT}{T}$$

This considers the variation of C_p with temperature. The latter variables are all a function of temperature, and any of them may be used as an entering argument. They reflect the fact that C_p and C_v are a function of temperature and are not constant. So for a given temperature change, the gas table changes in h and u are more accurate than using the ideal gas relationships.

The other three variables involve a knowledge of entropy. To use the air tables, it is sufficient to know only that a process (change in state) which has no change in entropy is called isentropic and that it is reversible and adiabatic (no heat transfer). The variables are used as follows:

1. To calculate the change in entropy for any process:

$$s_2 - s_1 = \phi_2 - \phi_1 - R \ln \frac{P_2}{P_1}$$

It is apparent that T and P must be known at the beginning and end states in order to calculate $s_2 - s_1$.

2. The variables p_r and v_r are used only for isentropic processes and relate to the beginning and ending pressure and volumes as follows:

$$\frac{p_{r_2}}{p_{r_1}} = \frac{P_2}{P_1} \quad \frac{v_{r_2}}{v_{r_1}} = \frac{V_2}{V_1}$$

The variables p_r and v_r are correctly referred to as “relative pressure” and “relative volume” and should not be confused with the “reduced” pressure and temperature used in the compressibility charts.

PROCESSES

Thermodynamic processes usually involve a “working fluid” such as a pure substance (like water) or a gas (like air). So tables of properties or ideal gas relationships are used. For the process path to be known, the process must be reversible. If the process involves friction or turbulence and is irreversible, then only the first law of thermodynamics applies.

So, generally, the processes are considered to be reversible (no friction or turbulence) and are one of the following:

- constant pressure
- constant volume
- constant temperature
- no heat flow (adiabatic)

Figure 11-7 shows the applicable relationships for the various processes.

Example 7

Air at 27 °C is heated to 927 °C. Find the change in enthalpy and internal energy, treating air as a perfect gas (C_p and C_v constant) and using the air tables.

Ideal-gas Properties of Air (SI units)

<i>T</i> , °K; <i>h</i> , kJ/kg; <i>u</i> , kJ/kg; ϕ , kJ/(kg)(°K)					
<i>T</i>	<i>h</i>	p_r	<i>u</i>	v_r	ϕ
300	300.19	1.3860	214.07	621.2	1.70203
1200	1277.79	238.0	933.33	14.470	3.17888

Source: Adapted from Keenan, J. M. and J. Kaye, “Gas Tables,” Wiley, New York, 1945

Solution

For air at room temperature $C_p = 1.0047$ and $C_v = 0.717$ kJ/kg, so

$$h_2 - h_1 = (927 - 27) \times 1.0047 = 904.2 \text{ kJ/kg}$$

$$u_2 - u_1 = (927 - 27) \times 0.717 = 645.3 \text{ kJ/kg}$$

Using air tables (which reflect the fact that C_p and C_v vary with temperature):

$$h_2 - h_1 = 1277.79 - 300.19 = 977.6 \text{ kJ/kg}$$

$$u_2 - u_1 = 933.33 - 214.07 = 719.26 \text{ kJ/kg}$$

First and Second Thermodynamics Law Formulae for Reversible Processes of an Ideal Gas*

Process	Closed System (non-flow)	Open System (steady flow)
General	$q = C_v(T_2 - T_1) + w$	$q = C_p(T_2 - T_1) + \Delta KE - \Delta PE + w$
$(Pv = RT)$	$w = \int_1^2 P dv$	$w = -\int_1^2 v dP - \Delta KE - \Delta PE$
$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$	$s_2 - s_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$	$s_2 - s_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$
	(s ₂ - s ₁ for closed or open systems)	
Polytropic $Pv^n = \text{constant}$	$q = \frac{k-n}{1-n} C_v(T_2 - T_1)$	$q = \frac{k-n}{1-n} C_v(T_2 - T_1)$
$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{n/(n-1)} = \left(\frac{v_1}{v_2}\right)^n$	$w = \frac{k-1}{1-n} C_v(T_2 - T_1)$	$w = n \frac{k-1}{1-n} C_v(T_2 - T_1) - \Delta KE - \Delta PE$
$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(n-1)/n} = \left(\frac{v_1}{v_2}\right)^{n-1}$	$s_2 - s_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$	$s_2 - s_1 = C_v \ln \frac{T_2}{T_1} - R \ln \frac{v_2}{v_1}$
$\frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{1/n} = \left(\frac{T_1}{T_2}\right)^{1/(n-1)}$	$s_2 - s_1 = \phi_2 - \phi_1 - R \ln \frac{p_2}{p_1} = \phi_2 - \phi_1 + R \ln \frac{v_2}{v_1}$	
Constant volume (Isometric) $v_2 = v_1, \quad n = \infty$	$w = 0$	$q = C_v(T_2 - T_1) \quad q = C_v(T_2 - T_1)$ $w = -v(p_2 - p_1) - \Delta KE - \Delta PE$
$\frac{p_2}{T_2} = \frac{p_1}{T_1}$	$s_2 - s_1 = C_v \ln(T_2/T_1)$	$s_2 - s_1 = C_v \ln(T_2/T_1)$
Constant pressure (Isobaric) $p_2 = p_1, \quad n = 0$	$w = p(v_2 - v_1)$ $w = R(T_2 - T_1)$	$q = C_p(T_2 - T_1) \quad q = C_p(T_2 - T_1)$ $w = -\Delta KE - \Delta PE$
$\frac{v_2}{T_2} = \frac{v_1}{T_1}$	$s_2 - s_1 = C_p \ln(T_2/T_1)$	$s_2 - s_1 = C_p \ln(T_2/T_1)$
Constant temperature (Isothermal) $T_2 = T_1, \quad n = 1$	$q = w = T(s_2 - s_1)$ $q = w = RT \ln \frac{v_2}{v_1} \text{ or } \frac{p_1}{p_2}$	$q = T(s_2 - s_1) = RT \ln \frac{v_2}{v_1} \text{ or } \frac{p_1}{p_2}$ $w = RT \ln \frac{v_2}{v_1} - \Delta KE - \Delta PE$ or $w = RT \ln \frac{p_1}{p_2} - \Delta KE - \Delta PE$
$p_2 v_2 = p_1 v_1$	$s_2 - s_1 = R \ln \frac{v_2}{v_1} \text{ or } \frac{p_1}{p_2}$	$s_2 - s_1 = R \ln \frac{v_2}{v_1} = R \ln \frac{p_1}{p_2}$
Adiabatic (Isentropic) $n = k$	$q = 0$ $w = C_v(T_1 - T_2)$ $w = \frac{p_1 v_1 - p_2 v_2}{k-1}$ $w = R(T_1 - T_2)/k - 1$	$q = 0$ $w = C_p(T_1 - T_2) - \Delta KE - \Delta PE$ $w = \frac{k(p_1 v_1 - p_2 v_2)}{k-1} - \Delta KE - \Delta PE$ $w = kR(T_1 - T_2)/k - 1 - \Delta KE - \Delta PE$
$s_2 = s_1$	$s_2 - s_1 = 0$	$s_2 - s_1 = 0$

*Per unit mass basis and constant (average) specific heats (C_v, C_p) assumed. $R = C_p - C_v, k = C_p/C_v, C_p = kR/(k-1), C_v = R/(k-1)$

$$\Delta u = u_2 - u_1 = C_v(T_2 - T_1), \quad \Delta h = h_2 - h_1 = C_p(T_2 - T_1)$$

$$\Delta KE \text{ (S I)} = \frac{\bar{V}_2^2 - \bar{V}_1^2}{2000 \times g_c}, \quad \Delta PE \text{ (S I)} = \frac{g(z_2 - z_1)}{1000 \times g_c}$$

ΔKE and ΔPE may be negligible for many open systems

Fig 11-7

THE SECOND LAW OF THERMODYNAMICS

Typically in the morning section of the EIT examination there will be several problems that involve the application of one of the statements of the second law or the Carnot cycle. Useful statements of the second law are:

- Whenever energy is transferred, some energy is reduced to a lower level.
- No heat cycle is possible without the rejection of some heat.
- A Carnot cycle converts the maximum amount of heat into work; it has the highest thermal efficiency.
- All Carnot cycles operating between two temperature reservoirs have the same efficiency.
- A Carnot machine's efficiency, or Coefficient of Performance (COP), is a function only of the two reservoir temperatures.

A Carnot cycle consists of the following four processes:

- 1-2 Reversible adiabatic compression
- 2-3 Reversible constant temperature heat addition
- 3-4 Reversible adiabatic expansion
- 4-1 Reversible constant temperature heat rejection

The normal property diagrams are shown in Fig. 11-8 and 11-9. If the processes proceed in a clockwise direction, the Carnot engine operates as a power producing engine; if in a counter-clockwise direction, the engine is a refrigerator or a heat pump.

Thermodynamics

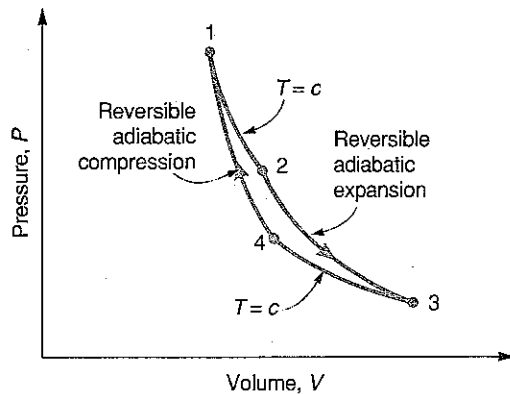


Fig 11-8

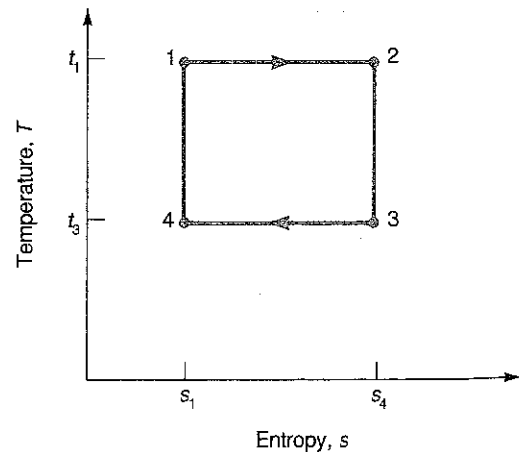


Fig 11-9

The efficiencies or COPs are

$$\eta = \frac{W_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{T_C}{T_H}$$

$$\text{COP}_{\text{REFR}} = \frac{Q_{\text{in}}}{W_{\text{in}}} = \frac{T_C}{T_H - T_C}$$

$$\text{COP}_{\text{HEAIPUMP}} = \frac{Q_{\text{out}}}{W_{\text{in}}} = \frac{T_H}{T_H - T_C}$$

Example 8

A Carnot machine operates between a hot reservoir at 200 °C and a cold reservoir at 20 °C. a) When operated as an engine it receives 1000 kJ/kg; find the work output. b) Find the COP when operated as a refrigerator and a heat pump

Solution

$$\text{a) } \eta = \frac{T_H - T_C}{T_H} = \frac{200 - 20}{473} = 0.381$$

$$W = \eta \times Q_{\text{in}} = 0.381 \times 1000 = 381 \frac{\text{kJ}}{\text{kg}}$$

$$\text{b) } \text{COP}_{\text{REFR}} = \frac{T_C}{T_H - T_C} = \frac{293}{200 - 20} = 1.63$$

$$\text{COP}_{\text{HEAIPUMP}} = \frac{T_H}{T_H - T_C} = \text{COP}_{\text{REFR}} + 1.0 = 2.63$$

ENTROPY

Thermodynamics

Entropy is another thermodynamic property that is useful in the evaluation of thermodynamic systems and processes. The following statements are useful in solving problems:

- Natural processes (which typically involve friction) result in an increase in entropy.
- Entropy will always *increase* when heat is added.
- Entropy will remain *constant* when processes are reversible and adiabatic.
- Entropy can *decrease* only when heat is removed.

For reversible processes:

$$ds = \frac{dq}{T}$$

$$Tds = du + PdV = dh - v dP$$

11-18 ■ Thermodynamics

For an ideal gas:

$$\begin{aligned} s_2 - s_1 &= C_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} \\ &= C_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \end{aligned}$$

In using the Air (Gas) tables, which take into account the variation of C_p with temperature

$$s_2 - s_1 = \phi_2 - \phi_1 - R \ln \frac{p_2}{p_1}$$

where ϕ is tabulated as a function of temperature.

Just as work for a closed system

$$W = \int_1^2 P dv$$

can be shown as an area on a P - v diagram (Fig 11-10), so can heat

$$Q = \int_1^2 T ds$$

be shown as an area on a T - s diagram (Fig 11-11), and the area enclosed by the process lines on a T - s diagram shows the net heat flow in a cycle. This, of course, is equal to the net work.

An **isentropic process** is defined as one which is reversible and adiabatic. Of course, on a property diagram showing entropy (s), the process would appear as a straight line. For several important thermodynamic devices, the isentropic process is a standard of comparison and is used in the calculation of the component efficiency (turbine, compressor, pump, nozzle).

Since all natural processes produce an increase in entropy, the ideal (isentropic) and the actual processes can be compared as shown in Fig 11-12 and 11-13.

$$\eta_{\text{turbine nozzle}} = \frac{h_1 - h_3}{h_1 - h_2}$$

$$\eta_{\text{compr, pump}} = \frac{h_2 - h_1}{h_3 - h_1}$$

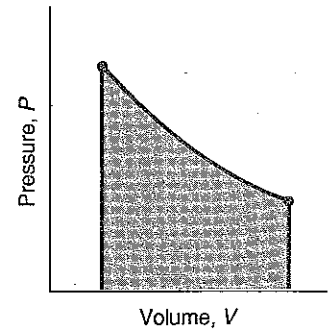


Fig 11-10

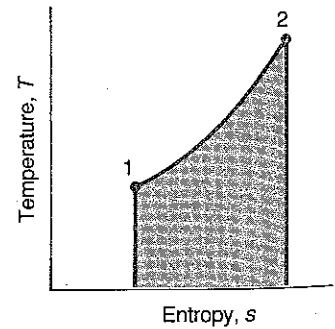


Fig 11-11