Section 8

Thermodynamics and Cycles

8.1 Quick reference: symbols – thermodynamics

Table 8.1

Symbol	*Quantity*
A	Area
As	Surface area
C	Specific heat
$\boldsymbol{c_p}$	Specific heat (constant pressure)
c_v	Specific heat (constant volume)
D	Diameter
E	Thermal 'internal' energy
E	Thermal internal energy per unit mass
F	Force
	Heat exchanger correction factor
	Black body radiation factor
	View factor
Fo	Fourier number
G	Irradiation
Gr	Grashot number
Gz	Graetz number
H	Convection heat transfer coefficient
	Planck's constant
h_{fg}	Latent heat of vaporization
h_m	Convection mass transfer coefficient
h_{rad}	Radiation heat transfer coefficient
J	Radiosity
K	Thermal conductivity
	Boltzman's constant
M (m)	Mass
Nu	Nusselt number
P	Pitch of a tube-bank
Pe	Peclet number (Re, Pm)
Pr	Prandtl number
P	Pressure
Q	Heat transfer
Q	Rate of heat transfer
Q	Rate of energy generation per unit volume

Engineers' Data Book, Fourth Edition. Clifford Matthews.

Table 8.1 (Cont.)

Symbol	*Quantity*
R	Universal gas constant
Re	Reynolds number
R_f	Fouling factor
R	Radius of cylinder or sphere
r, φ, z	Cylindrical co-ordinates
Symbol	*Quantity*
r, θ, φ	Spherical co-ordinates
St	Stanton number
T	Temperature
T	Time
U	Overall heat transfer coefficient
V	Volume
V	Specific volume
x, y, z	Rectangular co-ordinates
A	Thermal diffusivity
B	Volumetric thermal expansion coefficient
Δ	Hydrodynamic boundary layer thickness
δ_t	Thermal boundary layer thickness
E	Emissivity
ε_f	Fin effectiveness
η_f	Fin efficiency
Θ	Temperature difference
K	Absorption coefficient
Λ	Wavelength
M	Dynamic viscosity
N	Kinematic viscosity
P	Density
P	Reflectivity
Σ	Stefan-Boltzman constant
T	Shear stress
	Transmissivity
Φ	Stream function

8.2 Basic thermodynamic laws

The basic laws of thermodynamics govern the design and operation of engineering machines. The most important principles are those concerned with the conversion of heat energy from available sources such as fuels into useful work.

8.2.1 The first law

The first law of thermodynamics is merely a specific way to express the principle of conservation of energy. It says, effectively, that heat and work are two mutually convertible forms of energy. So:

$$\text{heat in} = \text{work out}$$

or, in symbols

$$\Sigma \mathrm{d}Q = \Sigma \mathrm{d}W \text{(over a complete cycle)}$$

This leads to the non-flow energy equation

$$\mathrm{d}Q = \mathrm{d}u + \mathrm{d}W$$

where u = internal energy.

8.2.2 The second law

This can be expressed several ways:

- heat flows from hot to cold, not cold to hot;
- in a thermodynamic cycle, gross heat supplied must exceed the net work done – so some heat has to be *rejected* if the cycle is to work;

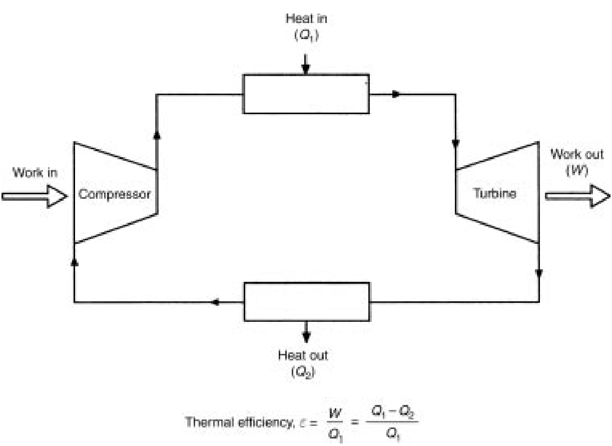


Figure 8.1

- a working cycle must have a heat supply and a heat sink;
- the thermal efficiency of a heat engine must always be less than 100 percent.

The two laws point towards the general representation of a heat engine as shown.

8.3 Entropy

- The existence of entropy follows from the second law.
- Entropy (s) is a property represented by a reversible adiabatic process.
- In the figure, each p–v line has a single value of entropy (s).

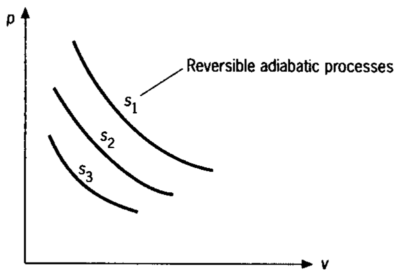


Figure 8.2

Symbolically, the situation for all working substances is represented by

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

where s is entropy.

8.4 Enthalpy

Enthalpy (h) is a property of a fluid itself.
Enthalpy, $h = u + pv$ (units kJ/kg)

It appears in the steady flow energy equation (SFEE). The SFEE is

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W$$

8.5 Other definitions

Other useful thermodynamic definitions are:

- A perfect gas follows:

$$\frac{pv}{T} = \text{constant} = R\ (\text{kJ/kgK})$$

- γ ratio $= c_p/c_v$ (ratio of specific heats) $\cong 1.4$
- A constant volume process follows:

$$Q = mc_v(T_2 - T_1)$$

- A constant pressure process follows:

$$Q = h_2 - h_1 = mc_p(T_2 - T_1)$$

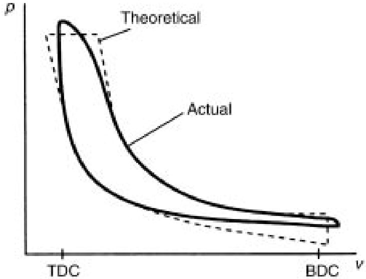
- A polytropic process follows:

$$pv^N = c \text{ and work done } = \frac{p_1 v_1 - p_2 v_2}{N - 1}$$

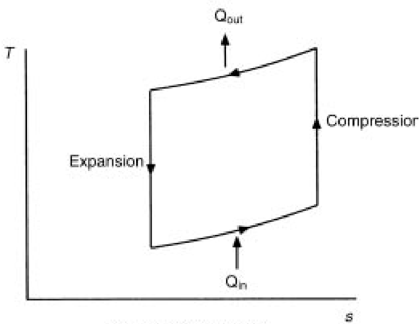
8.6 Cycles

Heat engines operate on various adaptations of ideal thermodynamic cycles. These cycles may be expressed on a p–v diagram or T–s diagram, depending on the application.

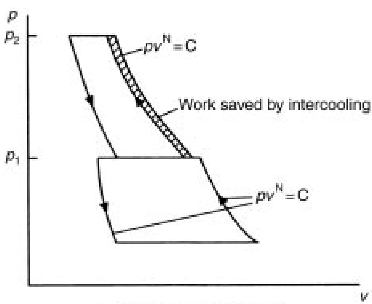
Reciprocating machines such as diesel engines and simple air compressors are traditionally shown on a p–v diagram. Refrigeration and steam cycles are better explained by the use of the T–s diagram.



2-stroke diesel engine



Gas refrigeration cycle



Two-stage air compressor
(with intercooler)

Figure 8.3

8.7 The steam cycle

All steam turbine systems for power generation or process use are based on adaptations of the Rankine cycle. Features such as superheating, reheating, and regenerative feed heating are used to increase the overall cycle efficiency.

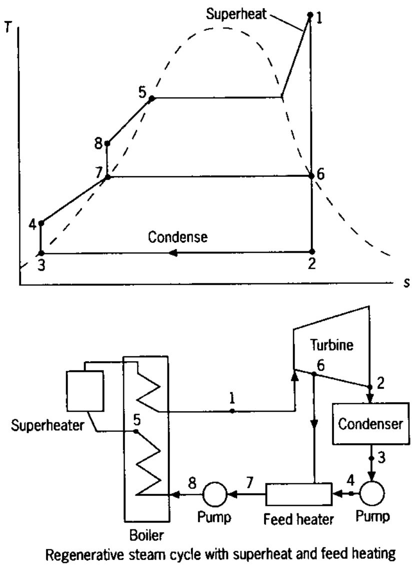


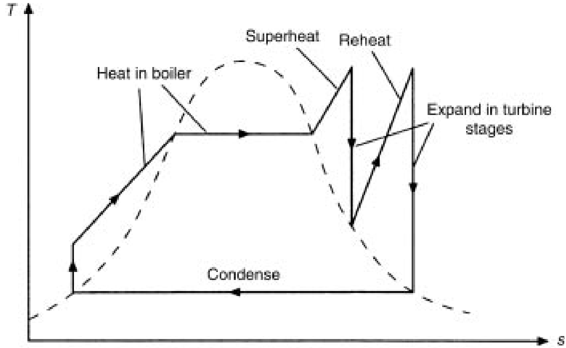
Figure 8.4 Regenerative steam cycle with superheat and feed heating

8.8 Properties of steam

Three possible conditions of steam are:

- wet (or 'saturated');
- containing a dryness fraction (x);
- superheated ('fully dry').

Standard notations h_f, h_{fg} and h_g are used.



Basic steam cycle with superheat and reheat

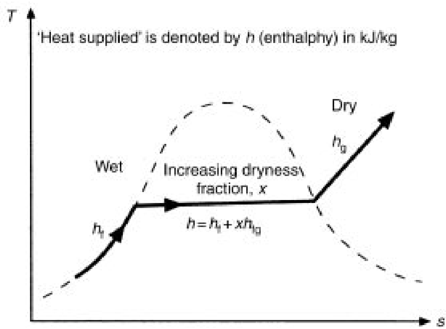


Figure 8.5

Published 'steam' tables list the properties of steam for various conditions. Two types of table are most commonly used; saturated state properties and superheat properties.

8.8.1 Saturated state properties

These list the properties corresponding to a range of temperatures (in °C) or pressures (in bar) and are formally termed; 'properties of saturated water and steam'.

	Pressure p (bar)	*Sat. temp.* t_s *(°C)*	*Specific volume* v_g *(m^3 kg)*	*Specific enthalpy (kJ/kg)*			*Specific entropy (kJ/kgK)*		
				h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
Example for 100°C	1.01325	100	1.673	419.1	2256.7	2675.8	1.307	6.048	7.355

Note that:

– The maximum pressure listed is 221.2 bar – known as the *critical pressure.*
– Pressure and temperature are dependent on each other.

Figure 8.6

The format is shown in Fig. 8.6 (below):

8.8.2 Superheat properties

These list the properties in the superheat region. The two reference properties are temperature and pressure: all other properties can be derived.

The format is shown in Figure 8.7.

Note that:

- In the superheat region, pressure and temperature are independent of each other – it is only the t_s that is a function of pressure.

8.9 Reference information

The accepted reference data source in this field is:

Rogers and **Mayhew,** 1994, *Thermodynamic and Transport Properties of Fluids – SI units* (Basil Blackwell). This is a full set of tables, including data on steam, water, air, ammonia, and other relevant fluids.

8.10 The gas turbine (GT) cycle

The most basic 'open cycle' gas turbine consists of a compressor and turbine on a single shaft. The compression and expansion processes are approximately adiabatic. Figure 8.8 shows the basic (simplified) cycle diagram.

			Temperature, t (°C)		
			250		600
p = 30 bar	Specific volume v_g = 0.0666 m^3/kg	v	0.0812		0.1324
Sat. temp. t_s = 233.8°C	Specific internal energy u_g = 2603 kJ/kg	u	2751	Listed for temp. intervals of 50°C	3285
	Specific enthalpy h_g = 2803 kJ/kg	h	2995		3682
	Specific entropy S_g = 6.186 kJ/kg	s	6.541		7.505

Figure 8.7

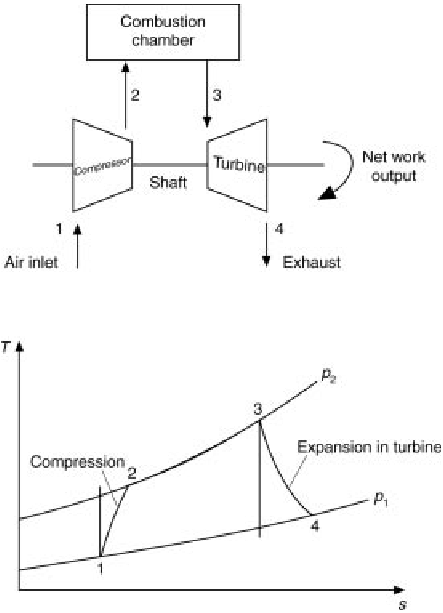

Combustion chamber
2
3
Compressor
Shaft
Turbine
Net work output
1
Air inlet
4
Exhaust
T
p_2
3
Expansion in turbine
Compression
2
p_1
4
1
s

Figure 8.8