In the case studies which follow, mechanical drives of varying degrees of complexity are used, from the simple sinusoidal swashplate drive to the more complex rhombic and yoke drives.

2.4 Case study—The Ford–Philips 4-215 engine

The 4-215 engine is a four-cylinder swashplate-drive double-acting engine. Its design and development began in 1972 under a joint program between N V Philips, of Holland, and the Ford Motor Company to develop an experimental automotive engine (van Giesel and Reinink 1977). The operating principle of the engine is shown in figure 2.3. The four cylinders are interconnected, so that the upper expansion space of one cylinder is connected to the lower compression space of the adjacent cylinder via a series-connected heater, regenerator and cooler. The pistons are driven by a swashplate (or alternatively by a 'wobble' plate), resulting in a pure sinusoidal reciprocating motion having a 90° phase difference between the adjacent pistons.

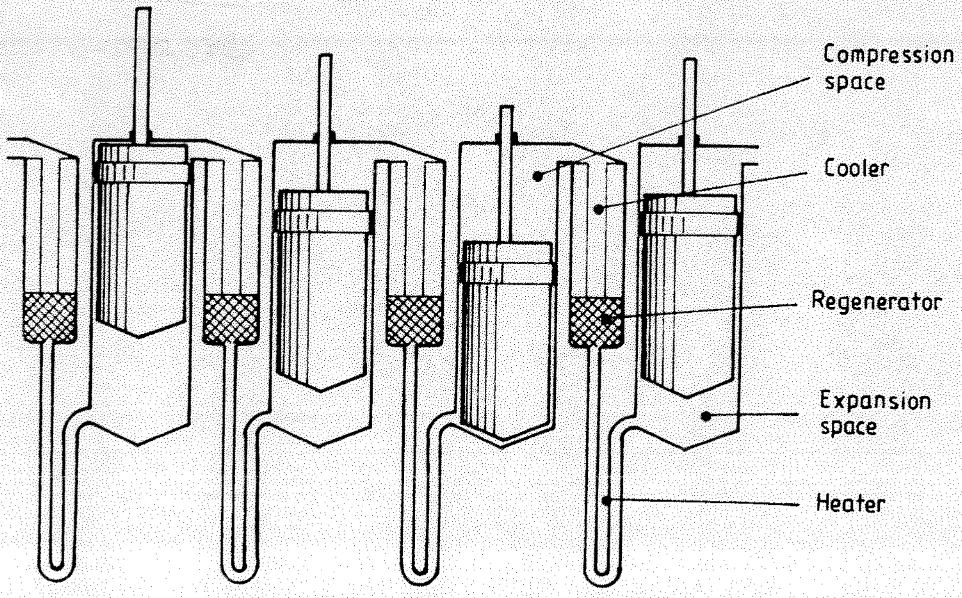

Figure 2.3 Arrangement of the swashplate double-acting engine.

The wobble plate drive was first considered for use in Stirling engines by Sir William Siemens in 1860 (figure 2.4). Babcock (1885), commenting on this engine in 1885 stated:

> No other form of air-engine offers so many advantages, but it has also its peculiar difficulties. If the latter can be overcome, it is likely to become the air-engine of the future.

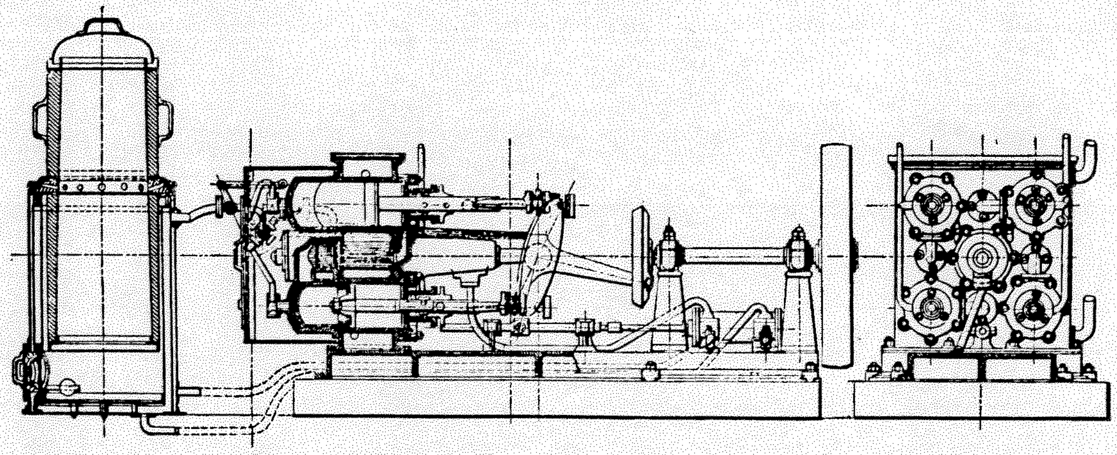

Figure 2.4 Wobble plate engine due to Siemens in 1860 (after Babcock 1885).

The swashplate drive engine was brought out of obsolescence almost a century after its invention. The major advantage of the engine is its high specific power output capability, since there is only one reciprocating component per cycle, and no pressurised crankcase is necessary. Unfortunately, the 'peculiar difficulties' exist even today, being mainly the problem of containing the working gas under the high mean operating pressure.

The Ford–Philips 4-215 engine uses hydrogen as the working gas under a maximum mean pressure of 200 atm, and reached an advanced level of development before the project was cancelled by Ford in 1979.

A general view of the engine is shown in figure 2.5 and a cross section view is shown in figure 2.6. The pertinent data defining the engine configuration and operating parameters are given in table 2.2. However, not all the required geometric data have been published in the open literature as yet, and therefore a number of assumptions have been made. Thus, for example, we have arbitrarily divided the total unaccounted for volume equally between the compression and expansion space clearance volumes.

The performance map is given in table 2.3. We notice that the engine is capable of producing an indicated power output of 200 kW at 4500 rpm.

In simulating the engine we have considered it as having a single cycle, simply multiplying the various volumes per cylinder by four. The sinusoidal volume variations can be stated in a simple form as

$$V_c = V_{clc} + \tfrac{1}{2} V_{swc}(1 + \cos\theta) \tag{2.15}$$

$$V_e = V_{cle} + \tfrac{1}{2} V_{swe}[1 + \cos(\theta + \alpha)] \tag{2.16}$$

where V_{swc} and V_{swe} are the compression and expansion space swept volumes respectively,

V_{clc} and V_{cle} are the compression and expansion space clearance volumes respectively,

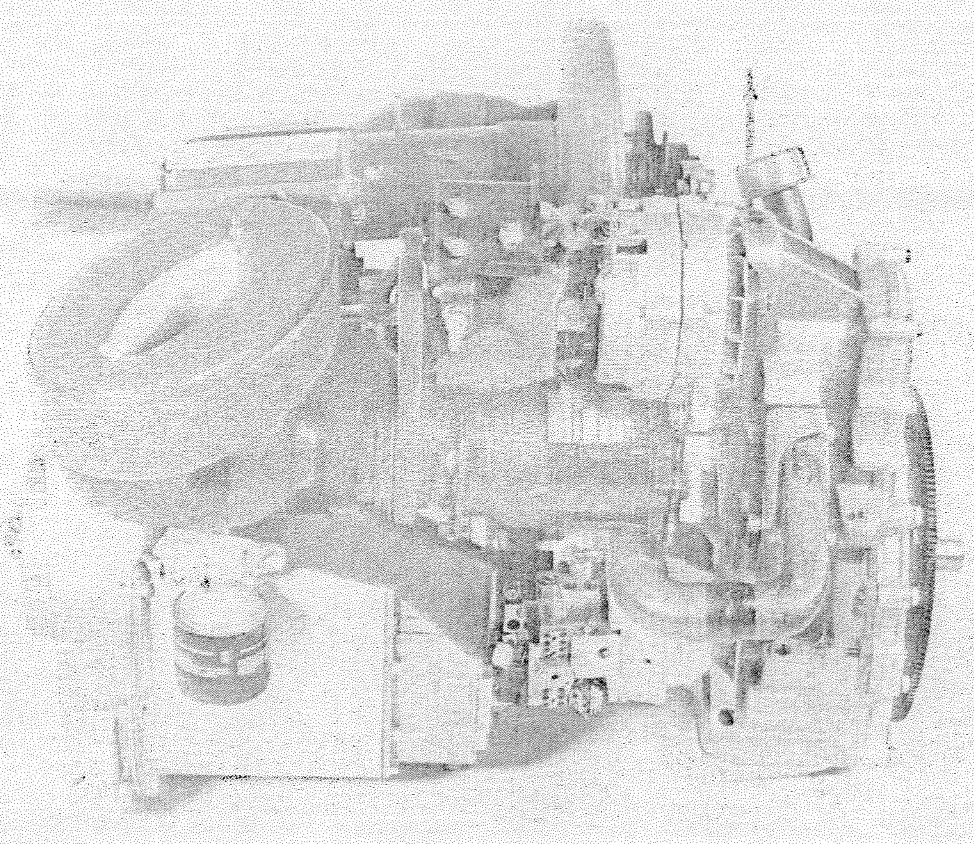

Figure 2.5 General view of the Ford–Philips 4-215 engine (courtesy Ford Motor Company).

θ is the crank angle, arbitrarily chosen to be zero when the compression space volume is a maximum,

α is the phase angle of the expansion space volume variations relative to the compression space volume variations. For the four-cylinder swashplate-drive engine α is 90°.

Differentiating equations (2.15) and (2.16) with respect to the crank angle θ we obtain

$$\mathrm{d}V_c/\mathrm{d}\theta = -\tfrac{1}{2}V_{swc}\sin\theta \tag{2.17}$$

$$\mathrm{d}V_e/\mathrm{d}\theta = -\tfrac{1}{2}V_{swe}\sin(\theta+\alpha). \tag{2.18}$$

The data given in table 2.2 have been used to obtain the various simulation parameters shown in table 2.4. Using these parameters on the set of equations given in table 2.1, and integrating numerically over a complete cycle, we obtain the performance characteristics of the Ideal Isothermal model shown in table 2.4. The indicated power output of 212.9 kW is higher than the actual indicated power of 130.1 kW for the same conditions. It is to be expected that the ideal simulation will give an exaggerated performance, mainly because of the use of lossless heat exchanger components in the simulation model. The

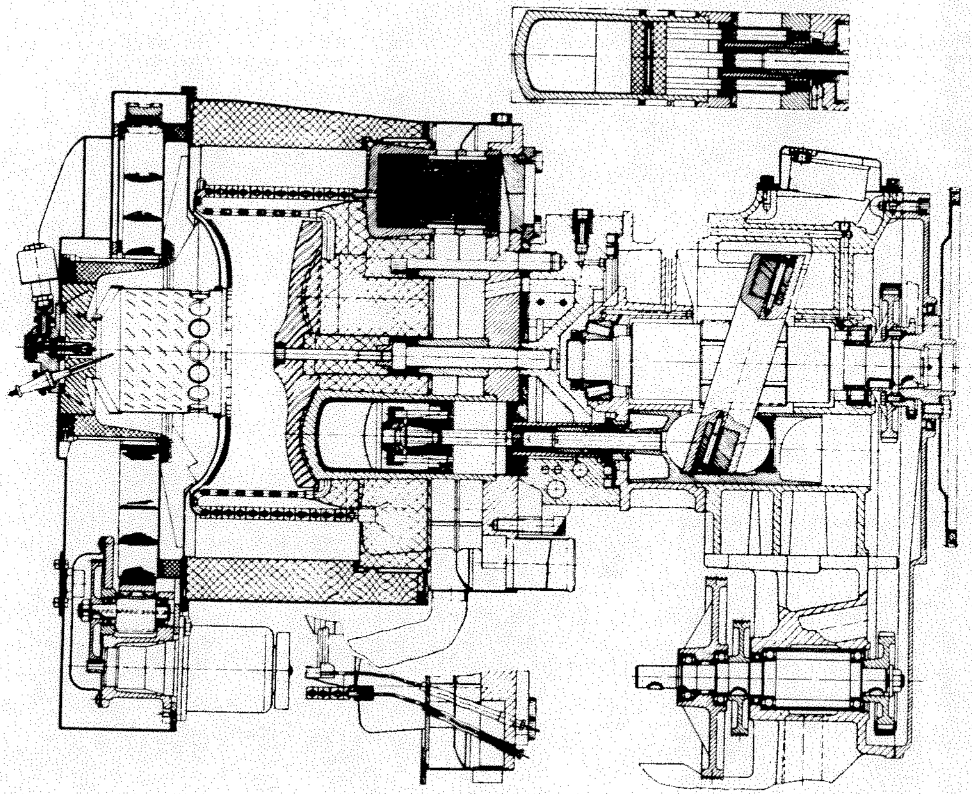

Figure 2.6 Cross section view of the Ford–Philips 4-215 engine (courtesy NASA Lewis Research Center).

thermal efficiency value of 67.1 % is the Carnot efficiency as expected for the Ideal Isothermal model.

The simulation results are shown diagrammatically in figure 2.7. The compression and expansion space volume variations and the resultant pressure variation are shown as functions of the shaft angle θ. The four processes of the ideal Stirling cycle tend to overlap under the sinusoidal volume variations; however, they can be inferred from the diagram. The compression process occurs in the first quadrant (0 to 90°). Some of the compression is seen to occur in the hot expansion space, but most of the working gas is compressed in the compression space. The displacement process occurring in the second quadrant (90 to 180°) is seen to be a constant volume process, to a close approximation. The expansion process occurring over the third quadrant (180 to 270°) is also non-ideal, in that some of the expansion is seen to occur in the compression space, and finally, the displacement process in the fourth quadrant (270 to 360°) is seen to be incomplete in that at the end of this process a significant amount of working gas still remains in the expansion space. Thus the sinusoidal volume variations do not result in the optimum ideal Stirling cycle, but are one of the many practical mechanical realisations of it. The pressure curve is not quite sinusoidal, being peaked towards the high pressure.

Table 2.2 Ford 4-215 engine data (after Belaire and Kitzner 1977).

General	
Working fluid	Hydrogen
Maximum mean pressure	20 MPa
Heater head temperature	1023 K
Cooling water temperature	337 K
Speed	4000 rpm
Bore	73 mm
Stroke	52 mm
Total internal engine volume, including cylinder swept volume, per cylinder	670 cm^3
Heater	
Number of heater tubes/cylinder	22
Heater tube internal diameter	4 mm
Heater tube length	462 mm
Cooler	
Number of cooler tubes/cylinder	742
Cooler tube internal diameter	0.9 mm
Cooler tube length	87 mm
Regenerator	
Regenerator diameter	73 mm
Regenerator length	34 mm
Regenerator matrix wire diameter	36 μm
Matrix mesh size	200
Matrix porosity	0.62
Number of regenerator units per cylinder	2

Table 2.3 Ford 4-215 engine performance map (after Kitzner 1981) giving the indicated power output (kW).

Speed (rpm)	Mean pressure (bar)					
	200	175	150	125	100	50
4500	200.2	179.3	157.0	133.4	108.4	54.2
3900	186.0	166.4	145.6	123.7	100.5	50.6
3300	166.3	148.7	130.1	110.5	89.8	45.4
2700	141.9	126.9	110.9	94.3	76.7	39.0
2100	113.4	101.5	88.8	75.5	61.5	31.5
1900	103.2	92.37	80.9	68.7	56.0	28.8
1700	92.6	82.95	72.6	61.8	50.4	25.9

Table 2.4 Ford–Philips 4-215 engine Ideal Isothermal simulation.

Engine and Operating parameters	
Clearance volumes	$V_{\mathrm{clc}} = V_{\mathrm{cle}} = 214.2$ cc
Swept volumes	$V_{\mathrm{swc}} = V_{\mathrm{swe}} = 870.6$ cc
Void volumes: Cooler	$V_{\mathrm{k}} = 164.3$ cc
Regenerator	$V_{\mathrm{r}} = 705.8$ cc
Heater	$V_{\mathrm{h}} = 510.9$ cc
Mean pressure	$p_{\mathrm{mean}} = 150$ bar
Mass of gas in engine	$M = 16.2$ g
Hot space temperature	$T_{\mathrm{h}} = 1023$ K
Cold space temperature	$T_{\mathrm{k}} = 337$ K
Ideal Isothermal performance	
Work done	$W = 3870.3$ J/cycle
Heat transferred to gas in hot space	$Q_{\mathrm{e}} = 5771.6$ J/cycle
Heat transferred to gas in cold space	$Q_{\mathrm{c}} = -1901.3$ J/cycle
Thermal efficiency	$\eta = W/Q_{\mathrm{e}} = 67.1\%$
Indicated power output	Power = 212.9 kW at 3300 rpm

Note. The engine is considered as having a single cycle.
All volumes per cylinder are multiplied by four.

The pressure/volume indicator diagram shown in figure 2.7 is the standard means of characterising an engine. The engine size is indicated by the total volume variation and its mass by the maximum pressure, the work done being equal to the area enclosed by the curve.

2.5 Case study—The General Motors GPU-3 engine

2.5.1 The rhombic drive mechanism

The rhombic drive mechanism was invented by R J Meijer of Philips in 1959 (Meijer 1959), and is shown schematically in figure 2.8. The system consists of separate displacer and power pistons which have conveniently separated functions. The displacer separates the hot and cold spaces at approximately the same pressure and is used to shuttle the working gas between these spaces. The power piston provides both the compression and the expansion processes. There are two cranks which are geared together so as to counter-rotate and drive the yokes, to which are attached the displacer and power piston rods. A pressurised buffer space allows the engine to operate at high mean pressures without requiring a pressurised crankcase. Thus only two shaft seals are required on the displacer and power piston rods.

The success of this arrangement is due to the fact that the two pistons have no side forces, as the horizontal components of the forces exerted by each pair

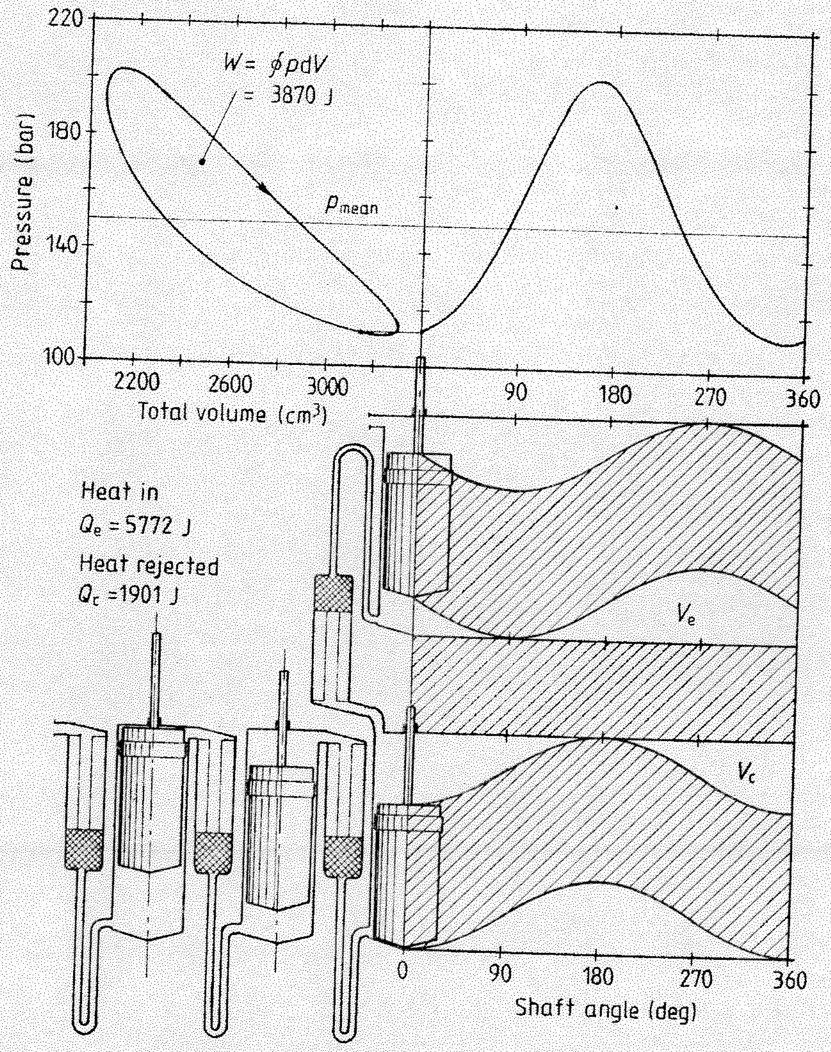

Figure 2.7 Ford–Philips 4-215 engine—Ideal Isothermal simulation.

of connecting rods are exactly balanced at each yoke. Furthermore, complete static and dynamic balancing is attainable in the single cylinder arrangement, allowing vibrationless high-speed operation. The principle disadvantage of the rhombic drive engine is its relative complexity.

The rhombic drive mechanism does not produce sinusoidal volume variations. The actual volume variations are functions of the various geometric parameters of the mechanism and are derived from geometrical considerations, as in figure 2.9. The complete set of equations is summarised in figure 2.10, in which the working space volumes and volume derivatives are shown as functions of the crank angle θ. The initial condition ($\theta = 0$) has been arbitrarily chosen as the point of maximum compression space volume.

2.5.2 The GPU-3 engine

The GPU-3 (Ground Power Unit) is a rhombic drive Stirling engine generator set which was developed by the General Motors Research