UNIT 61: ENGINEERING THERMODYNAMICS

Unit code: D/601/1410

QCF level: 5

Credit value: 15

OUTCOME 2
INTERNAL COMBUSTION ENGINE PERFORMANCE

TUTORIAL No. 5 – PERFORMANCE CHARACTERISTICS

2 **Be able to evaluate the performance of internal combustion engines**

Second law of thermodynamics: statement of law; schematic representation of a heat engine to show heat and work flow

Heat engine cycles: Carnot cycle; Otto cycle; Diesel cycle; dual combustion cycle; Joule cycle; property diagrams; Carnot efficiency; air-standard efficiency

Performance characteristics: engine trials; indicated and brake mean effective pressure; indicated and brake power; indicated and brake thermal efficiency; mechanical efficiency; relative efficiency; specific fuel consumption; heat balance

Improvements: turbocharging; turbocharging and intercooling; cooling system and exhaust gas heat recovery systems

On completion of this tutorial you should be able to do the following.

- Calculate the fuel power of an engine.
- Calculate the brake power of an engine.
- Calculate the indicated power of an engine.
- Calculate the Mean Effective Pressure of an engine.
- Calculate the various efficiencies of an engine.
- Examine how the performance of real engines may be improved.
- Explain the purpose f a turbo charger.
- Explain the purpose of a supercharger
- Explain the advantages of inter-cooling.
- Discuss the advantages of using waste heat recovery.
- Discuss the use of waster heat boilers.
- Discuss combined heating and power systems.

1 FUEL POWER (F.P.)

Fuel power is the thermal power released by burning fuel inside the engine.

F.P. = mass of fuel burned per second x calorific value of the fuel.

F.P. = m_f x C.V.

All engines burn fuel to produce heat that is then partially converted into mechanical power. The chemistry of combustion is not dealt with here. The things you need to learn at this stage follow.

1.1 AIR FUEL RATIO

This is the ratio of the mass of air used to the mass of fuel burned.

Air Fuel Ratio = m_a/m_f

The ideal value that just completely burns all the fuel is called the *STOICHIOMETRIC RATIO*.

In reality, the air needed to ensure complete combustion is greater than the ideal ratio. This depends on how efficient the engine is at getting all the oxygen to meet the combustible elements. The volume of air drawn into the engine is theoretically equal to the capacity of the engine (the swept volumes of the cylinders). The mass contained in this volume depends upon the pressure and temperature of the air. The pressure in particular depends upon the nature of any restrictions placed in the inlet flow path.

1.2 CALORIFIC VALUE

This is the heat released by burning 1 kg of fuel. There is a higher and lower value for fuels containing hydrogen. The lower value is normally used because water vapour formed during combustion passes out of the system and takes with it the latent energy.

WORKED EXAMPLE No.1

An engine consumes 0.01573 kg/s of air. The air fuel ratio is 12/1. The calorific value is 46 MJ/kg. Calculate the Fuel Power.

SOLUTION

Air consumed m_a = 0.01573 kg/s.
Mass of fuel m_f = 0.01573/12 = 0.00131 kg/s

Heat released F.P.= calorific value x m_f = 46 000 kJ/kg x 0.00131 kg/s
F.P.= 60.3 KW

SELF ASSESSMENT EXERCISE No.1

1. An engine consumes 43.1 g/s of air with an air/fuel ratio of 13/1. The calorific value is 45 MJ/kg. Calculate the heat released by combustion. (149 kW)

2. An engine requires 120 kW of fuel power by burning fuel with a calorific value of 37 MJ/kg. The air fuel/ratio required is 14/1. Calculate the mass flow rate of air required. (45.4 g/s)

2 BRAKE POWER (B.P.)

Brake power is the output power of an engine measured by developing the power into a brake dynamometer on the output shaft. Dynamometers measure the speed and the Torque of the shaft. The Brake Power is calculated with the formula

$B.P. = 2\pi NT$ where N is the shaft speed in rev/s

T is the torque in N m

You may need to know how to work out the torque for different types of dynamometers. In all cases the torque is **T = net brake force x radius**

The two main types are shown below.

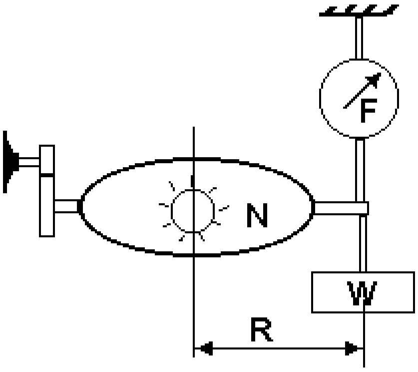

Figure 1

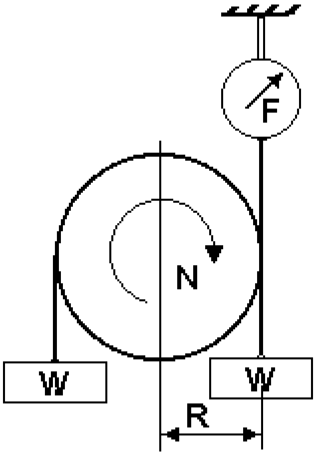

Figure 2

Figure 1 shows a hydraulic dynamometer which absorbs the engine power with an impeller inside a water filled casing. Basically it is a pump with a restricted flow. The power heats up the water and produces a torque on the casing. The casing is restrained by a weight pulling down and a compression spring balance pushing down also. The torque is then (F + W) x R.

Figure 2 shows a friction drum on which a belt rubs and absorbs the power by heating up the drum which is usually water cooled. The belt is restrained by a spring balance and one weight. the second equal weight acts to cancel out the other so the torque is given by T = F R.

3 INDICATED POWER

This is the power developed by the pressure of the gas acting on the pistons. It is found by recording the pressure against volume inside the piston. Such diagrams are called indicator diagrams and they are taken with engine indicators. The diagram shows a typical indicator diagram for an internal combustion engine.

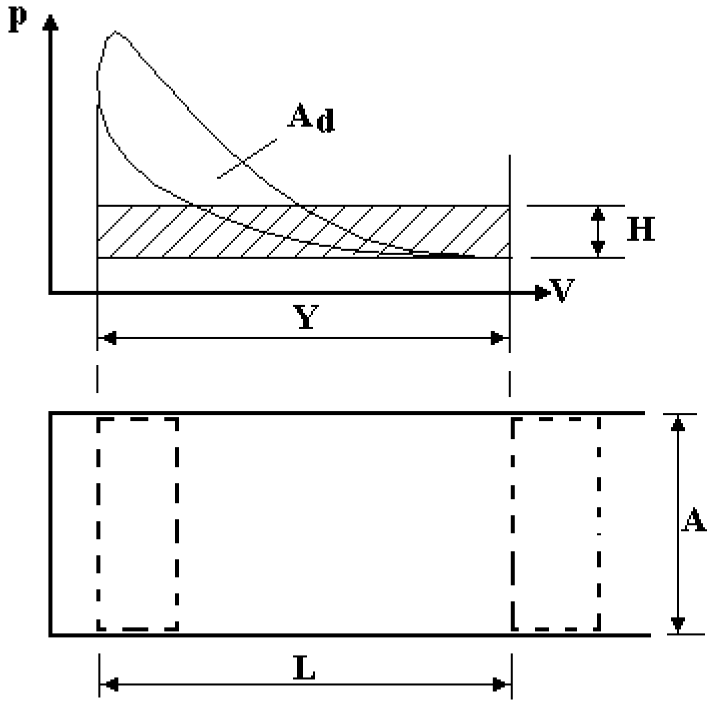

Figure 3

The average force on the piston throughout one cycle is F where

$$F = MEP \times \text{Area of piston} = pA$$

The Mean Effective Pressure p is the mean pressure during the cycle.

The work done during one cycle is

$$W = F L = pAL$$

L is the stroke.

The number of cycles per second is N. The Indicated Power is then

$$\text{I.P.} = pLAN \text{ per cylinder.}$$

Note for a 4 stroke engine N = ½ the shaft speed.

The mean effective pressure is found from the indicator diagram as follows.

The area enclosed by the indicator diagram represents the work done per cycle per cylinder. Let this area be A_d mm^2. The average height of the graph is H mm. The length of the diagram is Y mm. The hatched area is equal to A_d and so

$$A_d = YH$$
$$H = A_d/Y$$

In order to convert H into pressure units, the pressure scale (or spring rate) of the indicator measuring system must be known. Let this be S_p kPa/mm. The MEP is then found from

$$MEP = S_p \; H$$

This is also known as the Indicated Mean Effective Pressure because it is used to calculate the Indicated Power. There is also a Brake Mean Effective Pressure (BMEP) which is the mean pressure which would produce the brake power.

$$BP = (BMEP)\,LAN$$

The BMEP may be defined from this as

$$\mathbf{BMEP = BP/LAN}$$

4 EFFICIENCIES

4.1 BRAKE THERMAL EFFICIENCY

This tells us how much of the fuel power is converted into brake power.

$$\eta_{BTh} = \mathbf{B.P./F.P.}$$

4.2 INDICATED THERMAL EFFICIENCY

This tells us how much of the fuel power is converted into brake power.

$$\eta_{ITh} = \mathbf{I.P./F.P.}$$

4.3 MECHANICAL EFFICIENCY

This tells us how much of the indicated power is converted into brake power. The difference between them is due to frictional losses between the moving parts and the energy taken to run the auxiliary equipment such as the fuel pump, water pump, oil pump and alternator.

$$\eta_{mech} = \mathbf{B.P./I.P.}$$

WORKED EXAMPLE No.2

A 4 cylinder, 4 stroke engine gave the following results on a test bed.

Shaft Speed	N = 2 500 rev/min
Torque arm	R = 0.4 m
Net Brake Load	F = 200 N
Fuel consumption	m_f = 2 g/s
Calorific value	C.V.= 42 MJ/kg
Area of indicator diagram	A_d = 300 mm^2
Pressure scale	S_p = 80 kPa/mm
Stroke	L = 100 mm
Bore	D = 100 mm
Base length of diagram	Y = 60 mm.

Calculate the B.P., F.P., I.P., MEP, η_{BTh}, η_{ITh}, and η_{mech},

SOLUTION

BP = 2 πNT = 2π x (2500/60)x (200 x 0.4) = 20.94 kW

FP = mass/s x C.V. = 0.002 kg/s x 42 000 kJ/kg = 84 kW

IP = pLAN

p = MEP = A_d/Y x S_p = (300/60) x 80 = 400 kPa
IP = 400 x 0.1 x (π x 0.1^2/4) x (2500/60)/2 per cylinder
IP = 6.54 kW per cylinder.
For 4 cylinders IP = 6.54 x 4 = 26.18 kW

η_{BTh}= 20.94/84 = 24.9%
η_{ITh}= 26.18/84 = 31.1 %
η_{mech}= 20.94/26.18 = 80%

SELF ASSESSMENT EXERCISE No.2

1. A 4 stroke spark ignition engine gave the following results during a test.

Number of cylinders	6
Bore of cylinders	90 mm
Stroke	80 mm
Speed	5000 rev/min
Fuel consumption rate	0.225 kg/min
Calorific value	44 MJ/kg
Net brake load	180 N
Torque arm	0.5 m
Net indicated area	720 mm^2
Base length of indicator diagram	60 mm
Pressure scale	40 kPa/mm

Calculate the following.

i. The Brake Power. (47.12 kW)
ii. The Mean effective Pressure. (480 kPa)
iii. The Indicated Power. (61 kW)
iv. The Mechanical Efficiency. (77.2%)
v. The Brake Thermal efficiency. (28.6%)

2. A two stroke spark ignition engine gave the following results during a test.

Number of cylinders	4
Bore of cylinders	100 mm
Stroke	100 mm
Speed	2000 rev/min
Fuel consumption rate	5 g/s
Calorific value	46 MJ/kg
Net brake load	500 N
Torque arm	0.5 m
Net indicated area	1 500 mm^2
Base length of indicator diagram	66 mm
Pressure scale	25 kPa/mm

Calculate the following.

i. The Indicated thermal efficiency. (25.9%)
ii. The Mechanical Efficiency. (88%)
iii. The Brake Thermal efficiency. (22.8%)

3. A two stroke diesel engine gave the following results during a test.

Number of cylinders	4
Bore of cylinders	80 mm
Stroke	80 mm
Speed	2 200 rev/min
Fuel consumption rate	1.6 cm^3/s
Fuel density	750 kg/m^3
Calorific value	60 MJ/kg
Nett brake load	195 N
Torque arm	0.4 m
Nett indicated area	300 mm^2
Base length of indicator diagram	40.2 mm
Pressure scale	50 kPa/mm

Calculate

i. The Indicated thermal efficiency. (30.5%)
ii. The Mechanical Efficiency. (81.7%)
iii. The Brake Thermal efficiency. (25%)

4. A four diesel engine gave the following results during a test.

Number of cylinders	4
Bore of cylinders	90 mm
Stroke	80 mm
Speed	5 000 rev/min
Fuel consumption rate	0.09 kg/min
Calorific value	44 MJ/kg
Nett brake load	60 N
Torque arm	0.5 m
MEP	280 kPa

Calculate the following.

i. The Mechanical Efficiency. (66.1%)
ii. The Brake Thermal efficiency. (23.8%)
iii. The Indicated Thermal Efficiency. (36%)

5. PERFORMANCE IMPROVEMENT

5.1 INTERNAL COMBUSTION ENGINES

In the preceding work it has been shown that the efficiency of internal combustion engines depends upon the volume compression ratio and for gas turbines it depends upon the pressure compression ratio. This section debates some of the practical problems and solutions for improvement of performance.

5.1.1 ENGINE MANAGEMENT

High compression ratios in spark ignition engines leads to pre-ignition as the fuel detonates without the aid of a spark before the point of maximum compression. This produces very high peaks of pressure and damages the engine. Reducing this problem involves the use of fuels that are less prone to detonate (high octane ratings). Timing of the spark ignition is also vital. The correct timing depends upon many factors such as air/fuel ratio and engine load. Modern engines use fuel management systems in which the timing and the air/fuel ratio are controlled by a computer connected to sensors. This allows greater compression ratios and hence efficiency.

Fuel injection gives a measure of control over the combustion process and this is now possible with petrol engines as well as diesel engines.

5.1.2 TURBO CHARGING

The power produced by an engine basically depends on the amount of fuel burned. This is limited by the mass of air in the cylinder. To burn more fuel requires more air. Blowing air into the cylinders under pressure may do this and requires an air blower. This is a successful process in compression ignition engines but increases the problem of pre-ignition on spark ignition engines. The blower may be driven by a mechanical connection direct to the engine crankshaft. The Lobe compressor shown in figure 4 is commonly used. This arrangement is called SUPERCHARGING. On large engines, the blower is driven by a small gas turbine that uses the exhaust from the engine to power it. This is called TURBO CHARGING. Figure 5 shows a turbo charger.

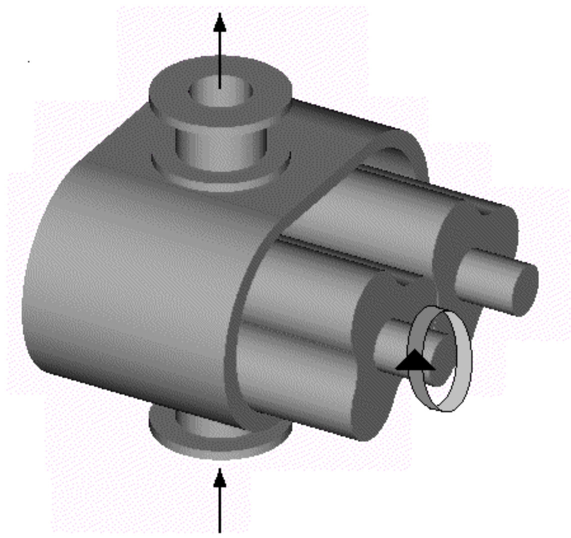

Fig. 4

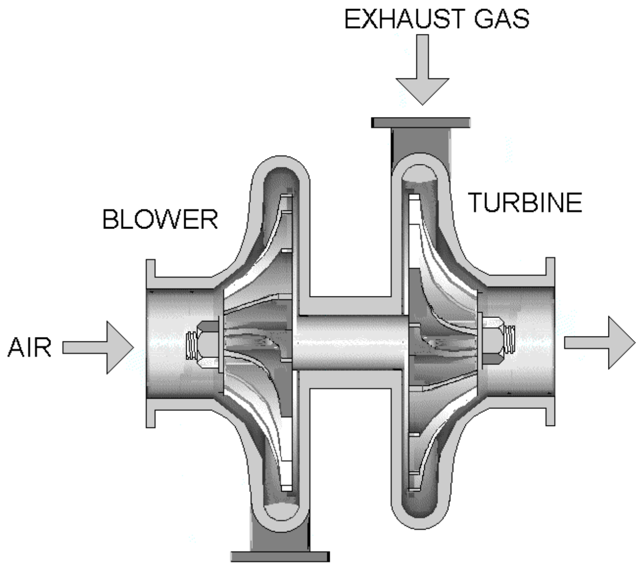

Fig. 5

5.1.3 INTER-COOLING

The mass contained in a volume of air depends upon the temperature. The colder the air, the more mass it contains. Compressed air is naturally hot so if it can be cooled after compression, a greater mass of air may be supplied to the cylinder.

Turbo charging and inter-cooling on large compression ignition engines leads to improved efficiency as well as increased power. Fig.6 shows an intercooler designed to fit under a car radiator.

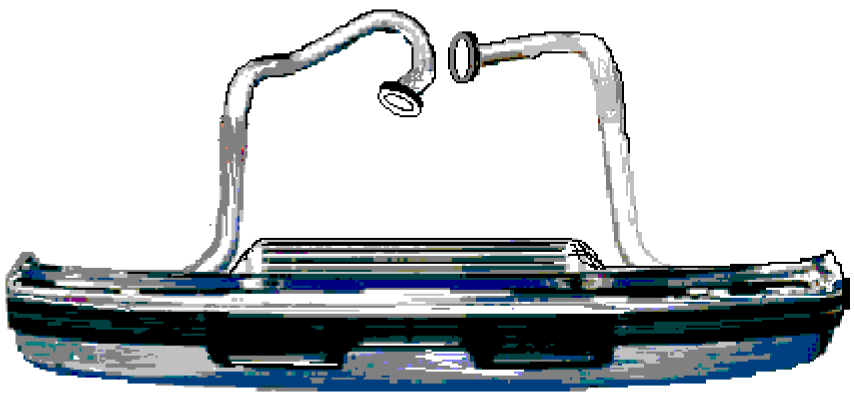

Fig. 6

6 EXHAUST GAS HEAT RECOVERY

When large amounts of hot exhaust gas is produced, by either gas turbines or large diesel engines, the heat in the exhaust gas may be recovered for useful applications such as using it to produce hot water or steam in a boiler. A factory might well use a gas turbine to produce electric power and hot water or steam. This is more economical than buying electricity.

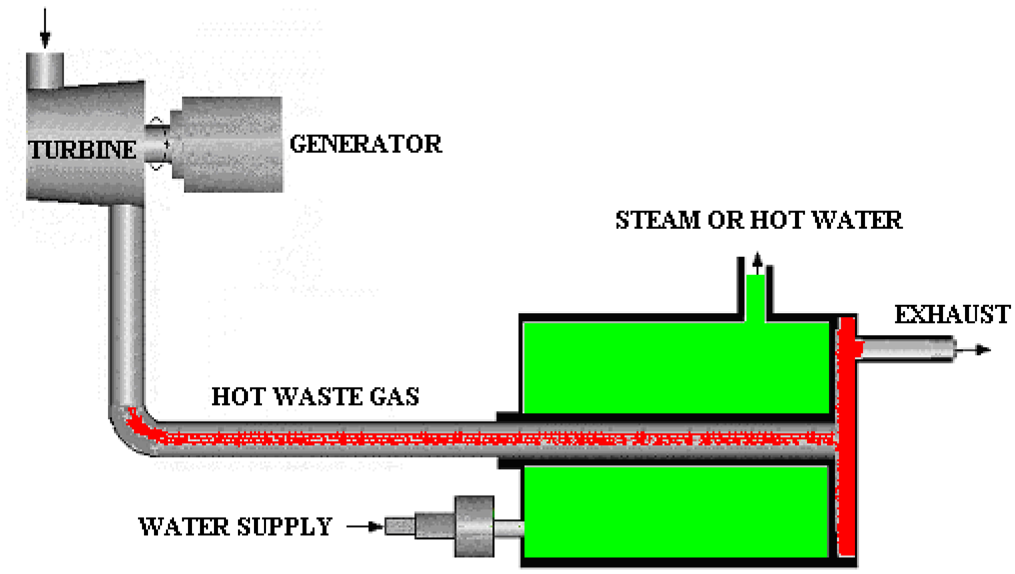

Fig. 7

When the generation of electric power is combined with a waste heat system, it is called COMBINED POWER AND HEATING. On a large scale, this is sometimes done on major power stations. The enormous quantities of waste heat produced in the form of hot water from the condensers may be pumped through a hot water pipe system to heat buildings or large greenhouses.

SELF ASSESSMENT EXERCISE No.3

This is an assignment suitable for testing a range of knowledge and communication skills. There is no definitive solution available for this.

A factory is to be built that uses both electricity and steam. There are two proposals to be considered.

PROPOSAL 1
Produce steam in an oil fired boiler and purchase electricity.

PROPOSAL 2
Generate electric power with a gas turbine and produce steam in a waste heat boiler using the exhaust gas.

OPERATING DATA FOR STEAM BOILER

Mass Flow rate	1 kg/s
Steam condition	5 bar and dry saturated.
Feed water temperature	15^oC.

When burning fuel, the combustion efficiency is typically 85%

When using exhaust gas, the heat transfer from the gas may be assumed to be equal to the heat gained by the water and steam. The exhaust gas is cooled to 100^oC before leaving the boiler.

GAS TURBINE DATA

Pressure ratio	7
Inlet air pressure	1 bar
Inlet air temperature	15^oC
Combustion chamber temperature	1500^oC

FUEL DATA

Any fuel to be burned in either the gas turbine or the boiler will be light oil with a calorific value of 42 MJ/kg. The cost of fuel is 12.7 pence per kg.

Electricity cost 2.5 pence per kWhr (1 kWhr = 3600 kJ)

PROPERTIES

AIR	BURNED GAS
Cp=1.005 kJ/kg K	Cp=1.1 kJ/kg K
γ=1.4	γ=1.3

Produce a report comparing the costs for both schemes. You will need to do the following tasks.

GUIDANCE

In the course of your work you will need to do the following.

STEAM BOILER

You will need to determine the following.

i. The energy required to make the steam.
ii. The fuel required in kg/s.
iii. The mass of exhaust gas required to produce the same steam in kg/s.

GAS TURBINE

You will need to equate the heat transfer from burning fuel to the energy required to raise the temperature in the combustion chamber.

You will need to determine the following.

vi. The mass flow of air.
v. The fuel burned in kg/s.
vi. The Power input of the compressor.
vii. The power output of the turbine.
viii. The net power for generating electricity.

COSTING

Base the cost of option 1 on the cost of fuel plus the cost of buying the same electricity as for option 2.

Base the cost on the cost of fuel only.

What other factors would you consider when making a decision on which option take?