MODULE 8:

Fuel Cell Hybrid Electric Vehicles

College of the Desert

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XCELLSiS
The Fuel Cell Engine Company

BALLARD

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CONTENTS

OBJECTIVES

At the completion of this module, the technician will understand the types and uses of:

- hybrid electric vehicles
- electric motors
- auxiliary power units
- generators
- energy storage systems
- regenerative braking
- control systems

MODULE 8: FUEL CELL HYBRID ELECTRIC VEHICLES

Key Points & Notes

8.1 Hybrid Electric Vehicles

A hybrid electric vehicle (HEV) augments an electric vehicle (EV) with a second source of power referred to as the alternative power unit (APU).

Pure electric vehicles currently do not have adequate range when powered by batteries alone, and since recharging requires several hours, the vehicles are viewed as impractical for driving extended distances. If air conditioning or heating is used, the vehicle's range is further reduced. Accordingly, the hybrid concept, where the alternative power unit is used as a second source of energy, is gaining acceptance and is overcoming some of the problems of pure electric vehicles.

Courtesy of Jo Borck

1916 Range & Lang Electric

More electric vehicles were in use in 1915 than there are at present.

Courtesy of Jo Borck

Figure 8-1 Electric Vehicles

The hybrid electric vehicle operates the alternative power unit to supply the power required by the vehicle, to recharge the batteries, and to power accessories like the air conditioner and heater. Hybrid electric cars can exceed the limited 100 mile (160 km) range-per-charge of most electric vehicles and have the potential to limit emissions to near zero. A hybrid can achieve the cruising range and performance advantages of conventional vehicles with the low-noise, low-exhaust emissions, and energy independence benefits of electric vehicles. Two types of hybrid vehicle configurations are the series and the parallel hybrids.

8.1.1 Series Hybrids

A series hybrid is similar to an electric vehicle with an on-board generator. The vehicle runs on battery power like a pure electric vehicle until the batteries reach a predetermined discharged level. At that point the APU turns on and begins recharging the battery. The APU operates until the batteries are charged to a predetermined level.

The length of time the APU is on depends on the size of the batteries and the APU itself. Since the APU is not directly connected to the drive train, it can be run at its optimal operating condition; hence, fuel economy is increased and emissions are reduced relative to a pure IC engine vehicle. A schematic of a series hybrid is shown in Figure 8-2.

Key Points & Notes

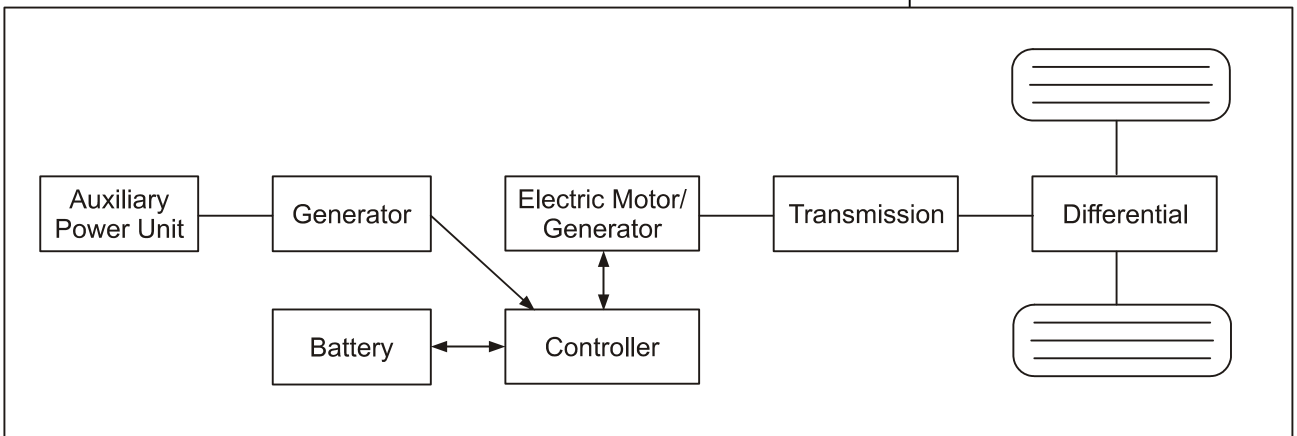

Figure 8-2 Schematic of a Series HEV

8.1.2 Parallel Hybrids

In the parallel hybrid configuration, an APU capable of producing motive force is mechanically linked to the drive train. This approach eliminates the generator of the series approach. When the APU is on, the controller divides energy between the drive train (propulsion) and the batteries (energy storage). The amount of energy divided between the two is determined by the speed and driving pattern.

L3 Research Aeris Parallel Hybrid

For example, under acceleration, more power is allocated to the drive train than to the batteries. During periods of idle or low speeds, more power goes to the batteries than the drive train.

When the APU is off, the parallel hybrid runs like an electric vehicle. The batteries provide electricity to the electric motor where it is converted to mechanical energy to power the vehicle. The batteries also provide additional power to the drive train when the APU is not producing enough and to power auxiliary systems such as the air conditioner and heater.

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The drive train for a parallel hybrid is more complex than that of a series hybrid as both the electric motor and the APU must be mechanically linked to the driveshaft. Since parallel hybrids only work with APU's that produce a mechanical output, fuel cells cannot be used for this option. Figure 8-3 shows a schematic of a parallel hybrid.

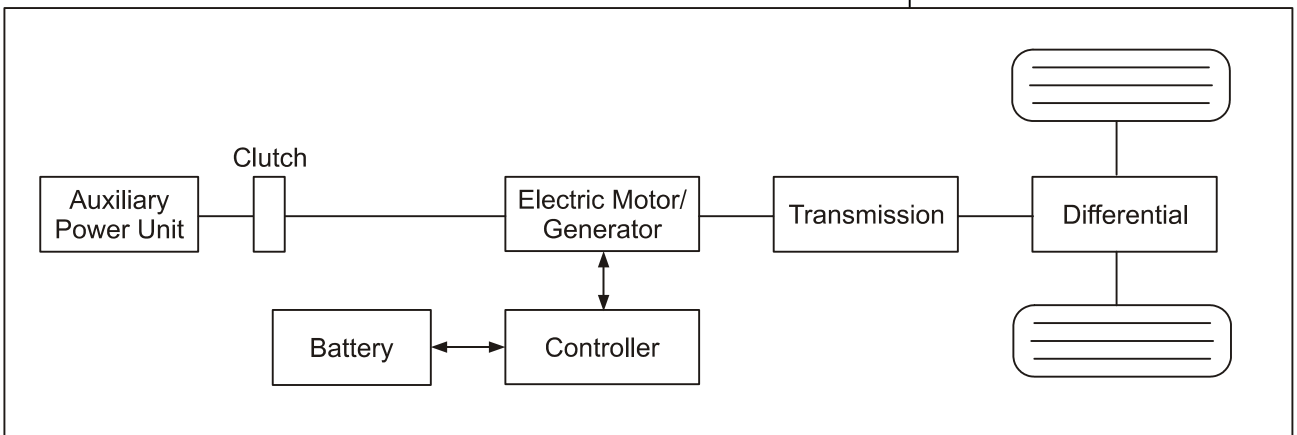

Figure 8-3 A schematic of a Parallel HEV

8.2 Major Components of Hybrid Vehicles

Key Points & Notes

8.2.1 Electric Drive Motors

Hybrid electric vehicles use an electric driveline and motor to provide the power for propulsion. The electric motor is a simple, efficient and durable device that is used every day in all sorts of applications. Electric motors range from those with fractional horsepower that run small appliances, to 5000-horsepower giants used in paper mills and other industries.

An electric motor converts electric energy to mechanical energy (motion) to drive the hybrid vehicle. Every motor can be used as a generator by rewiring it to transform mechanical energy into electrical current, but not all motors make efficient generators. For this dual use, the hybrid may use the electric motor to start the engine and then switch to generating electricity to keep the batteries charged. This reduces both the weight and cost of having two separate devices for engine starting and battery recharging.

In conventional vehicles, engine size determines the total power available to a moving vehicle. Hybrids, on the other hand, have electric motors that provide additional power when needed by the vehicle.

Both electric motors and engines can be rated in kilowatts (kW) — the preferred international standard — or in horsepower (hp). One hp equals 0.746 kW. When comparing horsepower ratings of a motor to an engine, it appears that electric vehicles are drastically under-powered. However, internal combustion engines are rated at the *maximum* power output, while electric motors are rated at their continuous power capabilities. A motor that can produce 10 hp continuously can easily produce three or four times that much power for a few minutes. Unlike internal combustion engines, electric motors emit zero harmful emissions.

The electric motor changes electric energy into mechanical power for work. Operation of the motor is based on three concepts:

- an electric current that produces a magnetic field
- the direction of current in an electromagnet that determines the location of the magnet's poles
- and the magnetic poles attraction or repulsion to each other

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An electric motor consists chiefly of a rotating electrical conductor situated between the north and south poles of a stationary magnet. It also contains a conductor known as an armature, a stationary magnet called the field structure, and a commutator.

The field structure establishes a constant magnetic field in the motor. The armature rotates and becomes an electromagnet when a current passes through it. Connection to the driveshaft allows it to drive the load. The commutator reverses the direction of the current in the armature and helps transmit current between the armature and the power source.

There are two types of motors: direct current and alternating current.

8.2.1.1 Direct Current Motors

In the direct current (DC) motors, the current always flows in the same direction. There are three types of DC motors: series, shunt and compound.

In the series motor, the armature and the field magnet are connected electrically in series. Current flows through the field magnet to the armature, increasing the strength of the magnets. The motor can start quickly under a heavy load, but such a heavy load decreases the motor speed.

The shunt motor connects the magnet and armature in parallel. Part of the current goes through the magnet while the rest goes through the armature. It runs at an even speed regardless of the load, but if the load is too heavy, the motor is difficult to start.

In the compound motor, two field magnets are connected to the armature, one in series and the other in parallel. The compound motor has the benefits of both the series and the shunt. It starts easily with a heavy load and maintains a relatively constant speed even when the load is increased.

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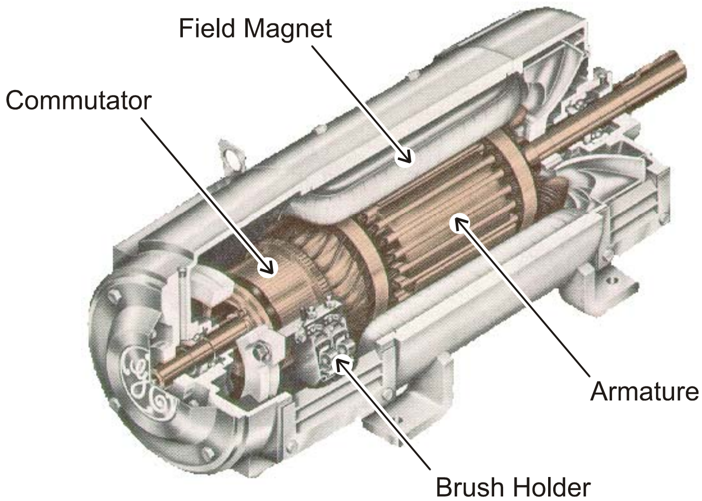

Figure 8-4 Direct Current Motor

8.2.1.2 Alternating Current Motors

Alternating current (AC) motors regularly reverse current flow direction. The reversal is typically 60 times per second or 60 Hz in North America and 50 Hz in Europe. Two changes of direction completes one cycle. The number of cycles per second is called the frequency of the alternating current.

The AC motor has many advantages over the DC motor. It is easy to build and convenient to use. Most AC motors do not require commutators because the current reverses its direction automatically. Those that use commutators do so to conduct the current from the external power source to the moving part of the motor and back.

The two types of AC motors are the induction and the synchronous motors.

In the induction motor, the rotor has no direct connection to an external source of electricity. The current flows around the field coils in the stator and produces a rotating magnetic field. This field induces an electric current in the rotor resulting in another magnetic field. The magnetic field from the rotor interacts with the magnetic field from the stator causing the rotor to turn.

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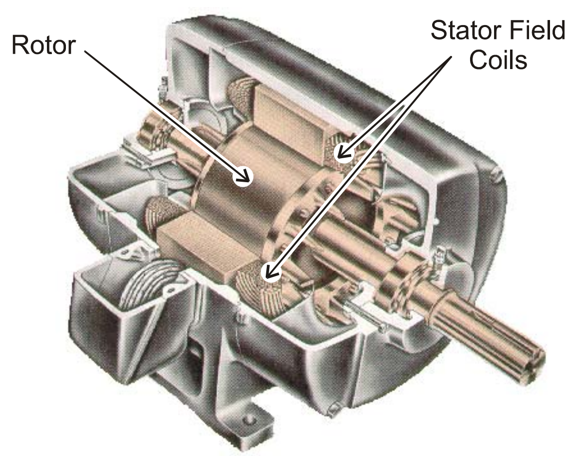

Figure 8-5 Alternating Current Induction Motor

In a synchronous motor, the stator also produces a rotating magnetic field. However, the rotor receives current directly from the power source instead of relying on the magnetic field from the stator to induce an electric current. The rotor moves at a fixed speed in step with the rotating field of the stator. Therefore, the synchronous motor maintains a fixed speed and uses less energy than an induction motor.

8.2.1.3 Electric Motor Configurations

The two possible configurations of electric drive motors in a hybrid vehicle are a single electric motor connected to the wheels through a drive train, or multiple electric motors, one located at each wheel.

The electric motor connected to the wheels through the drive train is the simplest design and is the present design of conventional vehicles.

Multiple electric motors, however, produce better traction and regenerative braking at each wheel, allow more room for other parts, and continue to function even when one or more motors malfunction. This configuration has been used in some all-terrain vehicles.

8.2.2 Auxiliary Power Units

The auxiliary power unit (APU) of a hybrid vehicle supplies the baseline power required to the vehicle, recharges the batteries and powers accessories such as the air conditioner and heater. The APU can consist of a mechanical type engine or a fuel cell. A mechanical type engine can be a spark ignition, compression ignition, rotary, turbine or Stirling engine.

8.2.2.1 Spark Ignition Engine

In 1862, Beau de Rochas proposed a sequence of operations that remains typical of most spark ignition engines. The four-stroke cycle requires two revolutions of the crankshaft for each power stroke and allows the piston to slide back and forth in the cylinder while transmitting the power to the drive shaft.

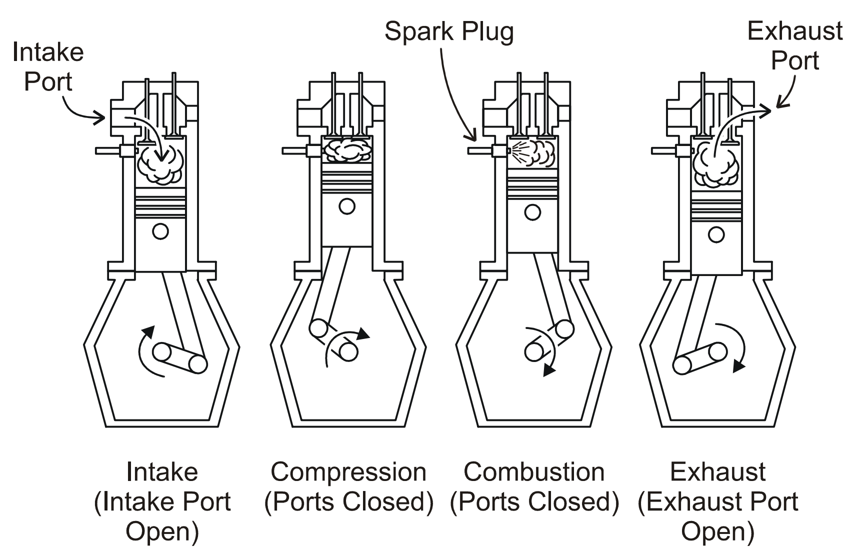

Figure 8-6 Four-Stroke Engine Operation

The spark ignition engine has a simple, mature, well understood design, a good power-to-weight ratio, and the ability to burn gasoline, methanol, ethanol, natural gas, propane or hydrogen. It also has well developed emission controls. The disadvantages, however, are poor part-load efficiency and relatively high uncontrolled emissions of hydrocarbons, carbon monoxide and oxides of nitrogen.

In order to produce a higher output from the same size engine and to obtain some valve simplification, the two-stroke cycle was developed by Dugald Clerk in 1878. This cycle is applicable both to compression ignition and to spark ignition operation, but has been primarily successful only with the latter.

The two-stroke engine's combustion cycle is completed in two strokes (one revolution) of the crankshaft as opposed to the four strokes (two revolutions) required by the four-stroke engine.

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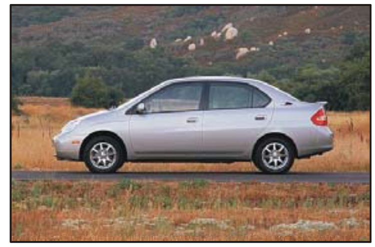
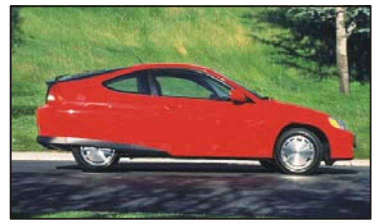


Toyota Prius Hybrid



Honda Insight Hybrid

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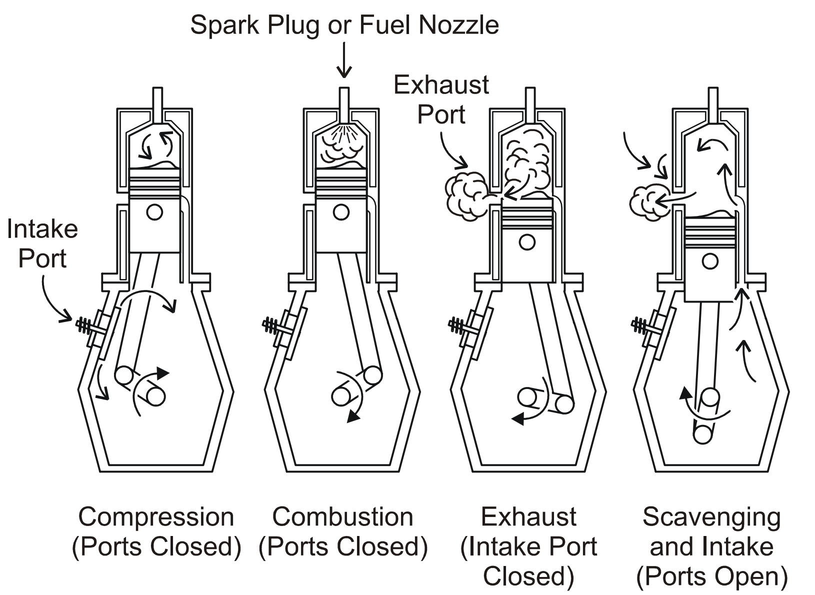

Figure 8-7 Two-Stroke Engine Operation

Compared to the four-stroke, the two-stroke engine has a higher power-to-weight ratio, a simpler design, lower manufacturing costs, and is lightweight. The emissions, however, are a major problem. There are relatively high uncontrolled hydrocarbons and carbon monoxide emissions, and emission control systems have not been sufficiently developed. Two-stroke engines are common in small gasoline motors, such as on chainsaws and smaller motorcycles.

8.2.2.2 Compression Ignition Engines

The compression ignition engine is typified by the diesel engine. The diesel cycle is similar to the Otto cycle except that a high compression ratio and air are required instead of a combustible mixture. Air is admitted to the engine on the intake stroke and the rapid compression of the air raises the temperature to such a point that a fuel, when delivered into the combustion chamber, ignites spontaneously. There is no requirement for a spark to initiate the combustion, or for a homogeneous mixture to propagate the flame.

The advantages of Compression Ignition engines are efficiency at high compression ratios, they are well developed and dependable, and have low carbon monoxide and hydrocarbon emissions. The disadvantages, however, are a high levels of carbon particulate and oxides of nitrogen emissions.

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8.2.2.3 Wankel (Rotary) Engines

In 1954, Felix Wankel found that an engine could be made of three variable-volume chambers formed between a stationary epitrochoid-shaped housing and a rotating equilateral triangular rotor. (A epitrochoid is a curve like an epicycloid, but generated by any point on a radius. An epicycloid is a curve described by a point on the circumference of a circle rolling on the outside of the circumference of another circle. Basically, the housing is circular, and the action is rotational.)

Together with proper arrangement of intake, exhaust and ignition mechanisms, this variation of volume in the three chambers makes it possible to carry out the four main events of the Otto cycle within each of the three chambers.

Wankel engines have a compact design, a high power-to-weight ratio, are lightweight, and use the same emission control systems as the four-stroke SI engines. However, they have relatively poor efficiency and high uncontrolled emissions of hydrocarbons, carbon monoxide and oxides of nitrogen. Wankel engines were produced commercially for Mazda cars in the 1980's, but were eventually replaced by conventional spark ignition engines.

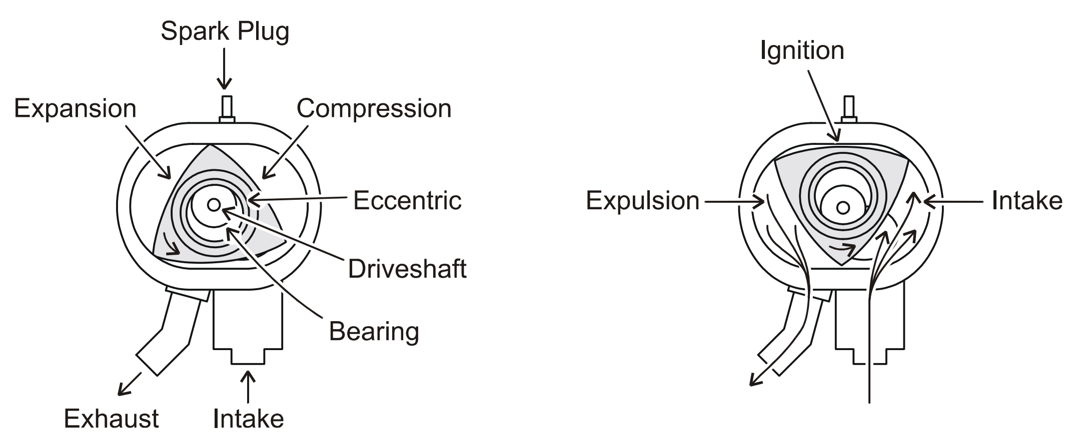

Figure 8-8 Wankel (Rotary) Engine Operation

8.2.2.4 Stirling Engines

An alternative to the internal combustion engine is an external combustion engine known as the Stirling engine. The Stirling cycle has two isothermal processes and two constant-volume processes. The thermal efficiency of the Stirling cycle with perfect regeneration is equal to that of the Carnot cycle for the same temperature range. The Stirling engine has low emissions, good efficiency, and operates quietly. The

Key Points & Notes

disadvantages are a complicated design, a low power-to-weight ratio, high cost and a large cooling requirement.

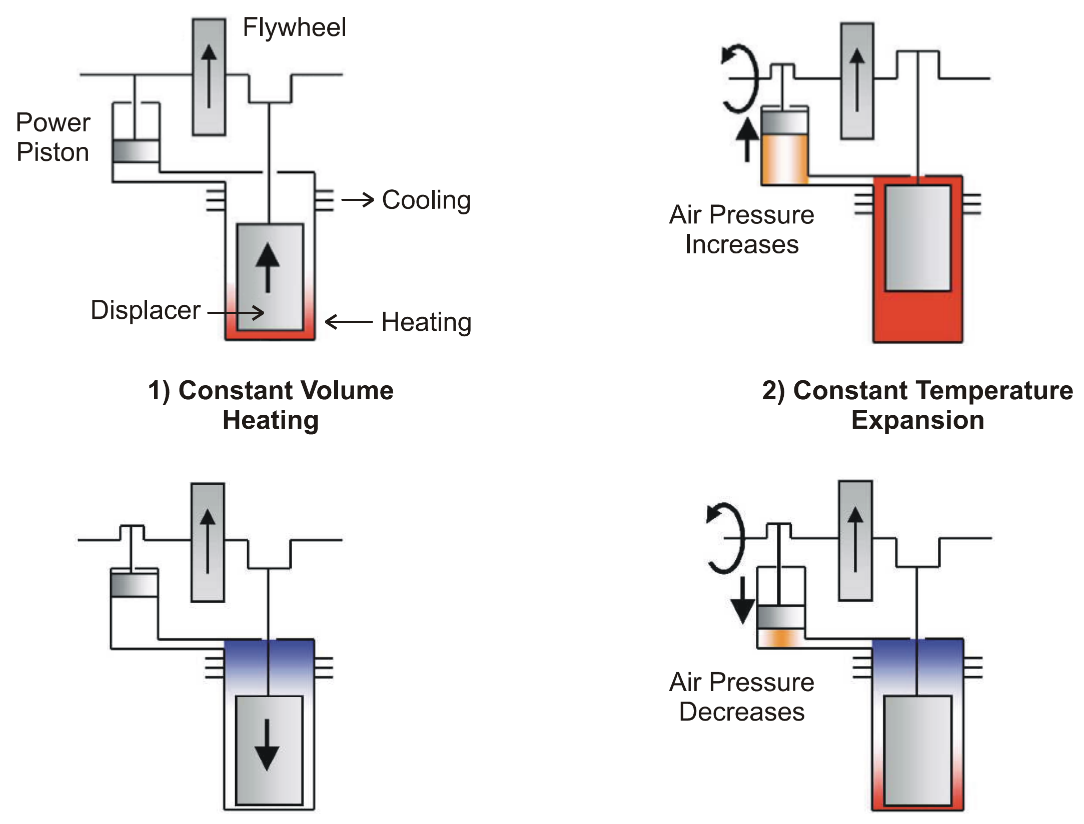

Figure 8-9 Stirling Engine Operation

8.2.2.5 Gas Turbines

Gas turbines, one of the oldest forms of combustion engines, are composed of a turbine, a combustion chamber and an air compressor.

Williams Gas Turbine Engine

The turbine has a rotor that is turned by moving fluid such as water, steam, gas or wind. It changes kinetic energy (energy of movement) into mechanical energy (energy in form of mechanical power). The mechanical energy is transmitted by the turbine through the spinning motion of the rotor's axle.

A gas turbine burns fuels such as oil, natural gas or kerosene. Gas turbines are small, lightweight, smooth running, have good power-to-weight ratios and low emissions. The fundamental problem with them, however, is their expense, poor efficiency at part load and their high operating tempera-

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ture. Gas turbines engines are used on jet aircraft and burn jet fuel, which is a kind of kerosene.

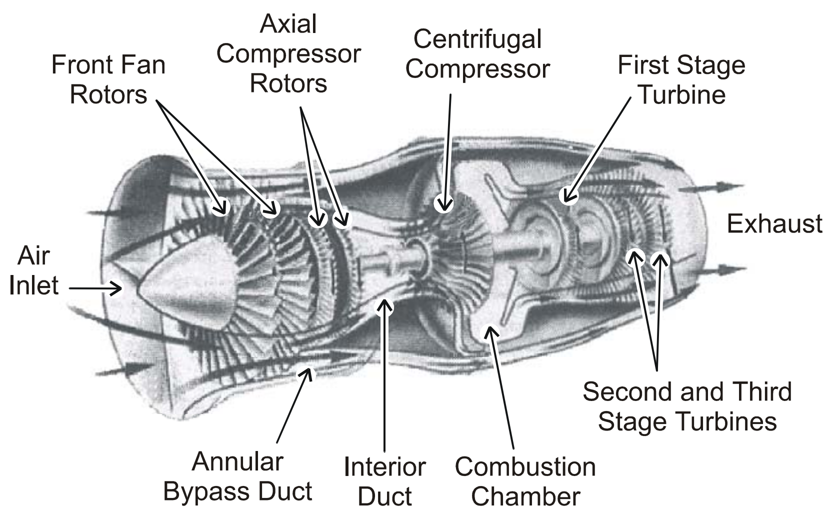

Figure 8-10 Gas Turbine Engine Major Components

8.2.2.6 Fuel Cells

Fuel cells are discussed in detail in other modules of this course. Fuel cells are convenient in electrical hybrid applications since they can be used in tandem with other electricity generating devices.

8.2.3 Generators

All the power systems described above, except for the fuel cell, require a generator to convert the mechanical power into electrical power when used in a series hybrid. Generators, like electrical motors, are either AC or DC.

8.2.3.1 AC Generators

An AC generator (or alternator) produces an electric current that reverses direction many times per second. It is also called a synchronous generator because it generates a voltage containing a high frequency proportional to, or synchronous with, the speed of the rotor.

A simple AC generator has each end of its wire loop, or armature, attached to a slip ring. A carbon brush connected to the outside circuit rests against each of the slip rings. As the armature rotates, the current moves in the direction of the arrows. The brush at the first slip ring conducts the current out of the armature, and the brush at the second slip ring brings it back in.

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When the armature rotates parallel to the magnetic field, no current is generated for a moment. When the armature rotates into the magnetic field again, the current reverses direction. It then flows out of the armature through the second slip ring and back into the armature at the first slip ring.

8.2.3.2 DC Generators

A DC generator produces an electric current that always flows in the same direction. It is different from the AC generator in both the way it is built and how it is used.

The commutator rotates with a loop of wire just as the slip rings do with the rotor of an AC generator. Each half of the commutator ring is called the commutator segment and is insulated from the other half. Each end of the rotating loop of wire is connected to a commutator segment. Two carbon brushes connected to the outside circuit rest against the rotating commutator. One brush conducts the current out of the generator and the other brush feeds the current back in.

The commutator is designed so that no matter how current in the loop alternates, the commutator segment containing outward-going current is always against the “out” brush at the proper time.

8.2.4 Energy Storage Systems

The peak power required in hybrid vehicles is met by devices like batteries, capacitors or a flywheel. These devices store energy and readily release it when needed.

8.2.4.1 Batteries

Batteries are one of the most important parts of a hybrid vehicle. A battery produces electricity by means of chemical action. It consists of one or more electric cells. Each cell has all the chemicals and parts needed to produce an electric current.

There are two types of batteries: primary and secondary (or storage) batteries. Primary batteries discharge and must be discarded after one or more of the chemicals is used up. Secondary batteries, on the other hand, can be recharged after they have delivered their electrical energy. Consequently, secondary batteries are ideal for hybrid application. They are able to supply power to the vehicle and be re-used.

The criteria used for battery selection are: temperature, energy density, power density, service life, shelf life, cost, reliability, cell configuration, charge/discharge cycle, safety, operating environment, recycling, minimal memory effect and efficiency.

8.2.4.2 Capacitors

A capacitor is a device that stores electrical energy in the form of an electrical charge.

A capacitor consists of two metal plates with an insulating material called a dielectric between them. Wires usually connect the plates to a source of electric current such as a battery. When an electric charge flows through the wires from one plate of the capacitor to the other, both plates become charged — one with a positive charge, and the other with a negative charge. The two plates then have potential difference in energy — a voltage — between them.

The plates release their charge when their wires are disconnected from the source and touched together. The ability of the capacitor to store electric energy is its capacitance. The main difference between a battery and a capacitor is that a capacitor can be rapidly charged and discharged.

8.2.4.3 Flywheels

The flywheel is an alternative energy storage system that is capable of replacing chemical batteries in conventional electric vehicles.

A flywheel is a balanced mass spinning around a constant axis that stores energy as rotational kinetic energy. Simply put, a flywheel is a mechanical battery that is capable of delivering multi-kilowatt-hours of energy to the drive system of an electric vehicle.

Flywheel energy storage (FES) systems have been researched for many decades, but their application has been limited due to the high cost of inefficient materials. However, recent advancement in fiber-composite materials, control electronics, and frictionless magnetic bearings have led researchers to believe that modern FES systems could be used to power efficient non-polluting electric vehicles.

The FES systems have been shown to theoretically rival chemical batteries in terms of power, energy density, cycle life, charge time, operating temperature range, environmental friendliness and maintenance needs.

The FES systems are now a viable technology for regenerative braking, for averaging peak power demands, and for storing energy on electric and hybrid vehicles. In hybrids, for example, FES systems can replace expensive ultra-

Key Points & Notes

Capacitors

Key Points & Notes

capacitors for energy storage energy and to average out power demands.

8.2.5 Regenerative Braking

Brakes are devices that slow or stop the movement of a wheel, engine or entire vehicle. Most brakes have a fixed part called a brake shoe or block that presses against a turning wheel to create friction (heat) that causes the wheel to stop or slow down.

In regenerative (or dynamic) braking, some of the energy is converted into electrical energy and stored. Pressing on the brake pedal first activates the regenerative braking system, and then the conventional friction brake. The rotational energy of the braking mechanism generates electrical power and stores it in the batteries.

Electric and hybrid vehicles are well suited to use regenerative braking, as the captured electricity can power the drive motor. This electricity can be used in place of, or to supplement the APU, further reducing fuel use and improving fuel economy.

8.2.6 Control Systems

The electronic control system regulates the high-intensity current, helping it work with the APU counterparts. It controls the power flow between the battery and the motor as well as regenerative braking. A control system contains two main components, namely the command and power components. The command component manages and processes the driver's instructions. The power component chops power flows to control the motor's power intake.

There are two choppers to manage this power flow. The primary chopper is the startup phase and works at low motor speeds. The excitation chopper regulates the motor at medium and high motor speeds.