The Engine

Small gasoline engines belong in the heat engine category. Other heat engines include automotive reciprocating piston engines, gas or steam turbines, steam engines, diesel engines, rotary combustion engines, rocket engines, and jet engines. Only small, one-cylinder and two-cylinder piston engines will be discussed in this book.

The small gasoline engine is called an internal combustion engine because an air/fuel mixture is ignited (fired) and burned inside the engine. See Figure 7-1. The heat from the burning mixture causes the gases to expand rapidly within the closed cylinder. The expanding gases apply strong force and push out in all directions within the cylinder, but only the piston can move.

The piston is pushed away from the center of combustion. If it were not fastened to the crankshaft, it would come out of the cylinder the way a bullet comes out of a gun. The crankshaft and connecting rod keep the piston under control and allow it to travel only a short distance. See Figure 7-2.

When the piston has moved downward as far as it can go, a port is opened. This allows burned gases to escape as the piston returns upward. The burned, escaping gases are called exhaust and come out through the exhaust pipe or manifold.
Figure 7-1.
A—An external combustion engine burns fuel outside the engine. B—An internal combustion engine burns fuel within the engine.

Figure 7-2.
Piston travel is controlled by the connecting rod and crankshaft. Notice the change from reciprocating (up and down) motion to rotary motion.
A manifold is a chamber that collects the exhaust and directs it to the exhaust pipe.

The piston does not pause long at the end of its stroke before the movement of the crankshaft and flywheel carry it back to the top of the cylinder. Bodies in motion tend to continue in motion. This tendency is called inertia. It is what keeps the crankshaft and flywheel moving in the engine.

When the piston reaches the top of its stroke, it is ready to go back down again. Because the piston continues this back and forth or up and down motion, piston engines are often called reciprocating engines.

**Basic Terminology**

To better understand how a gasoline engine works and to appreciate the power it provides, you must learn certain basic terms. These terms will be defined here only as far as necessary to provide a background for further discussion of measuring engine performance. Performance can be defined as the work engines do and how well they do it.

**Engine Bore and Stroke**

*Engine bore* is the diameter or width across the top of the cylinder. *Stroke* is the up or down movement of the piston. Length of stroke is determined by the distance the piston moves from its uppermost position (top dead center or TDC) to its lowest position (bottom dead center or BDC).

The amount of crank offset determines the length of the stroke. *Crank offset* is the distance from the centerline of the connecting rod journal to the centerline of the crankshaft. A 2" offset would produce a 4" stroke. See Figure 7-3.

When the bore diameter is the same as the stroke, the engine is referred to as *square*. When the bore diameter is greater than the stroke, it is termed *over square*. Where bore diameter is less than the stroke, the engine is called *under square*.

**Science of Engine Performance**

In an engine, energy stored in fuel is converted into motion. In order to understand how an engine operates and the factors that affect engine performance, a technician must understand a few basic scientific concepts. The following sections explain the fundamental principles on which the design and operation of all internal combustion engines are based.

**Energy**

Energy is difficult to define. It puts life into matter, giving it warmth, light, and motion. Energy cannot be seen, weighed, or measured. It does not take up space. However, we know it is there, because we can observe and measure its effects. The warmth and light of a bonfire, the electrical spark that jumps the gap of a spark plug, or the turning of a wheel are things we can sense. They are all the effects of energy.

Energy is the capacity to perform work. It is grouped into two distinct classes, potential energy (PE) and kinetic energy (KE). Potential energy is energy that is stored, waiting to be released. A compressed spring or boulder at the top of a hill are common examples of potential energy. Kinetic energy is the energy of motion. Common examples are an expanding spring or a boulder rolling down a hill.
Energy can be further classified based on the way it is stored and transmitted. For example, mechanical energy (ME) is energy that results in the motion of matter. Chemical energy (CE) is energy that is stored or translated through chemical reactions. Thermal energy (TE) is energy that results in heat.

Matter and energy cannot be destroyed. Only the nature of matter and the forms of energy change. For example, when a piece of charcoal burns and disappears, we may think it is completely gone. However, the charcoal material has combined with air and formed a like quantity of ash, water, and gases. The energy that did this existed as flame (light energy) and heat (heat energy). All of this will continue until another change takes place.

Whenever a form of matter can be separated from other forms of matter so that a part or all of its energy can be released, it is said to contain potential energy. Examples of such matter include crude oil and the gasoline taken from it. We have learned different ways to release a part of the energy stored in these substances.

Engines are designed to release and change the potential energy of gasoline into mechanical power. Mechanical power does the work at hand.

**Force**

Forces are being applied all around us. Force is the pushing or pulling of one body on another. Usually two bodies must be in contact for force to be transmitted. For example, as you read this you are applying a force to a chair if you are sitting or to the floor if you are standing. The force is equal to the weight of your body. You can easily measure it with a scale. This is known as gravitational force and it acts on all materials on and around the earth.

Some forces are stationary (motionless); others are moving. For example, if you push against a wall, force is applied but the wall does not move. The use of force may or may not cause motion. Force itself cannot be seen, but there are many ways of using it.

Centrifugal force acts on a body whenever it follows a circular or curved path. The body tries to move outward from the center of its path. Modern examples are the man-made satellites that orbit the earth. The circular path and speed of the satellite produces a centrifugal force outward that is equal to the earth's gravitational force inward so that each is opposed and balanced. Therefore, the satellite neither goes up nor comes down. This is one case where a force is applied without one body touching another body. A ball swung on a string applies centrifugal force as shown in Figure 7-4. The force that opposes centrifugal force is called centripetal force.

Many forces interact when a gasoline engine is operating. The rotational speed of the crankshaft and flywheel create centrifugal force, which causes tensile stress (tension or pull) within the materials making up these parts. If the outward pulling force becomes greater than the strength of the material, the engine could fly apart. The rapid reciprocation (backward and forward or up and down motion) of the piston may put high forces on the connecting rod, crank journal, and piston pin. Figure 7-2 shows how these parts work together.

One of the forces used efficiently in the gasoline engine is the one applied to the top of the piston by rapidly expanding gases in the combustion chamber. This force is produced by burning gasoline mixed with air. The greater the force applied to the piston, the greater the amount of power and work that can be done by the engine.
Force is measured in units of some standard weight such as pounds, ounces, or grams. For example, to support a shop vise weighing 16 lb, a person would have to apply a lifting force of 16 lb. Obviously, only half the lifting force would be needed to support an 8 lb vise.

**Pressure**

Force and pressure are often confused. These terms should be understood in the way they are applied. **Pressure** is a force applied to a given unit of area. For example, a piston with a face area of 5 square inches (in²) may have a total force of 500 lb applied to it by the expanding gases. However, the pressure being applied is 500 lb divided by 5 in², which equals 100 pounds per square inch (psi). This means that every square inch on the piston face has the equivalent of a 100 lb weight pushing on it.

When we speak of pressures in mathematical calculations, we use letters to represent several words. For example, psi means pounds per square inch. The psi formulas are as follows:

\[
\text{psi} = \frac{\text{Force}}{\text{Area}}
\]

or
\[
\text{Force} = \text{psi} \times \text{Area}
\]

or
\[
\text{Area} = \frac{\text{Force}}{\text{psi}}
\]

The area of a circle can be found by multiplying pi, or \(\pi (\pi = 3.1416)\), by the radius squared. The written formula is as follows:

\[
\text{Area} = \pi r^2
\]

Another method is to multiply the constant .7854 by the diameter squared. The written formula is as follows:

\[
\text{Area} = .7854D^2
\]

For example, we shall calculate a force applied to a 3" diameter piston, Figure 7-5, if the cylinder pressure is 125 psi.

\[
\begin{align*}
\text{Area} &= \pi r^2 \\
\text{Area} &= 3.1416 \times (1.5\text{ in} \times 1.5\text{ in}) \\
\text{Area} &= 3.1416 \times 2.25\text{ in}^2 \\
\text{Area} &= 7.0686\text{ in}^2
\end{align*}
\]

Then the piston area equals: 7.0686 in²

\[
\text{Force} = \text{psi} \times \text{Area}
\]

\[
\begin{align*}
\text{Force} &= 125\text{ psi} \times 7.0686\text{ in}^2 \\
\text{Force} &= 883.575\text{ lb}
\end{align*}
\]

This results in a total force of 883.575 lb.

**Work**

Work is accomplished only when a force is applied through some distance. If a given weight is held so that it neither rises nor falls, no work is done even though the person holding the weight may become very tired. If the weight is raised some distance, then work is being done. The amount of work performed is the product or result of the force and the distance through which the weight is moved.

If a weight of 20 lb is lifted 3', then 60 ft-lb of work is accomplished. The distance must always be measured in the same direction as the applied force. This results in the formula as follows:

\[
\text{Work} = \text{Force} \times \text{Distance}
\]

![Figure 7-5.](image)

The total force applied to a piston face is equal to its area in square inches multiplied by the psi (pounds per square inch).
Because the formula calls for multiplying feet times pounds, the answer is expressed in foot-pounds (ft-lb).

**Levers and Mechanical Advantage**

A gasoline engine utilizes the principles of a number of simple machines. One of the most common is the lever. The purpose of this simple machine is to change the amount of force required to perform a given amount of work. Since work equals force applied through a distance, the amount of force required to perform a given amount of work increases if the distance through which the force is applied is decreased. Similarly, the amount of force required to perform the work is decreased if the distance it is applied through is increased.

A lever produces a mechanical advantage, which allows a load to be moved with a reduced force. **Figure 7-6** illustrates how a heavy load can be moved a short distance by exerting a small force through a relatively great distance. The formula for computing leverage, as it applies to **Figure 7-6**, is as follows:

\[
MA = \frac{ED}{RD}
\]

- **MA** = mechanical advantage
- **ED** = effort distance
- **RD** = resistance distance

In **Figure 7-6**, a 600 lb weight is being lifted. To lift the weight a foot in the air, a weightlifter would need to exert slightly more than 600 lb through a distance of one foot. The result would be 600 ft-lb of work.

A much weaker person could perform the same amount of work by using the mechanical advantage offered by a lever. For example, the lever shown in **Figure 7-6** provides a mechanical advantage of three to one.

\[
MA = \frac{ED}{RD} = \frac{6'}{2'} = 3
\]

This means that someone using the lever can lift the same 600 lb weight one foot up by exerting only 200 pounds of force through a distance of three feet.

\[
E = \frac{R}{MA} = \frac{600 \text{ lb}}{3} = 200 \text{ lb}
\]

\[
E = \text{effort (force)}
\]

\[
R = \text{resistance (weight)}
\]

\[
MA = \text{mechanical advantage}
\]

Levers are commonly used to open and close valves in overhead valve engines. Since valves are equipped with heavy springs that keep them tightly sealed when the valve is closed, considerable force is required to open the valve. Simple levers convert the relatively large up and down provided by the camshaft lobe into a smaller, more forceful movement to open the valves.

**Power**

In studying the formula for work, note that it does not consider the time required to do the work. For example, if a small gasoline engine weighing 50 pounds is lifted 3' from the floor to the workbench, 150 ft-lb of work is done. The same amount of work would be performed whether it took 50 seconds (sec) to lift the engine or only 5 seconds.

---

**Figure 7-6.**

The mechanical advantage provided by a lever changes the ratio of force to distance required to perform a given amount of work.
Because it is important to know the rate at which work is done, the word power enters the picture. Power is the rate at which work is performed. The rate (amount of time) is given in seconds. Power can then be considered as foot-pounds per second. The formula for power is as follows:

\[ \text{Power} = \frac{\text{Work}}{\text{Time}} \]

or \[ \text{Power} = \frac{(\text{Feet} \times \text{Pounds})}{\text{Seconds}} \]

or \[ \text{Power} = \text{ft-lb per second (ft-lb/sec)} \]

When the engine is lifted in 5 seconds, 150 ft-lb of work is performed. Using the power formula, it can be seen that:

\[ \text{Power} = \frac{(150 \text{ ft-lb})}{5 \text{ sec}} \]

\[ \text{Power} = 30 \text{ ft-lb/sec} \]

When lifting the engine in 50 sec, the formula shows the following:

\[ \text{Power} = \frac{\text{Work}}{\text{Time}} \]

\[ \text{Power} = \frac{(150 \text{ ft-lb})}{50 \text{ sec}} \]

\[ \text{Power} = 3 \text{ ft-lb/sec} \]

Work is a force applied to an object that causes the object to move, and power is the rate at which the work is done. The standard unit of power is termed horsepower.

**Power**

For hundreds of years, men used horses to perform work. It was only natural that when machines were invented, their ability to perform work would be compared to the horse.

In his work with early steam engines, James Watt wanted some simple way to measure their power output. In measuring the power or rate of work performed by a horse, he found that most workhorses could lift 100 pounds a distance of 330' in 1 minute. Using the work formula (Work = Distance × Force), Watt found that the horse performed 33,000 ft-lb of work.

In determining the rate of power developed by the horse, we use the following formula:

\[ \text{Power} = \frac{\text{Work}}{\text{Time}} = \frac{33,000 \text{ ft-lb}}{1 \text{ min}} \]

or \[ 550 \text{ ft-lb/sec} = 1 \text{ Horsepower (hp)} \]

The 550 ft-lb/sec (ability to lift 550 pounds a distance of 1' in 1 second) was then established as 1 horsepower (hp). This standard is still in use today.

**Torque**

Torque refers to the ability of a force to cause an object to rotate. Therefore, any reference to engine torque means the turning force developed by the rotating crankshaft.

In order to find torque, we must know the force (in pounds) and the radius (distance, in feet, from the center of the turning shaft to the exact point at which the force is measured). The formula would read as follows:

\[ \text{Torque} = \text{Force} \times \text{Distance (Radius)} \]

or \[ \text{Torque} = \text{Pounds} \times \text{Feet} \]

or \[ \text{Torque} = \text{lb-ft} \]

**Figure 7-7** shows a torque wrench attached to a rotating crankshaft. If the handle of the torque wrench is supported so it cannot move, the torque applied by the engine would be registered on the torque wrench’s scale. However, at some point the crankshaft would have too much resistance on it, and the engine would stop.

A Prony brake like the one shown in **Figure 7-8** can be used to measure torque on a running engine. The arm of the brake is equipped with a friction band. As the band is tightened, more of the force generated by the engine is applied to the arm. This will allow the crankshaft to turn while still applying turning force to the scale. To measure the maximum torque applied by the engine, the friction band is tightened until the engine begins to bog down.

Suppose a scale placed exactly two feet from the center of the crankshaft. After the friction band is adjusted, the scale indicates a force of 100 lb. By using the formula for determining torque
Figure 7-7.
Torque is determined by multiplying the turning effort in pounds by the distance from the shaft center to the point at which force is read. (Dresser Industries Inc.)

Figure 7-8.
In a Prony brake setup, one end of the pressure arm surrounds a spinning flywheel driven by the engine. By tightening the friction device, torque is transmitted to and measured at the scale.

\[(\text{Torque} = \text{lb-ft or} \ \text{Torque} = \text{100 lb} \times 2')\], we find that this engine is developing 200 lb-ft of torque.

If the scale is 3' from the shaft center and the force is 50 pounds, the torque will be 150 lb-ft. When measuring torque, the reading is given in lb-ft. When measuring work, the reading is given in ft-lb.

**Wheel and Axle**

A wheel and axle arrangement can provide mechanical advantage similar to a lever. See Figure 7-9. The wheel is much larger than the axle. With each revolution of the wheel and axle assembly, a point on the outer edge of the wheel moves a much greater distance than a corresponding point on the axle. If the load is placed on the axle, and the wheel is turned, the force required to move the load is reduced. However, the distance that the load is moved is also reduced. On the other hand, if the load is placed on the wheel, the force required to move the load is increased, but the load moves farther with each rotation.

The mechanical advantage provided by a wheel and axle can be calculated by comparing the radius of the wheel to the radius of the axle:

\[
ME = \frac{R_1}{R_2}
\]

\[
ME = \text{mechanical advantage}
\]

\[
R_1 = \text{radius of the load carrying member} \quad \text{(wheel or axle)}
\]

\[
R_2 = \text{radius of the member to which force is applied} \quad \text{(wheel or axle)}
\]
Pulley, Gear, and Chain Drive Systems

A pulley or gear installed on a shaft is essentially a wheel and axle system. If a large pulley is installed on the shaft, the force measured at a point on the outer edge of the pulley will be relatively low, but the point will travel a greater distance with each revolution of the shaft. If a smaller pulley is installed, the force at a point on the outer edge of the pulley will be greater, but the point will travel a shorter distance with each revolution.

Pulley systems can be used between two shafts to increase the rotational speed or torque from one shaft to the other. The ratio of the diameter of the drive pulley to the driven pulley determines the factor by which the rotational speed and torque are changed. See Figure 7-10A. If the drive pulley is smaller than the driven pulley, torque is increased and rotational speed is decreased. If the drive gear is larger than the driven gear, the torque is decreased and the rotational speed is increased.

As an example, imagine an overhead cam engine where the crankshaft is fitted with a two inch pulley, which is connected by a belt to a four inch pulley on the camshaft. Two complete revolutions of the crankshaft are required for a single revolution of the camshaft. The camshaft turns at half the speed but twice the torque of the crankshaft.

Now, imagine an engine driving a low-pressure, high-volume air pump. The engine's crankshaft is equipped with a nine inch pulley, which is connected by a belt to a three inch pulley on the pump. Every revolution of the crankshaft results in three revolutions of the pump. The pump's crankshaft turns at three times the speed, but with one-third of the torque of the engine's crankshaft.

The same concepts can be applied to sprocket and chain systems. In a sprocket and chain system, like the one shown in Figure 7-10B, the ratio of the number of teeth on the drive sprocket compared to the number of teeth on the driven sprocket determines the factor by which torque and rotational speed are altered.

Gear systems, like the ones shown in Figure 7-10C, produce similar results. Again, the ratio of the number of teeth on the drive gear to the number of teeth of the driven gear determine the factor by which rotational speed and torque are altered. It should be noted that the direct contact between the teeth of the input and output gears causes the output gear to turn in the opposite direction as the input gear. If an idler gear is placed between the drive gear and output gear, those gears will rotate in the same direction. The idler gear has no effect on the gear ratio between the input gear and output gear, no matter how large or small it is.

Measurements of Engine Performance

The term engine performance refers to a measurement of engine output. Engine performance is based on measurement of engine output in three areas, power, torque, and efficiency. Power is the measure of how much work an engine can perform in a
given amount of time. Torque refers to how much of a load the engine can handle without bogging down. Efficiency is a measure of how well the engine uses its fuel and air resources to generate power.

**Engine Displacement**

Cylinder displacement is the volume increase in a cylinder as the piston moves from the top to the bottom of its stroke. To determine cylinder displacement, first determine the circular area of the cylinder \( 0.7854 \times \text{diameter squared} \), or \( D^2 \). Then, multiply that answer by the total length of the stroke (piston travel).

The formula is as follows:

\[
\text{Cylinder Displacement} = 0.7854 \times D^2 \times \text{Length of Stroke}
\]

If the engine has more than one cylinder, multiply the answer to the above formula by the number of cylinders.

\[
\text{Engine Displacement} = \text{Cylinder Displacement} \times \frac{\text{Number of Cylinders}}{\text{Number of Cylinders}}
\]

For example, say that a two-cylinder engine has a bore of 3 1/4" and a stroke of 3 1/4". Using the displacement formulas, you would have the following:

\[
\text{Cylinder Displacement} = 0.7854 \times \left(3.25^2 \times 2\right) = 53.92 \text{ in}^3
\]

**Figure 7-11.** Engine displacement is the difference in the volume of the cylinder and combustion chamber above the piston when it is at TDC and when it is at BDC. The red area shows displacement.

(BDC) and the volume remaining when the piston is at the top of its stroke (TDC). For example, if cylinder volume measures 6 in\(^3\) when the piston is at BDC (view A in Figure 7-12) and 1 in\(^3\) when at TDC, (view B in Figure 7-12), the compression ratio of the engine is 6 to 1. Many small gasoline engines have 5 or 6 to 1 compression ratios. Certain motorcycle engines have 9 to 1 or 10 to 1 compression ratios.

**Engine Horsepower**

Engine horsepower can be calculated by dividing the total rate of work (ft-lb/sec) by 550 ft-lb/sec.

**Compression Ratio**

The compression ratio of an engine is a measurement of the relationship between the total cylinder volume when the piston is at the bottom of its stroke and the volume remaining when the piston is at TDC. A compression ratio is the relationship between the cylinder volume with the piston at BDC (A) and the piston at TDC (B). The volume has been compressed to one-sixth of its original size, which indicates a 6 to 1 compression ratio. (Briggs and Stratton Corp.)
For example, if an engine lifted 330 pounds a distance of 100 feet in 6 seconds, its total rate of work would be as follows:

\[(100 \text{ ft} \times 330 \text{ lb})/6 \text{ sec} = 5500 \text{ ft-lb/sec}\]

Dividing this by 550 ft-lb/sec (1 hp) as follows:

\[(5500 \text{ ft-lb/sec})/(550 \text{ ft-lb/sec}) = 10 \text{ hp}\]

You find that the engine is rated at 10 hp. The horsepower formula would then be as follows:

\[\text{Horsepower} = \frac{\text{Rate of Work in ft-lb/sec}}{550 \text{ ft-lb/sec}}\]

This formula can also be used to determine the exact horsepower needed for other tasks.

**Kinds of Horsepower**

The word *horsepower* is used in more than one way. Some of the common terms include brake horsepower, indicated horsepower, frictional horsepower, and rated horsepower. While all of these terms describe engine power, they each measure it in different ways.

**Brake Horsepower**

*Brake horsepower* (bhp) indicates the actual usable horsepower delivered at the engine crankshaft. Brake horsepower does not remain constant with changes in engine speed. It increases with engine speed. At very high and generally unusable engine speeds (depending on engine design), the horsepower output will drop off somewhat.

**Figure 7-13** shows how horsepower increases with speed for two different engine models. The top speeds in this chart do not run high enough to show a drop in horsepower.

### Measuring Engine Brake Horsepower

There are two common methods of measuring brake horsepower. It can be measured by using a Prony brake or an engine dynamometer. A *Prony brake* is a friction device that grips an engine-driven flywheel and transfers the force to a measuring scale. See **Figure 7-8**. One end of the Prony brake pressure arm rests on the scale and the other wraps around a spinning flywheel driven by the engine under test. A clamp is used to change the frictional grip on the spinning flywheel.

To check brake horsepower, the engine under test is operated with the throttle wide open. Then engine speed is reduced to a specific number of revolutions per minute by tightening the pressure arm on the flywheel. At exactly the right speed, the arm pressure on the scale is read. By using the scale reading (W) from the Prony brake, the flywheel rpm (R), and the distance in feet from the center of the flywheel to the arm support (L), brake horsepower can be computed. The formula used to determine brake horsepower on the Prony brake is as follows:

\[\text{bhp} = \frac{(2\pi \times R \times L \times W)}{33,000 \text{ ft-lb/min}}\]

or \[\text{bhp} = \frac{R \times L \times W}{5252 \text{ ft-lb/min}}\]

where:

\[R = \text{Engine rpm or speed}\]

\[L = \text{Length from center of flywheel to the point where beam presses on scale in feet}\]

\[W = \text{Weight as registered on scale in pounds}\]

\[1 \text{ hp} = 33,000 \text{ ft-lb/min}\]

As with the Prony brake, the *dynamometer* loads the engine and transfers the loading to a measuring device. Instead of using a dry friction loading technique (clamping pressure arm to a spinning wheel), the dynamometer utilizes either hydraulic or electric loading. Several different types are illustrated in **Figure 7-14**.
Figure 7-14.

The variety of dynamometers shown use different principles of construction. A—The engine drives an electric generator that is attached to a spring scale. When an electrical load is placed in the circuit, the generator housing (an enclosure holding the moving parts) attempts to spin, applying a force to the scale. B—A hydraulic water brake is attached to the scale. The engine is loaded by admitting more and more water into the brake, causing the housing to try to rotate, exerting a force on the scale. C—An eddy current brake. D—A Prony brake. (Go-Power Corp.)

**Indicated Horsepower**

*Indicated horsepower (ihp)* is a measure of the power developed by the burning fuel mixture inside the cylinder. It is essentially a measure of the total potential horsepower the engine is capable of developing. To measure ihp, you must determine the pressure inside the cylinder during the intake, compression, power, and exhaust strokes. A special measuring tool is used to continuously monitor cylinder pressure. This pressure information is placed on an indicator graph, like the one in Figure 7-15.

At this point, the *mean effective pressure (mep)* must be determined. To do this, subtract the average pressure during the intake, compression, and exhaust strokes from the average pressure developed during the power stroke. The mean effective pressure varies depending on engine type and design. After finding the mep, the following formula is used to determine the indicated horsepower:

\[
\text{Indicated horsepower (ihp)} = \frac{\text{PLANK}}{33,000}
\]

where:

- \( P \) = mep in pounds per square inch.
- \( L \) = length of piston stroke in feet.
- \( A \) = cylinder area in square inches.
- \( N \) = power strokes per minute: \( \text{rpm}/2 \) (four-cycle engine).
- \( K \) = number of cylinders.

![Graph showing cylinder pressure developed in a four-cycle engine](image)

**Figure 7-15.**

This graph shows the simulated cylinder pressure developed in the cylinder of a specific four-cycle engine. Atmospheric pressure is shown by the dotted line. The graph makes it possible to establish a mean effective pressure (mep).

**Frictional Horsepower**

*Frictional horsepower (fhp)* represents that part of the indicated horsepower lost because of the drag of engine parts rubbing together. Figure 7-16. Despite smooth contact surfaces and proper lubrication, a certain amount of friction (resistance to movement between two objects that are rubbing together)
Frictional horsepower is determined by subtracting brake horsepower from indicated horsepower or by the following formula:

\[ Fhp = ihp - bh \]

**Rated Horsepower**

An engine used under a brake horsepower load that is as great as the engine’s highest brake horsepower rating will overheat. Excessive pressure on the bearings (loading) will seriously shorten the engine’s service life. In some cases, complete engine failure can occur in a very short period of time.

As a general rule, never load an engine to more than 80% of its highest brake horsepower rating. For example, if a job requires a horsepower loading of 8 hp, you would use an engine with at least a 10 hp rating. Then, the load would be no more than 80% of the engine’s maximum hp.

An engine’s rated horsepower generally will be 80% of its maximum brake horsepower. Note in Figure 7-17 how the rated horsepower (recommended maximum operating bhp) is less than engine maximum bhp.

**Figure 7-16.**
Frictional horsepower is determined by subtracting crankshaft brake horsepower from indicated horsepower. (Deere & Co.)

is always present and represents a sizable horsepower loss. Actual loss will vary with engine design and use, but will generally run about 10%. Friction loss does not remain constant. It increases with engine speed.

**Figure 7-17.**
The maximum operating brake horsepower loading is charted for a specific engine. At all speeds, the rated hp is about 80% of the maximum bhp. (Briggs and Stratton Corp.)
Corrected Horsepower

Standard brake horsepower ratings are based on engine test conditions with the air dry, temperature at 60°F, and a barometric pressure of 29.92 inches of mercury, or Hg (standard atmospheric pressure at sea level). Horsepower, however, can be greatly affected by changes in atmospheric pressure, temperature, and humidity (amount of moisture in the air).

**Corrected horsepower** is a guess at horsepower of a given engine under specific operating conditions that are not the same as those present during actual dynamometer testing. Facts to consider are:
- For each 1000' of elevation above sea level, horsepower will drop around 3 1/2%.
- For each 1” drop in barometric pressure, horsepower will drop another 3 1/2%.
- Each 10°F of temperature increase results in a horsepower loss of 1%.
- New engines will develop somewhat less horsepower (due to increased friction) until they have been operated a number of hours.
- An increase of 200°F–400°F in head operating temperature can lower horsepower by 10%.
- Quality of fuel, mechanical conditions, and state of tune can also affect horsepower.

When horsepower tests are conducted under conditions varying from standard, corrections must be applied to establish true horsepower.

**Correction Factor**

The correction factor (a factor is a condition that would change an answer) is determined by using the following formula:

\[
\text{Correction Factor} = \frac{\text{Temperature Correction} \times \text{Pressure Correction} \times \text{Humidity Correction}}{100}
\]

For example, suppose that the dynamometer tests were carried out at a temperature of 90°F with an atmospheric pressure of 28.5” Hg and a wet bulb temperature (determines humidity) of 73.5°F. First, see the chart in Figure 7-18. Follow dotted line A from top of chart (90°F temperature) down until it crosses the temperature line B. By moving left along the chart, you can see the dotted line shows a temperature correction factor of 1.028.

Now, follow dotted line C up from the 28.5” Hg marking at the bottom of the chart until it crosses pressure line D. By moving left at this point, a pressure correction factor of 1.068 is shown.

To find the humidity correction factor, use the chart in Figure 7-19. Follow the dotted line up from the 90°F dry bulb temperature mark until it meets the 73.5°F dotted wet bulb temperature line. Move across to the right and note that the humidity correction factor is 1.0084.

Using the correction factor formula as follows:

\[
\text{Correction Factor} = \frac{\text{Temperature Correction} \times \text{Pressure Correction} \times \text{Humidity Correction}}{100}
\]

\[
\text{Correction Factor} = 1.028 \times 1.068 \times 1.0084
\]

\[
\text{Correction Factor} = 1.1071
\]

If the dynamometer test had shown 3.15 horsepower, this reading could be changed to standard test conditions by applying the correction factor of 1.1071 as determined earlier. Thus:

\[
\text{Corrected } hp = \text{Correction Factor} \times \text{Test } hp
\]

\[
\text{Corrected } hp = 1.1071 \times 3.15 \text{ hp}
\]

\[
\text{Corrected } hp = 3.4874 \text{ hp}
\]
**Engine Torque**

Engine torque, for any engine and set of test conditions, will change according to engine speed. The pressure of the burning air-fuel mixture against the piston is transferred to the crankshaft by the connecting rod. The greater the pressure, the more torque the crankshaft will develop.

The point where gas pressure will be highest is the speed at which the engine takes in the largest volume of air-fuel mixture. This point will vary according to engine design but will always be at a lower speed than that at which the greatest horsepower is reached. Horsepower generally increases as engine speed increases until the engine reaches a very high rpm, and horsepower finally begins to drop off. Torque, on the other hand, decreases at a much lower rpm.

As engine speed is increased beyond idle, its torque increases. As it continues to speed up, a point will be reached where the natural restriction to airflow through the carburetor, intake manifold, and valve ports begins to limit the speed at which the air-fuel mixture can enter the cylinder. At this point, the highest torque is developed.

When engine speed goes higher than this point, the intake valve will open but the piston moves far down on the intake stroke before the mixture can get into the cylinder. This cuts down the amount of air-fuel mixture entering the cylinder. As a result, burning pressure is lowered as well as the torque. Beyond this point, torque will decrease as speed increases.

**Torque and Horsepower**

Unlike torque (which drops off when engine revolutions per minute exceed the point of maximum volumetric efficiency), horsepower continues to increase until engine speed is very high. Beyond a certain speed, however, horsepower will actually decrease.

Keep in mind that torque measures the twisting force generated by the crankshaft while horsepower measures the engine's ability to perform work. Even though torque may decline at higher speeds, the shaft is turning much faster. Therefore, it is able to perform work at a greater rate.

Figure 7-20 shows the relationship between torque and horsepower curves for one specific engine. Note the arrow indicating the rated horsepower. This is the horsepower at which the engine can be operated continuously without damage.
Summary

Engine bore is the diameter across the top of the cylinder. Stroke is the up or down movement of the piston. Length of stroke is determined by the distance the piston moves from its uppermost position to its lowest position.

Energy is the capacity to perform work. Types of energy include potential energy, kinetic energy, mechanical energy, chemical energy, and thermal energy. Force is the pushing or pulling of one body on another. The greater the force applied to the piston, the greater the amount of power and work that can be done by the engine. Pressure is a force per given unit of area. Work is accomplished only when a force is applied through some distance. Power is the rate at which work is performed. The standard unit of power is horsepower. The mechanical advantage provided by levers, belt-and-pulley systems, chain-and-sprocket systems, and gear systems can increase force and decrease distance or decrease force and increase distance components of any work input into the system.

Cylinder displacement is the volume increase in the cylinders as the pistons move from the top to the bottom of their strokes. The compression ratio of an engine is a measurement of the relationship between the total cylinder volume when the piston is at the bottom of its stroke (BDC) and the volume remaining when the piston is at the top of its stroke (TDC).

Engine horsepower is calculated by dividing the total rate of work (ft-lb/sec) by 550 (ft-lb/sec). Brake horsepower indicates the actual usable horsepower delivered at the crankshaft. Brake horsepower increases with engine speed. Indicated horsepower refers to the power developed by the burning fuel mixture inside the cylinder. To measure indicated horsepower, you must determine the pressure inside the cylinder during the intake, compression, power, and exhaust strokes. Frictional horsepower represents the part of the indicated horsepower lost because of engine parts rubbing together. Frictional horsepower is determined by subtracting brake horsepower from indicated horsepower.

Engine displacement refers to the total volume increase in the cylinder as the piston moves from the top of its stroke to the bottom of its stroke. An engine's compression ratio is a measurement of the relationship between total cylinder volume at BDC compared to the volume remaining when the piston is at TDC.

An engine's rated horsepower is generally 80% of its maximum brake horsepower. Standard brake horsepower ratings are based on ideal engine test conditions. Horsepower can be greatly affected by changes in atmospheric pressure, temperature, and humidity. Corrected horsepower is an estimation of the horsepower of a given engine under specific operating conditions. Engine torque refers to the turning force developed by the crankshaft. Engine torque will change according to speed.

Volumetric efficiency is the measurement of how well an engine draws the air-fuel mixture into the cylinder. Practical efficiency is an overall measurement of how efficiently an engine uses the fuel supply. Mechanical efficiency is the percentage of power developed in the cylinder (indicated horsepower) compared to the power that is actually delivered at the crankshaft (brake horsepower). Thermal efficiency indicates how much of the power produced by the burning air-fuel mixture is actually used to drive the piston.

Review Questions

Answer the following questions on a separate sheet of paper.

1. Gasoline-powered reciprocating-piston engines, gas or steam turbines, steam engines, and rocket and jet engines are all examples of the _____ engine category.
2. What force acts opposite to the direction of centrifugal force?
3. _____ is a force applied to a given area.
4. If a force of 35 lb is applied to an area of 5 sq in, what is the pressure in psi?
5. If 48 foot-pounds of work is performed to lift an object 12 feet, how much does the object weigh?
6. Give the formula for work.
7. The top area of a 2 1/2" diameter piston would be how many sq in?
8. If 60 lb is lifted 5' in 6 sec, what amount of power is exerted in ft-lb/sec?
9. What is the definition of horsepower? How much is 1 hp?
10. How do you compute engine displacement?
11. A measure of the horsepower delivered at the engine crankshaft is called ______.
12. A Prony brake with a 12" arm is applied to an engine flywheel. At 1200 rpm, the scale registers 20 lb. Calculate the horsepower to two decimal places.
13. What is indicated horsepower?
14. When testing an engine on the dynamometer, what are the standard test conditions?
15. An engine’s rated horsepower is approximately ______% of its maximum brake horsepower.
16. What is the engine horsepower reduction for each 1000' of elevation?
17. Explain the horsepower correction factor.
18. Volumetric efficiency reaches its maximum value at the same engine speed as ______.
19. True or False? Horsepower of an engine is greatest at maximum rpm.
20. On the average, what percentage of the energy from fuel is used to produce power?

Suggested Activities

1. Using the principles studied in this chapter, determine the horsepower required of several individuals to walk up one flight of stairs. The following items will be needed: a stopwatch, tape measure, and bath scale.
2. Design and build a Prony brake for a small gasoline engine.
3. Use a dynamometer to develop a graph like the one in Figure 7-20. Compare the graph with the manufacturer’s graph for the same model of engine.
4. On an engine with the head removed, measure the position of the top of the piston (in relation to the top of the block) at TDC and again at BDC. Determine the stroke of the engine.
5. On the same engine, measure the diameter of the piston and determine if the engine is square, oversquare or undersquare.
6. Determine the cubic inch displacement of the engine from the facts learned in activities above.
SECTION 3

Engine Systems

Chapter  8. Fuel Supply, Air Induction, and Emissions
Chapter  9. Carburetion
Chapter 10. Ignition Systems
Chapter 11. Lubrication Systems
Chapter 12. Cooling Systems
Learning Objectives

After studying this chapter, you will be able to:

- Define engine performance.
- Define and compute bore and stroke.
- Understand the concept of energy and differentiate between kinetic and potential energy.
- Understand the concepts of force and pressure.
- Explain the concepts of work, power, and torque.
- Understand how levers and belt-and-pulley, chain-and-sprocket, and gear systems provide mechanical advantage.
- Calculate an engine's displacement and compression ratio.
- Differentiate between the various types of engine horsepower.
- Define and calculate engine torque.
- Explain volumetric efficiency, practical efficiency, mechanical efficiency, and thermal efficiency.

Instructions: After studying the chapter, complete the following questions and problems.

1. Inertia is the tendency of an object in motion to ______.
   A. quickly slow down and come to a stop
   B. remain in motion
   C. move back and forth
   D. None of the above.

2. A measurement of the work an engine does and how well it does the work is referred to as engine ______.

3. Engine ______ is the diameter or width across the top of the cylinder.

4. ______ is the up or down movement of the piston.

5. Crank ______ is the distance from the centerline of the connecting rod journal to the centerline of the crankshaft.
6. When an engine is referred to as over square, the _____ is greater than the _____.
   A. stroke, bore
   B. bore, stroke

7. Which of the following best describes the difference between kinetic energy and potential energy?
   A. Potential energy is stored only in mechanical systems and kinetic energy is stored only in chemicals.
   B. Potential energy produces heat and kinetic energy produces motion.
   C. Potential energy is stored energy and kinetic energy is energy of motion.
   D. Potential energy can be converted into other forms of energy, but kinetic energy cannot.

8. A ball swung on a string applies centrifugal force on the string. _____ force opposes the centrifugal force.

9. The centrifugal force at the outer edge of a flywheel applies _____ stress on the material that makes up the flywheel.

10. _____ is a force per given unit of area.

11. What is the total force applied to the face of the following pistons? Round your answers to the nearest one-tenth pound and show your work in the space provided.
   A. Diameter = 0.875", pressure = 135 psi
   B. Diameter = 2.250", pressure = 125 psi
   C. Diameter = 3.500", pressure = 120 psi

12. If a total force of 275 lb is applied to a piston diameter of 2", what is the pressure? Round your answer to the nearest 1/10. Show your work in the space provided.

13. If a man weighing 170 lb walks up 12 steps, each step having a rise of 6", how much work has been done when he reaches the top step? Show your work in the space provided.
Name ____________________________

14. Compute the effort (in lbs) required to lift the 1200 lb weight in the following figure. Show your work in the space provided.

15. If a 3000 lb automobile is lifted to a height of 6' on a hoist and it takes 30 seconds to do it, how much power has been expended to do the work? Show your work in the space provided.
   A. foot-pounds per second
   B. horsepower

16. If 30 lb of force is applied to the end of a 6" wrench to tighten a bolt, what is the torque applied to the bolt? Show your work in the space provided.

17. If a smaller pulley is used to drive a larger pulley, the _____.
   A. torque at the driven pulley is decreased and its rotational speed is increased
   B. torque at the driven pulley is increased and its rotational speed is decreased
   C. torque and rotational speed of the driven pulley are increased
   D. torque and rotational speed of the driven pulley are decreased
18. Calculate the following engine displacements (in cubic inches) with the information given. Round your answers to the nearest thousandth of an inch and show your work in the space provided.
   A. Bore = 1.378, stroke = 1.142, one cylinder
   B. Bore = 2.940, stroke = 2.750, two cylinders
   C. Bore = 3.250, stroke = 2.880, four cylinders


20. If two engines have the same piston diameters, but Engine A has a 6:1 compression ratio, while Engine B has a 5:1 compression ratio, which engine has the longer stroke?
   A. Engine A
   B. Engine B

21. _____ horsepower is an indication of the amount of useable power delivered at the engine crankshaft.

22. Identify the type of horsepower (indicated, frictional, rated, or corrected) described below.
   A. Includes effect on horsepower by atmospheric conditions
   B. Power developed by burning fuel inside a cylinder
   C. Horsepower recommended for best efficiency
   D. Horsepower lost due to parts rubbing together

23. Determine the indicated horsepower of the following single cylinder, four-cycle engine at 2500 rpm using the PLANK formula. (Show your work in the space provided and round your answer to the nearest 1/10th ihp.)
   mep = 110 psi, stroke = 2.88", bore = 3.25"

24. List three atmospheric conditions that will cause a decrease in engine horsepower.
Chapter 7  Measuring Engine Performance

Name

25. List five nonatmospheric conditions that can reduce horsepower.

26. Find the corrected horsepower for the following engine test conditions. Show your work in the space provided.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>80°F</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>27.7 in Hg</td>
</tr>
<tr>
<td>Wet bulb temperature</td>
<td>68°F</td>
</tr>
<tr>
<td>Dynamometer horsepower</td>
<td>8.2</td>
</tr>
</tbody>
</table>

27. What is the torque being generated if a dynamometer shows a rotational resistance of 125 pounds at a distance of two feet? Show your work in the space provided.

28. As engine rpm increases, torque 
   A. increases up to a point, then decreases
   B. decreases and then increases to peak rpm
   C. is constant to peak rpm
   D. increases to peak rpm

29. _____ efficiency takes into consideration power losses caused by friction, incomplete burning of the air-fuel mixture, heat loss, and other factors.

30. How well an engine breathes, or draws the air-fuel mixture into the cylinder is referred to as its _____ efficiency.

31. The percentage of power developed in the cylinder (indicated horsepower) compared with that which is actually delivered at the crankshaft (brake horsepower) is called _____ efficiency.
32. Volumetric efficiency can be improved by _____.
   A. altering cam timing
   B. using a larger intake valve
   C. improving exhaust flow
   D. All of the above.

33. Thermal efficiency for gasoline engines varies from one engine to another, but is generally about _____.
   A. 10%
   B. 25%
   C. 45%
   D. 60%

Research and write complete answers to the following questions.

34. Explain how and why temperature and barometric pressure affect engine horsepower.

_____________________________________________________________________________

_____________________________________________________________________________

_____________________________________________________________________________

35. What happens to the air-fuel mixture ratio when the operating altitude is increased? How can the effect be corrected?

_____________________________________________________________________________

_____________________________________________________________________________

_____________________________________________________________________________