Introduction to Aircraft Engines

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The purpose of a powerplant on an airplane is to produce the force of thrust to propel the airplane forward so as to create the airflow over the wings for lift production and for overcoming any rearward weight component of the aircraft. Newton's 3rd law of motion is at play here. "For every action there is an equal and opposite reaction." Accelerating air rearward by a propeller or by a turbine engine creates the action and reaction of thrust in a forward direction.

A deflating balloon illustrates this concept. As air first escapes out of the balloon, the static pressure inside the balloon is greater than outside the balloon. The extra pressure moves the air out of the balloon as the first action. The air accelerates out the back of the balloon creating a high dynamic pressure stream of air propelling the balloon forward. It is important to note that the thrust is the reaction and the air coming out the back of the balloon is not pushing off the surrounding air. The balloon could be surrounded by a partial vacuum and it would still create thrust.

When a quantity of air is accelerated, thrust force is created. One basic formula to remember is that force equals mass times acceleration. The force of thrust is created when air is accelerated rearward. Propeller driven airplanes take a relatively large mass of air and accelerates a small amount, creating the reaction force of thrust.

The kinetic or heat energy of a moving mass of air is calculated using the quantity of the fluid molecules that are moving (mass) and the velocity of the mass flow taken to the second power. Turbojet engines have very high velocity through the core of the engine, and therefore the mass and velocity is very high creating very high temperatures and wasted heat. Fuel has to be combusted to generate the high energy gas flow, and some of that energy is wasted heating the air the aircraft is flying through.

The kinetic energy formula $K = \frac{1}{2} mV^2$ explains why increasing velocity of the air exponentially increases kinetic heat energy, leading to inefficiency and wasted fuel. Most pure jet gas turbine engines have a fan on the front of the engine that creates the majority of the thrust by accelerating a large mass of air rearward for a modest gain in velocity. In some cases, only about 10% of the air actually goes through the core of the engine. This greatly reduces fuel consumption while at the same time reducing noise levels significantly.

The turbo prop is able to produce high thrust in the lower speed range with an efficient constant speed propeller. The turbofan is more efficient and capable at medium speeds, and up to speeds approaching the speed of sound. Very few turbojet engines have no fan on the front of the engine at all. Most turbojets have at least one fan with air bypassing the core. Only supersonic jets and experimental jets are pure turbojets and are designed to go faster than the speed of sound. All thrust is generated by accelerating air rearward by some means. The greatest thrust therefore is produced at sea level for all powerplants. The greatest efficiency is the reciprocating propeller driven aircraft but only at low altitudes. Turbo prop and turbojet aircraft must fly at a high altitude in order to be efficient. Specific fuel consumption is the highest with the turbojet; however, the turbojet is able to fly high and achieve very high speeds compared to propeller driven aircraft.

Looking at overall efficiency, the propeller is most efficient but can only be used for lower altitudes and low speeds. The turbofan is most efficient at speeds close to the speed of sound and a pure turbojet with no fan is efficient for supersonic flight above the speed of sound.

The opposed 4 and 6 cylinder engines are used in general aviation airplanes weighing less than 12,500 pounds, or small aircraft. The opposed cylinder arrangement seen here works well for single engine small airplanes and light twin engine airplanes. The engine can be mounted high enough on the fuselage in order to have adequate ground clearances for the rest of the engine and for the needed propeller clearance. Cylinders are opposed but offset so that each piston and connecting rods have a place on the crank without sharing the same throw and crankpin. Reciprocating motion is converted to rotary motion using the crankshaft. The crankshaft has throws where connecting rods are attached. The other end of the connecting rod is connected to the piston using the king pin.

An opposed engine is one where an even number of cylinders are arranged to form two banks of cylinders. For example, a four cylinder opposed engine would have a right bank of two cylinders and a left bank of two cylinders. In opposed engines each cylinder has a throw to connect with on the main crank, and each cylinder bank is offset a little in the opposed arrangement so that the crank throw is not shared. Four cycles occur in each cylinder as the engine runs; however, when one cylinder is taking in air, another cylinder is exhausting air or compressing air so that the power strokes are timed so that a cylinder fires on one side and then fires on the other side to balance out the forces and lessen vibrations. This is a simple animation of the reciprocating motions in an opposed engine.

At top dead center position of the piston at the beginning of the intake stroke, the intake valve is opening while the exhaust valve is closing from the prior exhaust cycle. There is a valve overlap time period at the beginning of the intake stroke that makes the air flow through the engine more efficient. Just before the beginning of the intake stroke the intake valve opens and the down going piston creates a low pressure area above the piston. Also, the exhaust valve fully closes during the beginning of this stroke. As the piston moves farther down, the intake valve fully opens and the fuel air mixture is drawn into the cylinder. Reaching bottom dead center, the intake valve closes and both valves are closed for the next stroke.

Both valves are closed at the beginning of the compression stroke. The cylinder space is greatest when the piston is at bottom dead center position and the air fuel gas is compressed during this stroke. The compression ratio is the space above the piston at bottom dead center compared to the space at top dead center. A compression ratio greater that about 10:1 is possible in the design of the engine. Close to the end of the compression stroke, with still about 20 degrees to go to top dead center, the spark plug ignites the fuel air charge. At the very end of the compression stroke, the burning fuel increases pressure more and also increases temperature and rate of combustion.

At the beginning of the power stroke, the rapidly expanding gases from combustion push the piston down with a relatively constant force. At the end of the power stroke, the exhaust valve already starts to open to get gas out of the cylinder efficiently for the next cycle, thus scavenging unburnt fuel from the previous cycle for the next intake cycle. Gasses are pushed out during the exhaust stroke. At the end of the exhaust stroke, both valves are open for volumetric efficiency. At the beginning of the next intake stroke, the exhaust valve will fully close. Back to the intake stroke, the intake valve is fully open and the 4 cycles are repeated.

Radial engines have a master articulating rod so that cylinders can be arranged around a circle shaped case. Radial engines are constructed with an odd number of cylinders arranged around a central case. We will animate how the pistons move using the master articulating rod and connecting rods for the remaining cylinders. Let's take a look at this simple animation of the crank rotation and piston movement in a radial engine.

Intake and exhaust valves open and close and the spark plugs fire off at the right time to create the same 4 cycles as found in the more common opposed engine. Radial engines are rarely used in aircraft today. Some agricultural aircraft continue to use the radial engines, as well as WWII restored aircraft.

Turbine engines will be discussed in detail later, but here is a brief overview. A turbine engine can be used to turn a propeller and this is called a turbo-prop powerplant. Turbine engines have a gas cycle that is similar to the 4-cycle opposed engines and all gas engines for that matter. This turbo shaft engine could be used to turn a propeller to generate thrust horsepower. Where the hot combustion gasses are driving turbine wheels is known as the hot section.

The major sections of a turbo prop on this PT-6 turboshaft engine has the first gas cycle of intake and compression near the rear of the powerplant. Air is vented into the intake section and a screen keeps debris from being sucked into the engine. Once the air enters the engine the air is compressed by a set of axial flow compressors and then a centrifugal flow compressor. The compressed and greatly heated air is fed into the combustion chamber where fuel is injected into the engine. Igniters in this section triggers combustion and the hot gases move forward towards the turbine and exhaust sections. The turbines extract energy from the hot gasses and converts the energy to mechanical rotation of the compressor drive shaft and well as rotation of the output shaft that will ultimately rotate propellers or perform some other output purpose.

Basically, air is squeezed or compressed through two types of compressors and then delivered to the combustion chamber where fuel is injected under high pressure. The fuel is ignited and the turbine wheels extract power from the hot high velocity gasses moving over them. One turbine drives the compressors while the other is used to drive the gear box and ultimately rotate the propeller shaft to produce thrust horsepower. The gas cycle of suck, squeeze, bang, and exhaust is the correct order, however the sections can be rearranged so that the exhaust is at the front of the engine instead of the back. This arrangement works well for a turbo-prop aircraft where power is extracted from the turbines to drive the propeller at the front of the engine.

All gas engines have a gas cycle where air is compressed and heated, mixed with fuel, to have power of combustion to move air rearward for thrust or to extract power to rotate a fan and or propeller to create thrust. In a turbine engine we have one continuous gas cycle; while in a reciprocating engine we have 4 cycles for two revolutions of the crank shaft – two up strokes and two down strokes.

Aircraft engines must be designed to operate in an aircraft in all phases of flight required for the missions of the aircraft. All aircraft engines must be very reliable to avoid having an accident if the engine were to fail. At the same time, the engine must last and maintain its integrity for many years or hours of operation. The engine must stand up over many hours of life and still be reliable. An engine must be durable. The power output for the weight and size must be high to be practical. The engine must be compact enough so that it can be mounted on the airframe to have pilot visibility over the nose in single engine aircraft yet have clearance from the ground while having a low drag profile once the engine is installed with cowling. Engines must be able to withstand large variations is operating conditions such as high altitude and extreme heat and cold. Relatively speaking, the engine must be economical enough to compete with other manufacturers to minimize the cost of operating the aircraft. Last, the engine should be easy to start and operate without hours of special training. Ultimately, all gas engines are air cooled. An aircraft engine is considered air cooled rather than water cooled because the cooling outside air picks up heat directly from cooling fins attached to the cylinders. A true water cooled engine extracts heat from the cylinders with a water coolant that in turn is cooled by air in a radiator.