Course : Diploma in Aeronautical & Aerospace Technology (EGDF11)

Module Title : Aircraft Propulsion System

Module Code : EGF211

TOPIC 5 : Aircraft Fuel System

OBJECTIVES:

At the end of this topic, the students should have an understanding of:

- Combustion process, thermal efficiency and correct fuel air mixture for combustion
- Cause and effect of fuel pre-ignition and detonation
- Features of aircraft fuel system, fuel feed system for multiple-gas turbine powered and helicopter powered aircraft, different types of gravity feed systems, including cross-feed and manifold feed, and fuel system for carburettor and fuel-injection engines
- Fuel characteristics, need for prevention and removal of microbial elements and ice from fuel, and need for proper fuel handling
- Functions of fuel system components of fuel tank filler cap, pumps, filters and strainers, valves and heaters
- Fuel system instruments, plumbing features, and proper method for fuelling and defueling and jettison system features

5 Aircraft Fuel System

5.1 Combustion Process

Transformation of energy during combustion process

Petrol is a hydrocarbon compound, C_8H_{18} It can release 20,000 BTU of heat energy per pound of fuel. During combustion process, chemical reaction occurs between the hydrogen and carbon in the fuel and the oxygen in the air.

When the mixture of fuel and air is ignited and burns, heat is generated to perform useful work. In the same process, CO_2 and water are produced.

Stoichiometric Mixture

When 1 kg of petrol is burned with 15 kg of air, it releases the maximum amount of heat without any unburned oxygen and free carbon. This is called the stoichiometric mixture of 1:15 When a mixture is too rich, insufficient oxygen will cause incomplete combustion resulting in carbon being produced causing black smoke or soot to form

When a mixture is too lean, too much oxygen will result in less energy being produced

5.1.1 Thermal Efficiency

A reciprocating engine could convert into useful work only one third of heat energy released by petrol when burned. Thus, this type of engine is inefficient in the use of fuel

Thermal efficiency of an engine is the ratio of the amount of work actually done, to the amount of work, which can be achieved by the fuel when burned.

Example:

Fuel normal weight per gallon = 6 lbs. Each lb. contains about 20,000 BTU of heat energy. Each BTU can do 778 ft.lb. of work

If an aircraft engine consumes 9.25 gallons of petrol/hour to produce 118 brake horsepower, its thermal efficiency is 27%.

9.25 gallons per hr. = 9.25 · 6 = 55.5 lbs per hr. or 55.5/60 = 0.925 lbs per min

0.925 · 20,000 BTU per lb = 18,500 BTU per min in fuel burned by engine

Power in fuel = {118 HP · 33,000 ft.lb.} / {778 ft.lb. work per BTU} = 5,005 BTU per min

Thermal efficiency = 5,005/ 18,500 = 0.27 or 27%

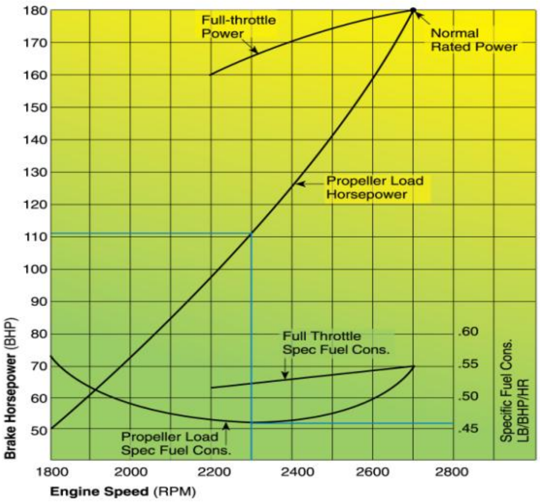
5.1.2 Specific Fuel Consumption

Specific fuel consumption (SFC) for a reciprocating engine is a better measure of engine performance than thermal efficiency.

SFC is defined as the amount of fuel burned per hour for each brake horsepower produced.

The following curve shows the relationship between the brake SFC and the engine cruising speed.

Notice this engine has the best brake SFC at speed of 2300 rpm producing 110 brake horsepower or 61% of the rated power



5.1.3 Mixture Ratio For Reciprocating Engine

For the reciprocating engine, the fuel air mixture and engine power vary in accordance with operating environment:

- Design of fuel induction (injection) system
- Valve timing
- Highest temperature that can be tolerated by the engine cylinder

A fuel injection system is used to assist in metering fuel

The Exhaust Gas Temperature indicator with a thermocouple probe installed at the exhaust pipe helps manage the correct fuel-air ratio to be applied to the fuel metering system.

A lean mixture results in higher EGT and a rich mixture produces lower EGT.

For a given power setting, the volume of air flowing through the carburetor remains constant, and as the air becomes less dense with higher altitude and hence less oxygen for the given volume of air, the end result is a richer mixture of fuel entering the cylinder. To compensate for this problem, the mixture control will decrease the amount of petrol the carburetor discharges into the induction air thereby keeping the mixture ratio somewhat constant.

5.1.4 Effects of Fuel Detonation & Pre-ignition

Detonation:

When the unburned fuel-air mixture in the cylinder is heated and compressed to a critical temperature and pressure during the power stroke, it explodes. This explosion, heard as the pinging or knocking sound, causes a great increase in pressure and creates shock waves inside the cylinder. Damage to the engine could happen.

When detonation occurs, the aircraft engine suffers power loss, creating vibration and decrease in EGT, followed by a slow increase in temperature of the cylinder head.

Pre-ignition

Pre-ignition happens when there are hot spots inside the cylinder. Hot spots can be particles of carbon or red-hot edges of a valve.

When fuel-air mixture is prematurely ignited and burns because of hot spots during the compression stroke, the heated air starts to expand opposing the upward movement of the piston. This will cause power loss.

The time period for the mixture to burn is increased and more heat is thus released with cylinder head temperature rising. The unburned fuel-air mixture in the cylinder head begins to compress with its temperature rising, and then ignites and explodes.

5.2. Aviation Fuels

5.2.1 Reciprocating & Turbine Engine Fuels

"AvGas" is not a "jet fuel" but a refined gasoline mixture intended for piston driven propeller aircraft. This gasoline mixture is officially known as "100 Low Lead" or "100LL." It is slightly higher than normal gasoline in its octane rating (100 as opposed to the 93-95 found in most higher performance gasoline) but it also contains a lead additive (tetraethyl lead TEL) that prevents aircraft engines from knocking

Jet A and Jet A-1 are kerosene-type fuels for jet engine operation. The primary physical difference between the two is freeze point. Jet A, which is mainly used in the United States, has a freeze point of -40 ºC or below when solid crystals start to form

Jet A-1 must have a freeze point of -58 ºC or below when solid crystals start to form

Jet A does not normally contain a static dissipater additive, while Jet A-1 often requires this additive.

The primary criterion for fuel system performance is pumpability – the ability to move fuel from the fuel tank to the engine. Pumpability is influenced both by fuel fluidity and fuel system design.

5.2.2 Jet Fuel Volatility

The jet fuel has to be volatile enough so that it can readily burn easily with air for cold engine starting on the ground or in-flight relight. However it must not be too volatile so that it poses a threat to safety and fuel loss when it vaporizes too easily.

Ordinary fuel (petrol) with 7-psi vapor pressure under normal ambient conditions is too rich a mixture with air for combustion.

Jet-A and Jet A-1 fuel has a low vapour pressure of around 0.125 psi and under normal operating conditions would not form an explosive fuel-air mixture.

5.2.3 Jet Fuel Viscosity

Viscosity is a measure of a liquid's resistance to flow under pressure. Viscosity and freezing point are the physical properties used to quantitatively characterize the fluidity of jet fuel.

Jet fuel is exposed to very low temperatures both at altitude and on the ground at locations subject to cold weather extremes. The fuel must retain its fluidity at these low temperatures or fuel flow to the engines will be reduced or even stop.

The spray pattern and droplet size of the fuel in the combustion section are influenced by fuel viscosity. If it is too high, an engine can be difficult to relight in flight.

Fuel viscosity influences the pressure drop in the fuel system lines. Higher viscosities result in higher line pressure drops, requiring the fuel pump to work harder to maintain a constant fuel flow rate.

5.2.4 Microbial Growth in Jet Fuel

There is always moisture in the air especially in the tropical areas with high humidity. When the wing tanks are cold after a long flight and refueling begins, moisture in the air will condense inside the tanks.

Water thus formed will collect at the lowest point of the wing tanks. If this water is not completely drained before each flight, the amount of water will increase and soon the microscopic organism in the water will grow to form sludge or fungus that holds the water in contact with the wing structure, resulting in a corrosive attack on the wing skin.

Biobore treatment can be employed to kill the fungus if found. Chemical additives may be added to the jet fuel to prevent fungus growth.

5.2.5 Fuel Anti-Icing

All turbine aircraft fuels contain some dissolved water. It cannot be extracted because it does not exist as particulate water.

When an aircraft rises to flight altitude, the fuel cools and its capacity to retain dissolved water is reduced. Some of the dissolved water separates out as discrete water that can form into ice crystals or remain as a super-cooled liquid. When super-cooled water strikes a tubing bend or a filter, it can freeze quickly and block a fuel line or filter. If suspended ice crystals are present, they can also block a filter.

To prevent dissolved water in the fuel from freezing during flight, the cold fuel is routed to the engine fuel-cool oil cooler where heat is transferred from the oil to the fuel. Anti-icing aviation fuel additive can be added to the fuel. It controls icing in aircraft fuel by depressing the freezing point of water.

5.2.6 Fuel Handling

Three important factors are required to manage fuel properly: Cleanliness, safety and fire precaution. Great care is to be taken at fuel storage facilities to prevent water entry to fuel and fuel trucks.

Fuel trucks and aircraft are to be grounded properly during aircraft re-fueling to prevent any static electricity from igniting fuel vapour. On older aircraft re-fueling, there are quantity gauges on the fueling truck and aircraft fueling control panel for correct quantity of fuel to be added to any fuel tank. The fueling tank valves will shut off fuel supply when the predetermined quantity is reached. This procedure is manually controlled.

On modern day aircraft, fueling is done automatically by a computerized system. When the quantity of fuel required for each tank is known and set, all the hoses connected to each fueling valve will open and fueling will begin until the pre-dialed quantity is reached.

When an aircraft requires to be de-fueled, a de-fueling truck is used to store the fuel, which is sent back to the refinery or is used for purpose other than for aircraft operation.

5.3 Aircraft Fuel System Construction

The features of an aircraft fuel system consist of the following components:

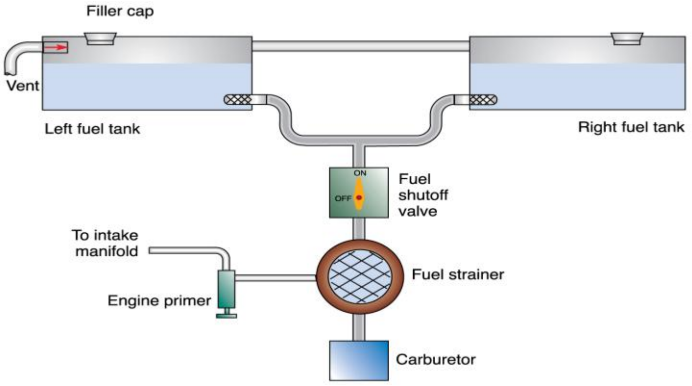
- Fuel system independence
- Fuel flow
- Fuel system hot weather operation
- Fuel tank capacity.
- Fuel tank test.
- Fuel tank installation
- Fuel tank expansion space
- Fuel tank sump
- Fuel tank vent
- Fuel tank outlet
- Fuel pumps
- Fuel valves and controls
- Fuel strainer or filter
- Fuel system drains
- Fuel jettison system

5.4 Types of Aircraft Fuel System

5.4.1 Gravity Feed Fuel System For A Float Carburetor

Gravity-feed is the simplest fuel system for some small training aircraft.

Fuel stored in separate wings flows into a joint pipe through an on-off shutoff valve, fuel strainer and then to the carburetor. The two tanks are inter-connected by a pipe above the tank airspace and vented to atmosphere via a vent. A primer pump is used to draw fuel from the strainer and sprays it into the engine for starting

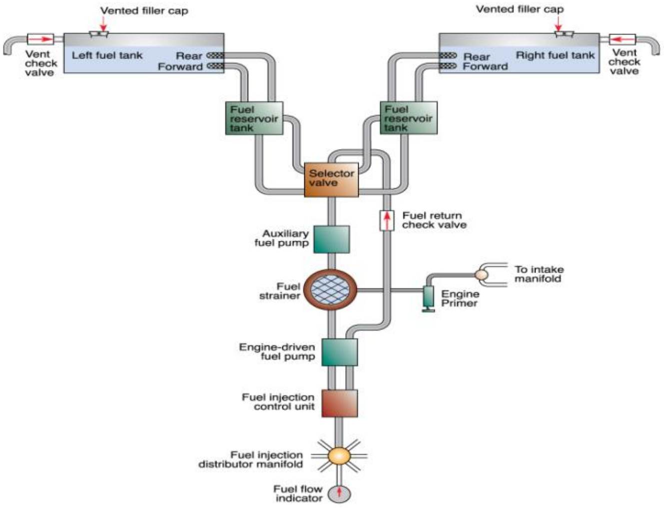


5.4.2 Gravity Feed System For A Fuel-injected Engine

For small high-wing aircraft with fuel-injected engine, fuel from left and right wing tank flows into its respective fuel reserve tank connected to a common selector valve. The selector valve has 3 positions: OFF, LEFT ON and RIGHT ON.

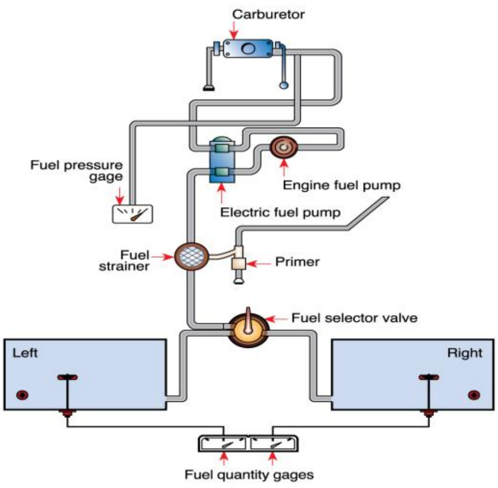
The fuel flows through an electric auxiliary pump, main fuel strainer and finally into the engine driven fuel pump. From there, part of the fuel flows into the fuel injection control unit that delivers the fuel via a check valve, selector valve to the reservoir of the fuel tank.

The other part of fuel flows to fuel injection distributor manifold. An engine primer can be used to draw fuel from the strainer and deliver to the fuel manifold.



5.4.3 Low-wing, Single-engine Fuel System for a Float Carburetor

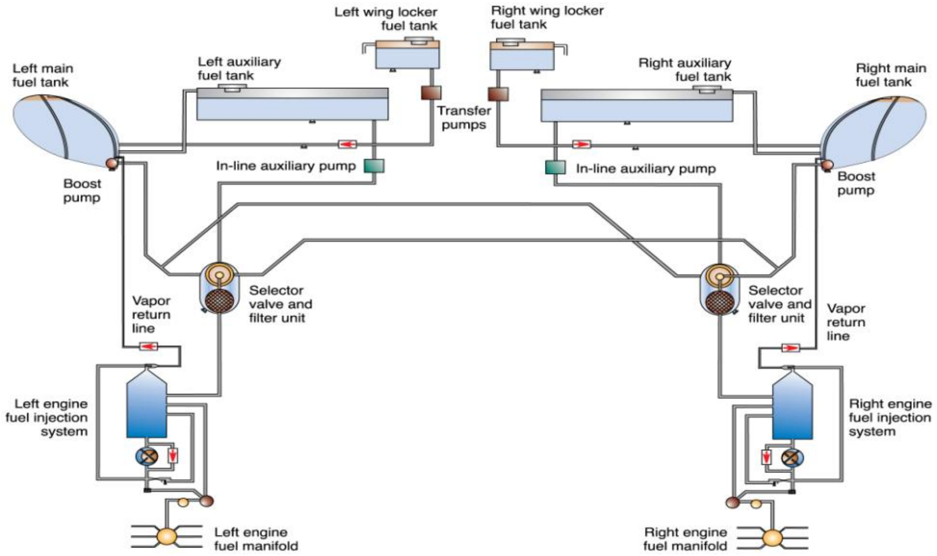
For a small low-wing aircraft fitted with a float carburetor, fuel flows from the right and left fuel tank to a common selector valve. It then flows to the strainer and the engine fuel pump. An electric pump is installed to help to start the engine. A diaphragm-type pump is used to supply fuel for normal operation in case the engine driven pump fails.



5.4.4 Low-wing, Twin-engine Fuel System for Fuel-injected Engines

On either side of the aircraft, the fuel system consists the main tank in the wing tip, one auxiliary tank and one locker tank that supplies fuel to the main tank when needed. Fuel flows from main tank through the selector valve and the filter and then to the engine-driven pump via the fuel injection unit. Fuel in the locker tank can be transferred to the main tank. Auxiliary pump in the main tank can be used for priming, purging and for backing up the engine driven pump.

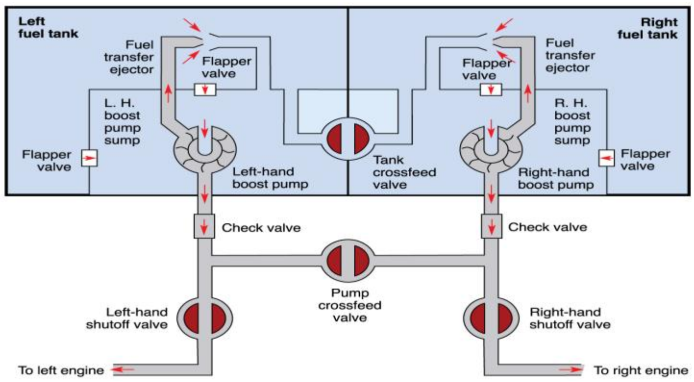
Electric pump is installed in the line between: wing locker tank and main tank to transfer fuel; and between auxiliary tank and fuel selector valve. It supplies fuel to injector pump and to prevent vapors from forming in the line between auxiliary tank and injector pump.



5.4.5 Twin-engine Cross-feed Fuel System.

The twin-engine cross-feed fuel system, as shown below, has a mirror image of components installed.

The system consists of a fuel tank, fuel transfer ejector, shutoff valve, cross-feed valve, boost pump, and check valve. Engine can draw fuel from either tank. Fuel can transfer from one tank to another via the cross-feed valve



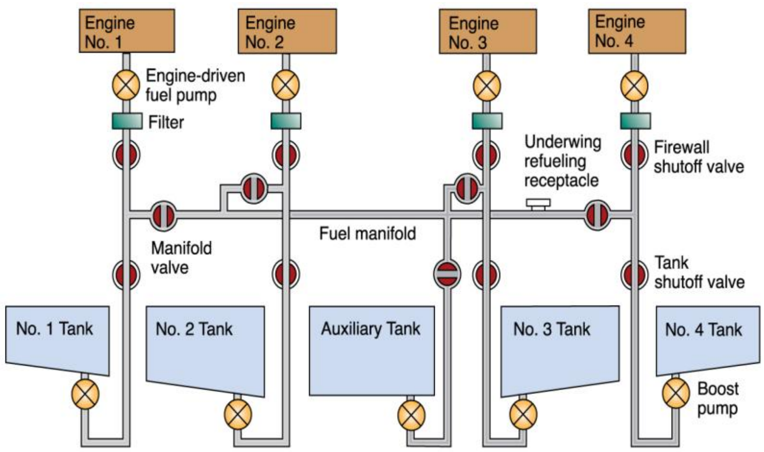
5.4.6 Four-engine Manifold Cross-feed Fuel System

Large aircraft cross-feed fuel system, as shown below, incorporates a manifold that connects all the fuel tanks and all engines. This manifold can be used for single-point draining and fueling and supply fuel to all engines. The features of this system are:

- All engines can be fed from all tanks simultaneously
- All tanks can be filled through a single receptacle
- Any engine can be fed from any tank
- A malfunctioned tank can be isolated from the rest of the system

The system consists of the following components: boost pump, tank shutoff valve, firewall shutoff valve, filter, and manifold valve.

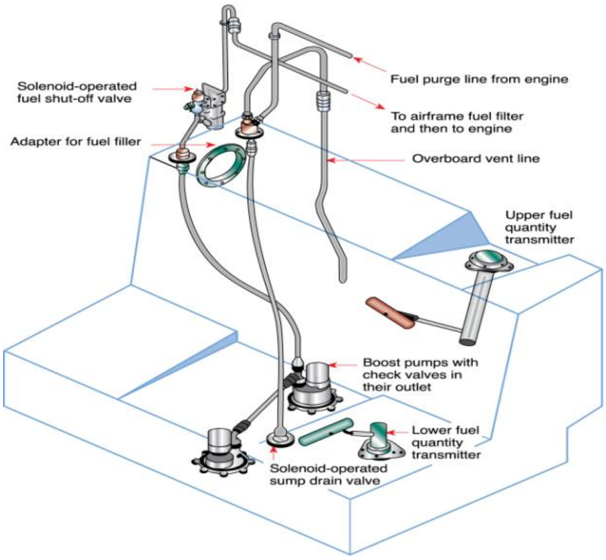
For fuelling, fueling hose is attached to a receptacle with a control panel managing the flow quantity. All manifold and tank valves are open. Firewall shutoff valve is closed. Fuel will flow to the tanks when the hose valve is opened



5.4.7 Helicopter Fuel System

Figure below shows a single-engine helicopter fuel system.

The bladder-type fuel cell is mounted in the fuselage and connected to the fuel filler port on the outside of fuselage. 2 boost pumps inside the tank. Fuel flows through boost pump, check valve, and supply line. Fuel then flows through a shut-off, filter and through to engine filter, engine FCU and engine driven pump



5.4.8 Large Turbine Engine Transport Fuel System

In large turbine engine powered aircraft like the Boeing 727, there are 3 fuel tanks, one main and two wing tanks.

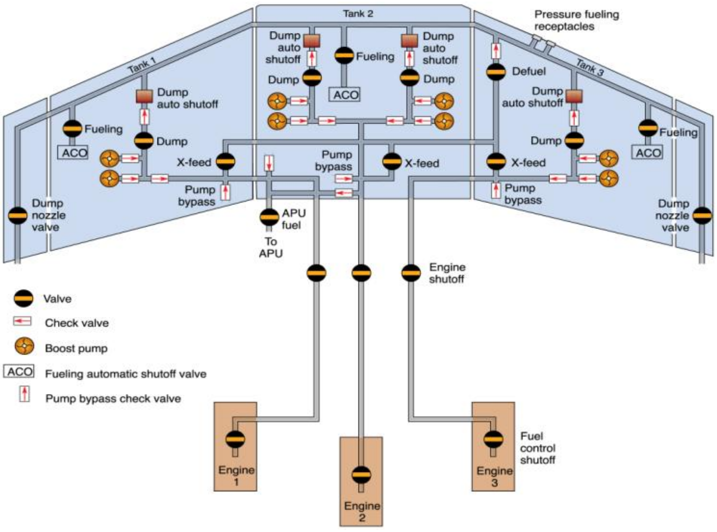
In the Boeing 747 there are one main tank in the center section of fuselage, two wing tanks on each side of the wing, and a tail tank. All the tanks are inter-connected for fuel balancing purpose and also to supply fuel to engines via common manifold.

All tanks are fitted with booster pumps and check valves. Cross-bleed valves allow fuel transfer between tanks.

Tail tank fuel can be transferred to main tank either way on latest modern aircraft for aircraft balancing purpose

Normal engine operation is tank-to-engine feed using boost pump supplying fuel to the engine driven pump and through engine shut-off valve opening. All tanks are fitted with a venting system with vent surge tanks and flame detection and extinguishing system.

Below shows a Boeing 727 fuel tank system layout



5.5 Fuel System Components

5.5.1 Fuel Tanks

Three types of fuel tanks:

- Built-up tanks,
- Integral tanks
- Bladder tanks

Baffles are installed in large fuel tanks to prevent fuel surging back and forth. Flapper-type check valves installed to prevent fuel from flowing away from tank outlet

At each low point of tank there is a sump for drainage of contaminants and water. Fuel tanks are vented to atmosphere. All corners of fuel tanks of modern large aircraft are sealed with sealants

Built-up fuel tank

Tanks made of sheet aluminium alloy or stainless steel either welded or riveted togetherIt has the flowing basic components installed: filler cap with scupper drain, sump with standpipe and drain valve, vent and baffle plates

Integral fuel tank

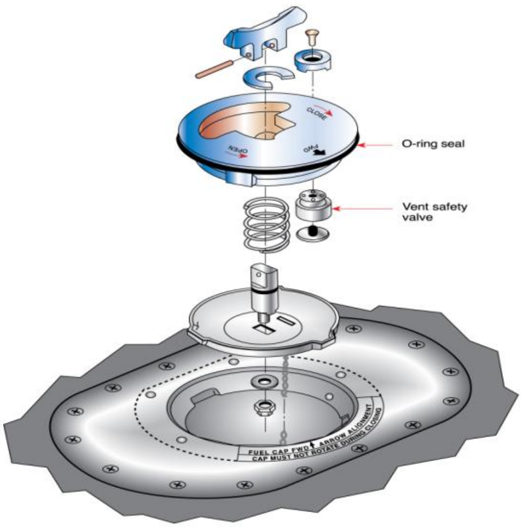
An integral fuel tank is also part of the aircraft structure. They are used because of weight saving They are fabricated with aluminium alloy sheets, angles, ribs, baffles, spars and rivets. Tanks are vented to atmosphere and provisioned with sump drains and manholes Fuel quantity tank probes are installed inside tank to measure fuel quantity

Bladder-type fuel tank

A bladder-type fuel tank consists of two parts: a bladder cell that is made of rubberized fabric materials to contain the fuel and the aircraft structure to hold the cell. The bladder is inserted into the empty tank space and secured by clamps, clips or lacing. Inter-connecting hoses are joined together and clamped.

5.5.2 Fuel Tank Filler Caps

Filler caps are used to seal the tank inlet to prevent leakage If filler cap with a venting safety valve malfunctions, the empty air space that does not vent will result in creating a low pressure in the tank. When this happens, fuel will not flow properly to the engine If low pressure happens to a bladder-type fuel tank, the bladder cell will collapse. A typical filler cap is shown below:



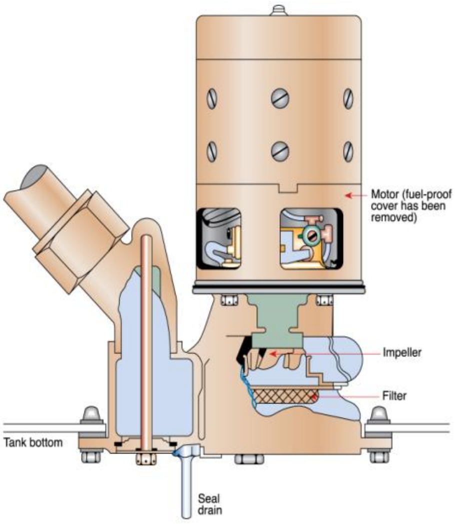
5.5.3 Fuel Pumps

In the fuel tanks, there are centrifugal booster pumps that supply fuel to the inlet of the engine fuel pumps to ensure there is positive pressure at the engine pump inlet and no air fills up the fuel line between the fuel tank and engine pump inlet.

Many such boost pumps have two-speed motors. The low speed operation is to supply fuel to the engine for starting and a backup for takeoff and landing. High speed is used to transfer fuel between tanks to ensure the aircraft wing loads are balanced.

In the early days, transfer of fuel is done by the flight engineer manually. However, in modern day aircraft, it is done automatically.

The pumps are used to dump fuel through the dump chute when fuel needs to be discarded for emergency landing to avoid overweight landing. Figure below shows a typical booster pump



5.5.4 Fuel Filters & Strainers

Filters and strainers are used to remove contaminants such as microorganism, dust, foreign particles and broken sealants in the fuel tank.

Strainers are installed at the fuel tank outlets, inlet to fuel metering units or engine fuel pumps.

Outlet strainers are of the coarse mesh finger screen that contains a fine screen that does the filtering. Main strainers located at the lowest point in the fuel system.

Turbine engine fuel filters contain filter elements that can remove particles in 10-25 micron size

Another type of filter is the wafer-type screen that can remove tiny particles

Some fuel filters have pressure switch across filter element. Should the filter become clogged, pressure drop across the filter will increase thereby closing the electrical contact and hence turning a warning light on in the cockpit

Below shows a main filter and a micro-filter on engine fuel system

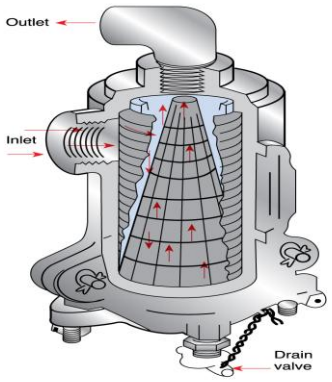
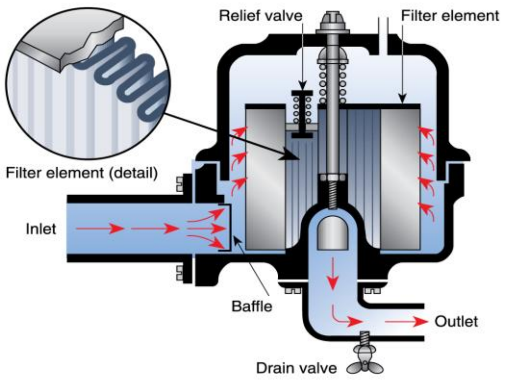


Figure shows a main fuel strainer



Microfilter used in turbine engine fuel system

5.5.5 Fuel Valves

Fuel valves are used to control and allow fuel flow to meet the required quantity without appreciable pressure drop across it. The valves have detent to indicate the position marking There are four types of valves:

- Plug type valve – This valve has a conical nylon or brass plug that rotates in a mating hole in the valve body.
- Puppet-type valve -- This valve has a cam that is rotated by a handle. The cam forces the poppet to unseat allowing fuel to flow through from the tank to the engine
- Electric motor-operated valve -- Commonly used on large aircraft. The valve has a motor that drives a crank arm that moves a gate to either cover or uncover an opening allowing fuel to stop or flow through. Seal or O-ring is installed to prevent fuel leakage from gate passages.
- Solenoid-operated poppet-type SOV -- This valve uses DC electricity to operate a solenoid to open another solenoid to close the valve

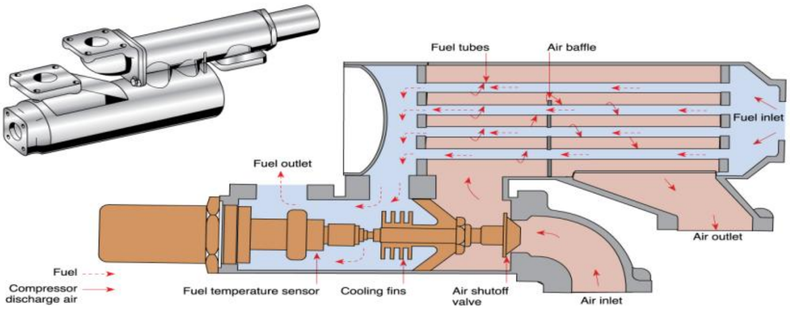
5.5.6 Fuel Heaters

Fuel heaters are used to prevent formation of ice on the fuel lines at high altitude.

When fuel temperature indication in the cockpit shows fuel filter icing warning of ice formation on the fuel filter, fuel heat switch is turned on to allow the fuel heat valve to open to direct hot air from the engine compressor bleed system through the fuel heater unit.

There are two types of fuel heaters

- Air-to-fuel heater or heat exchanger (as shown below) – uses compressor-bleed hot air for source of heat. The sensor in the exchanger controls the hot air flow rate.
- Oil-to-fuel heater -- The heat is derived from the hot engine oil .



Air-To–Fuel Heat Exchanger

5.6 Fuel System Instruments

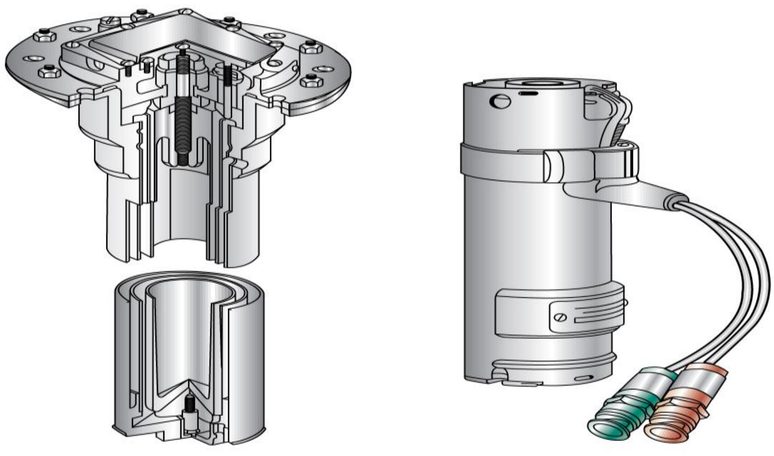
5.6.1 Fuel Quantity Measuring System

The most commonly used fuel quantity measuring system is the electronic (capacitance-type) fuel-quantity indicating system. The system consists of following components:

- Inside the fuel tanks at several strategic locations, there are several capacitor-type probes installed

- A bridge circuit to measure the capacitance of all the probes
- An amplifier to raise the amplitude of the bridge circuit signal to drive an indicator
- An indicator in the cockpit to show the quantity of fuel in the tank

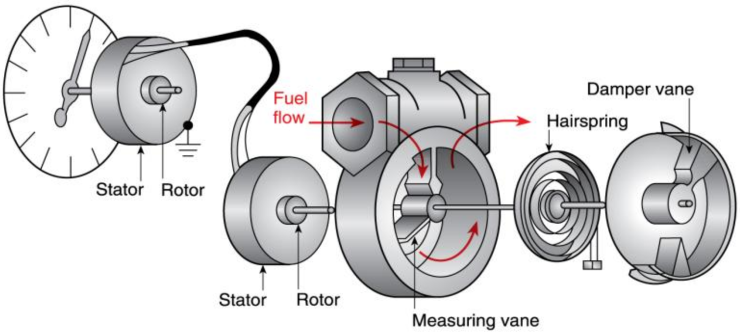
The total capacitance of all the probes remains constant despite the change in capacitance of individual probe when the fuel level in the tank changes with different altitude and turbulent flight conditions. The system measures the weight of the fuel instead of volume that is affected by density



5.6.2 Fuel Flowmeters

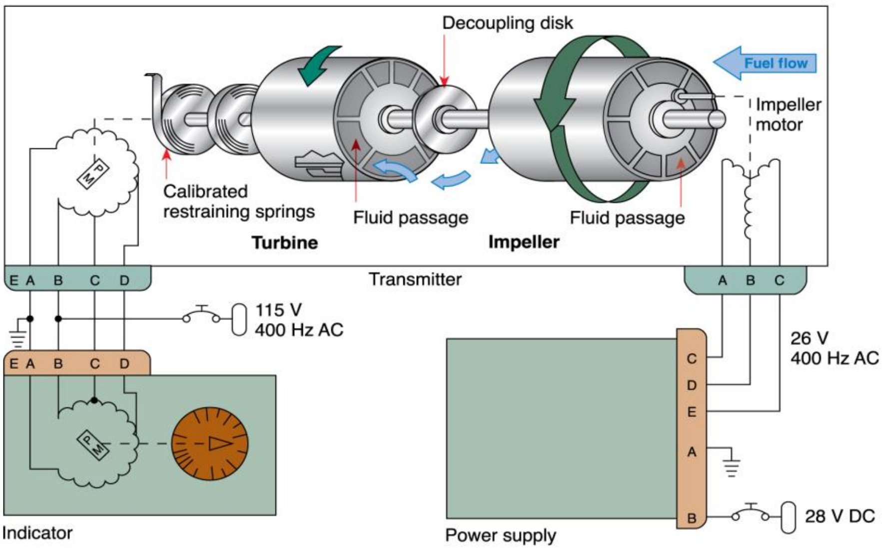
Reciprocating engine fuel flowmeters make use of vane deflection as a means of measuring fuel flow rate in terms of volume and not mass.

The flowmeter is installed between the carburetor and engine driven pump. The vane is moved by the flow and is resisted by calibrated hairspring. Movement of the vane is transmitted via the rotor of a transmitter to the cockpit indicator as shown in the diagram



Fuel flowmeters used for turbine engine are measured in terms of mass flow and a typical flowmeter is as shown below:

The flowmeter system consists of a motor, an impeller, a turbine, calibrated restraining springs and a transmitter. The impeller imparts swirling motion to the fuel flowing through it and the outflow deflects the turbine, which is restrained by calibrated hairsprings. The deflection is transmitted electrically to the cockpit indicator.



5.6.3 Computerized Fuel Flow System

Computerized fuel flow system (CFS) – for reciprocating engine

The CFS provides following information to the pilot:

- Quantity of fuel in mass and volume remaining onboard the aircraft
- Fuel time remaining at the current flow rate
- Quantity of fuel used since start of engine
- Fuel flow rate

The system uses a small turbine rotor installed between the fuel injection unit and flow divider and all fuel must pass through the turbine before entering the cylinder. As the rotor spins, it interrupts a beam of light between a light source and a phototransistor. Pulses of lights become pulses of electricity that enters the computer for processing.

5.6.4 Fuel Pressure Warning System

Fuel pressure warning system for a reciprocating engine involves measuring the differential pressure between the fuel pressure and air pressure at the carburetor. When the system senses air being drawn from the fuel tank causing the pressure to drop, the pressure warning system switch will be activated sending an electrical signal to the warning light to flash

5.6.5 Fuel Temperature Indicators

Fuel temperature sensors are used to sense the temperature of the fuel in the tank so that it does not reach 0 deg. If it does, hot engine compressor bleed air can be directed through the fuel heater to prevent ice formation.

5.7 Fuel System Plumbing Requirements

Fuel line routing

All fuel lines must be installed such that there is sufficient gap between it and the adjacent part or component or else chafing will occur during aircraft maneuver or airframe vibration

Fuel line alignment

All lines must be installed with provision for thermal expansion and contraction. All clips, clamps, brackets must be installed within tolerance limits.

Fuel line bonding or earthing – to prevent static electricity build up, all components for the fuel system are to be earthed.

Support of fuel system components

All fuel lines must have clamps and brackets installed for proper support. The supporting clamps and brackets are distanced as per the figure below:

Tubing O.D. (inch)	Approximate Distance Between Supports (inches)
1/8 to 3/16	9
1/4 to 5/16	12
3/8 to 1/2	16
5/8 to 3/4	22
1 to 1 1/4	30
1 1/2 to 2	40

5.8 Refueling and Defueling

5.8.1 Fuel Jettison System

Fuel jettison system is designed to allow flight crews to dump fuel after take-off in order to reduce the weight of the aircraft to an acceptable level for emergency landing.

Fuel jettison system is to satisfy the flowing conditions:

- Free from fire hazards
- During discharge, the fuel must be kept clear of all parts of aircraft
- Fumes or fuel must not enter any interior part of the aircraft
- Do not affect the operation of the aircraft

The system consists of fuel lines, valves, boost pumps, dump chutes and the operating mechanism

5.8.2 Refueling & Defueling Procedures

Fueling or defueling an aircraft must follow the procedure as shown below:

- Identify actual type of fuel in the tank
- Position fueling truck ahead of aircraft and parallel to the wing
- Parking brakes of the truck are put on
- Truck is equipped with fire extinguisher
- Truck and aircraft are bonded and truck is grounded
- The fuel hoses are clean
- Ensure no spilling of fuel to the ground. If occurred, the fuel must be mopped up
- For pressure fueling, be sure the truck pump pressure is correct for the aircraft.

- Drain the tank to check for presence of water

Fire safety precaution during fueling and defueling operations

Safety precautions include the following process:

- Fueling and defueling must be done in the open air
- All electrical circuit breakers must be pulled and collared
- Radar operation during fueling and defueling must not be performed within sight
- Fire extinguishers are ready for use