Introduction

Comparison with axial fans – totally different

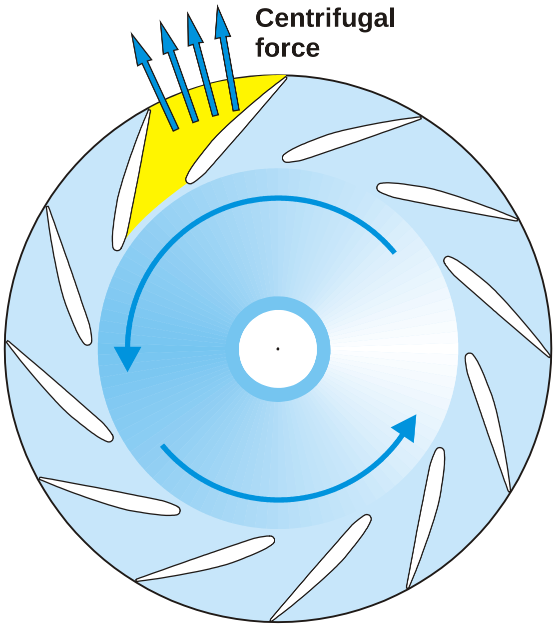
The two most common types of fan are axial and centrifugal. A centrifugal fan works in a completely different way to an axial fan and different mechanical principles must be used to explain how it works.

An axial fan relies on aerodynamic lift being created by its blades. The blades are normally aerofoil shaped and create lift in the same way as an aeroplane wing. The lift produces an axial thrust on the blades in the opposite direction to the airflow, which in turn produces an equal and opposite force on the air, propelling the air axially through the fan. With a centrifugal fan, the blades are used to drag the air around in circular motion, whilst the centrifugal forces accelerate the airflow radially outwards.

Roughly how they work

Air enters a centrifugal fan impeller axially, then passes through the impeller radially, the airflow is then collected in the volute casing and discharged at right angles to the inlet flow.

As the impeller rotates, the air contained within the blade passage is forced outwards due to the centrifugal force. This process happens continually producing a continuous flow through the impeller.



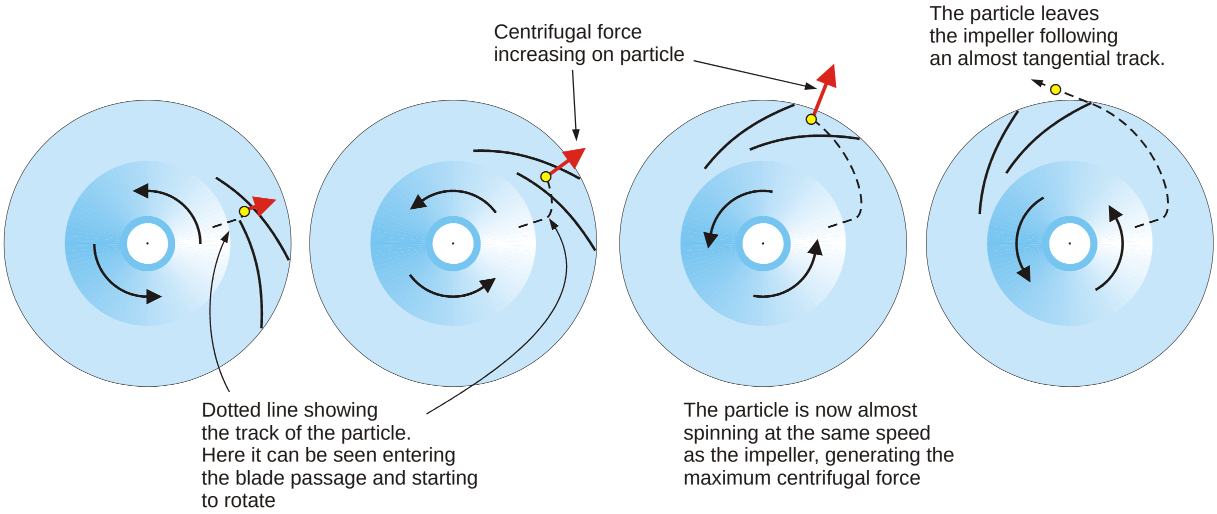
Motion of air through an impeller

There are three stages to the pressure development through a centrifugal fan impeller:

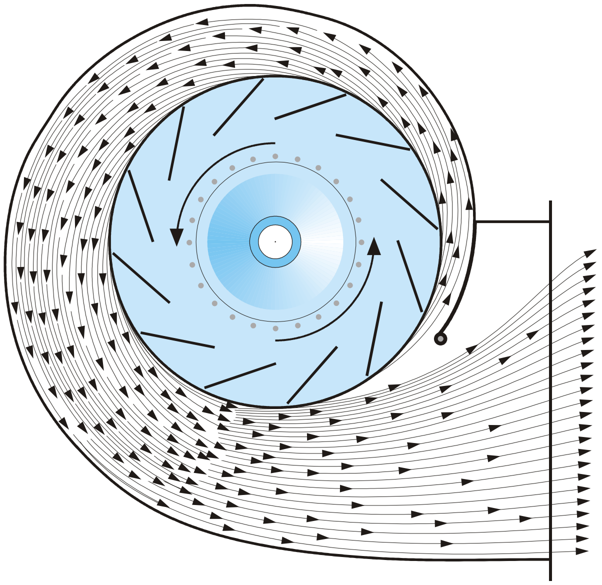
1) We know that air is forced through the impeller in the radial direction due to centrifugal effects. As the radius of the impeller increases the magnitude of the centrifugal force on the air increases. This increase in centrifugal force with radius produces a pressure gradient, whereby the static pressure in the blade passage increases with radius.

2) Generally the outlet area of the blade passage is larger than the inlet area, thus the blade passage acts as a diffuser. The relative velocity reduces as the air flows through the blade passage, leading to an additional increase in the static pressure at the impeller outlet.

3) In an open inlet centrifugal fan, air enters the impeller radially. The motion of the blades adds rotational momentum to the flow, increasing the velocity of the flow in the tangential direction. As the air moves radially through the impeller, the absolute velocity of the flow will increase, with the maximum absolute velocity at the impeller outlet. This increase in the absolute velocity of the air leads to an increase in the kinetic energy and dynamic pressure across the impeller.



Airflow through the Casing



The purpose of the casing is not only to collect the air leaving the impeller and to point it in a useful direction, but also to transfer a significant proportion of the dynamic pressure from the air, which is leaving the impeller, into more useful static pressure.

The casing of a centrifugal fan is usually volute shaped, which allows diffusion of the air leaving the impeller to take place.

As the cross sectional area of the volute casing increases the flow will be slowed down and since velocity is directly proportional to dynamic pressure, the dynamic pressure will decrease:

$$p_{dynamic} = \frac{1}{2}\rho v^2$$

ρ = density

v = velocity

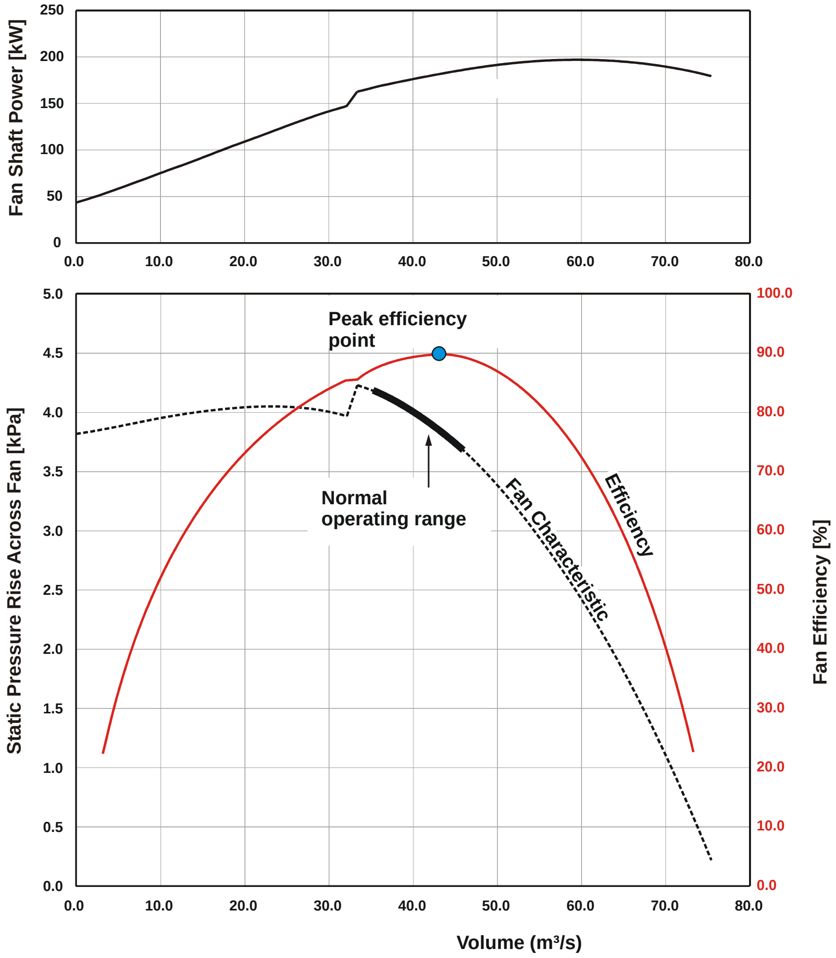
Since no work is done to the air in the casing the total pressure will remain constant (assuming minimal losses due to friction and recirculation), therefore the decrease in dynamic pressure will coincide with a rise in the static pressure.

$$p_{total} = p_{static} + p_{dynamic}$$

For a typical fan around 45% of the static pressure at the fan outlet is provided directly from the static pressure rise through the impeller. Whilst approximately 55% of the static pressure at the fan outlet is provided from the conversion of dynamic to static pressure in the casing. Typically around 90% of the dynamic pressure leaving the impeller is recoverable as static pressure in the casing.

Different Types of Impeller

There are a large variety of centrifugal fan impellers, each has specific advantages and disadvantages that make them suitable for different applications. A centrifugal impeller most commonly has radial, backward or forward curved blades.

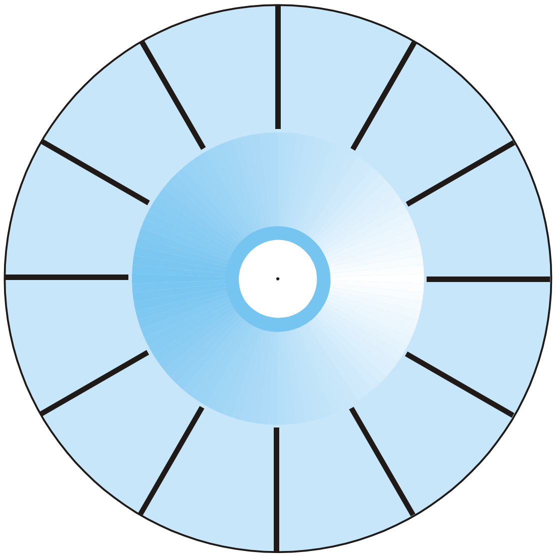


The performance of a centrifugal fan may be described in terms of pressure and volume flowrate. A pressure-volume curve is used to display the relationship between the pressure and volume flowrate for a particular fan, this curve is known as the fan characteristic. A typical characteristic is shown above.

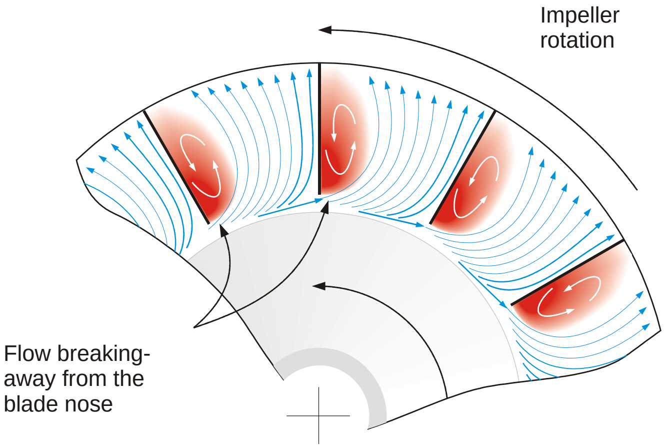
The power characteristic indicates how the power of the fan changes with volume flowrate. The power characteristic shown is non-overloading, which means that the absorbed power has a maximum value and starts to decrease as the flow is increased beyond this maximum power. With an overloading power characteristic, the power increases with the volume flowrate. The power characteristic is dependent on the type of impeller.

The efficiency curve shows how the efficiency varies with volume flowrate, ideally the fan should be operated at peak efficiency, providing the lowest power consumption for a given duty. Operating at peak efficiency also minimises noise levels.

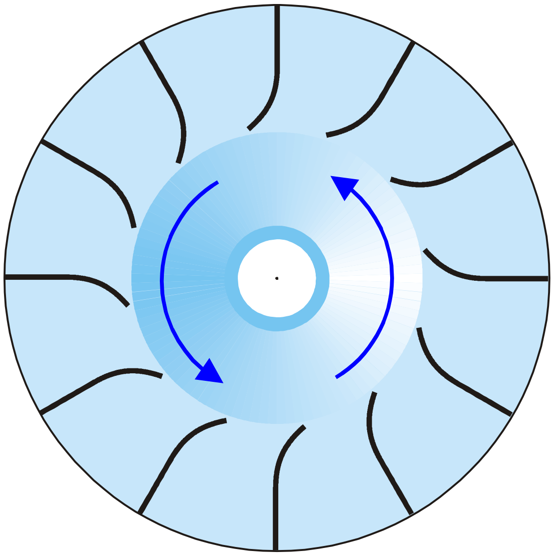
Radial Blades



The radial bladed impeller has 6-16 blades which are radial with no curve at the leading edge, this provides poor air entry conditions. The impeller may either have a conventional backplate or have paddle type blades attached to a spider hub. These fans have the lowest efficiencies of the centrifugal fan types, in the region of 50-60%, however they are capable of achieving high peak pressures. The power characteristic is overloading. These types of fan are capable of dealing with high concentrations of gasborne solids of significant size.

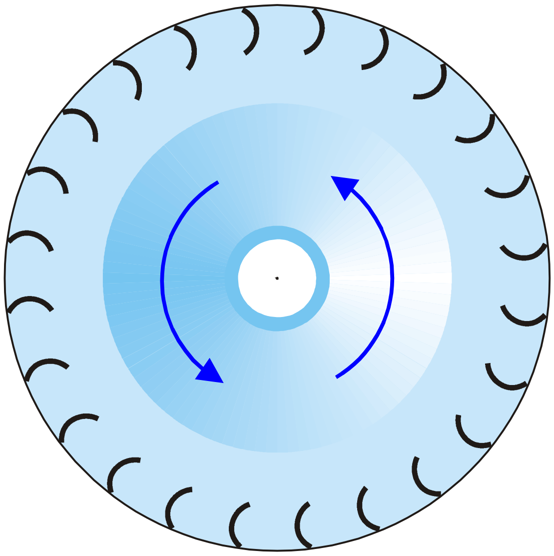


Radially Tipped



The radial tipped fan impeller has blades which are backward inclined to the direction of rotation at the inlet and radial at the outlet. The power characteristic is overloading, with a power curve, which rises steeply from minimum to maximum flow, but not as steeply as the forward curved type fan. Generally the peak efficiencies are in-between those for backward bladed and forward curved fans.

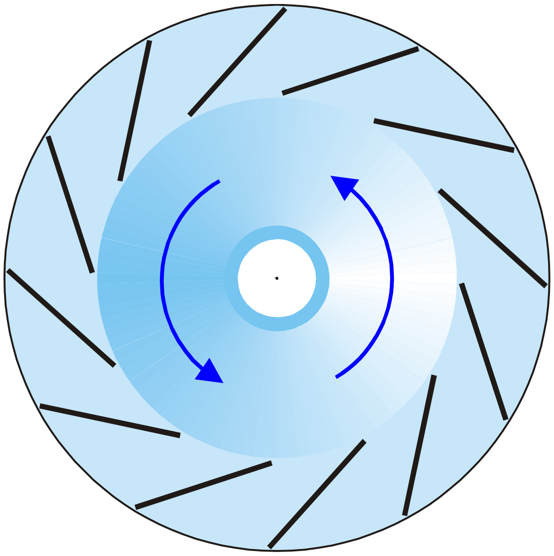
Forward Curved

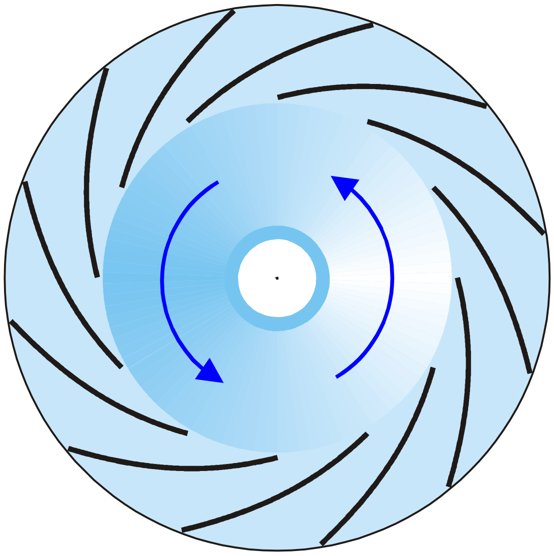


The forward curved impeller has in the region of 24-64 shallow blades, which have the inlet and outlet edges curved forward into the direction of rotation. The fan has an overloading power characteristic and might overload its drive unit if operated significantly above its rated air volume duty. It can handle large volumes of air and has the smallest dimensions of all the impeller types for a given duty. The peak efficiency of this style of fan is in the region of 70%, which is significantly lower than a backward bladed fan.

Backward Bladed impeller

A backward bladed impeller has 10-16 blades that are inclined backward from the direction of motion, and have the form of either flat or curved plates, or aerofoils. This type of fan has a non-overloading power characteristic, and offers high efficiency. The aerofoil bladed variety offers peak efficiencies exceeding 90%, although the plate bladed types can still achieve peak efficiencies exceeding 80%.

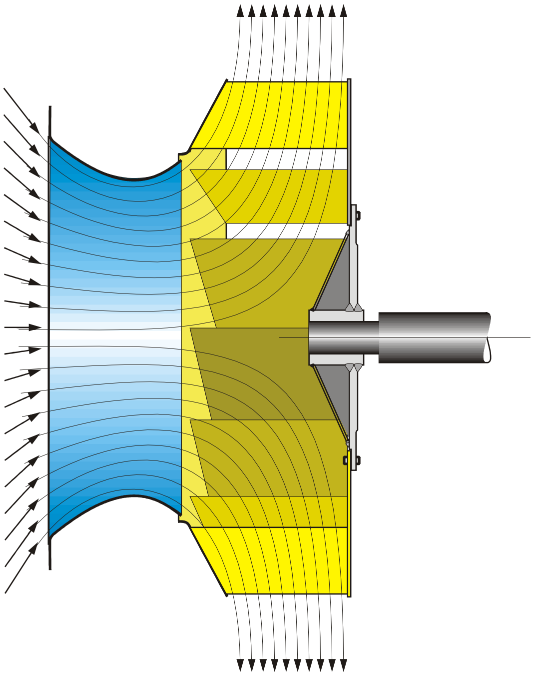




Backward inclined impellers are capable of attaining higher efficiencies then their radial counterparts. This may be explained partly by the fact that the blade passage acts as a rotating diffuser. Backward inclined blades offer a longer length of diffuser compared to radial blades. By diffusing the air more gradually, the airflow is more uniform within each blade passage, leading to more efficient flow through the impeller. Backward curved or aerofoil bladed impellers offer a further increased length of blade passage, which explains their high efficiency.

Fan Components

Inlet Cone



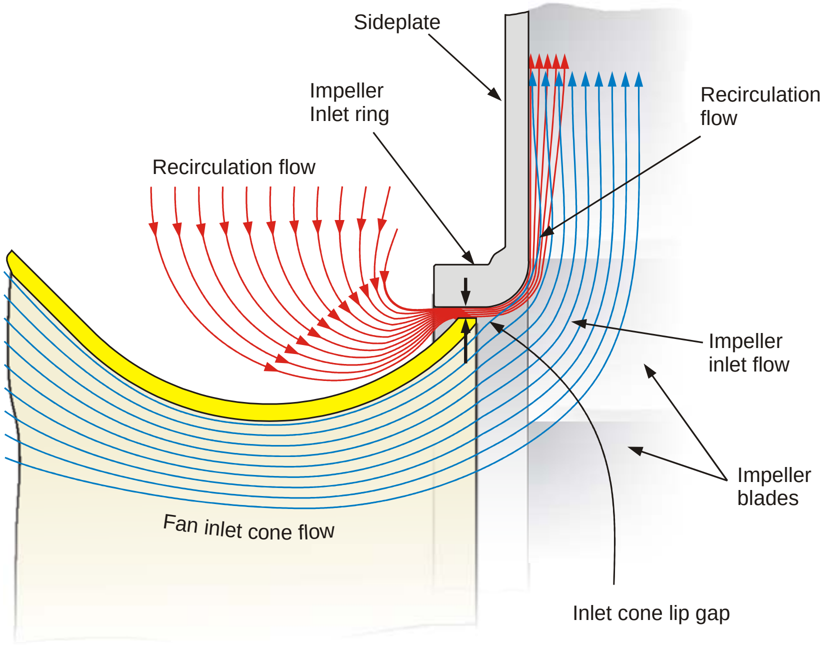
For an open inlet centrifugal fan, the inlet cone is the first part of the fan that the airflow comes into contact with. It is vitally important that the air is guided into the impeller inlet, otherwise the impeller will not operate efficiently and the performance will be greatly reduced.

The velocity of the air at the inlet is high, so the shape of the inlet cone should be as streamlined as possible, to allow a uniform and turbulence-free flow into the impeller. The majority of inlet cones are bell-shaped, since this offers the least resistance aerodynamically and is therefore the most efficient inlet shape.

As the air leaves the inlet cone it must turn through 90° to fill the impeller blade passage, therefore the radius at the inlet cone throat should be designed to make this transition as easy as possible.

Air is reluctant to turn through 90° and will therefore tend to head toward the impeller backplate resulting in separated flow at the sideplate. This causes a fraction of the blade passage to be filled with flowing air and the impeller does not run at full capacity. The clearance between the inlet cone and the impeller can be utilised to take advantage of the Coanda effect.

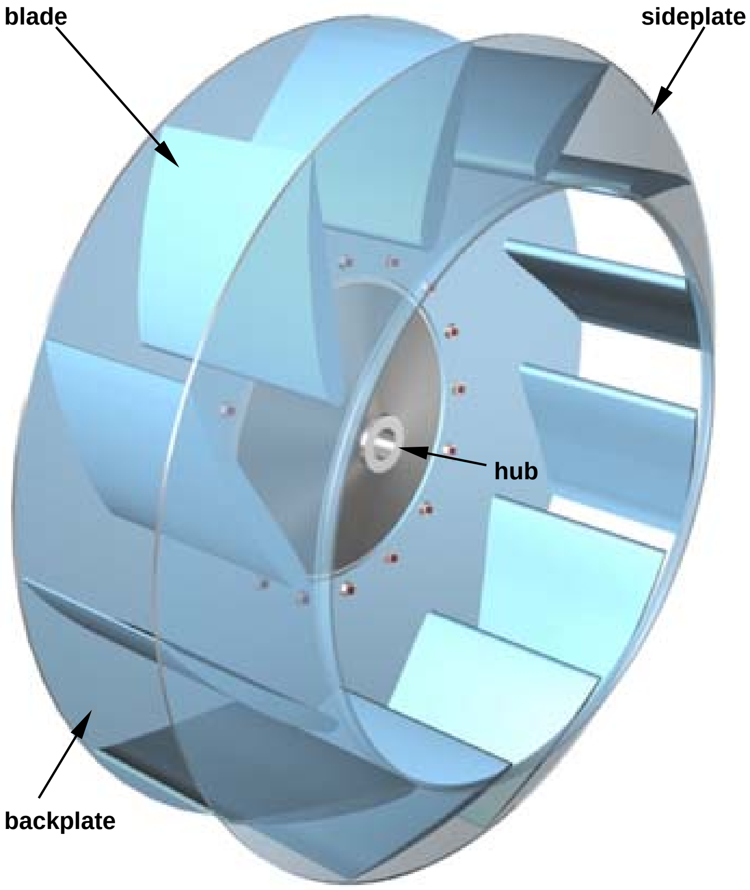
The Coanda effect is the phenomenon where fluids bend around solid objects. This occurs since the flow close to a solid surface is slower than the free stream velocity, viscous drag has the effect of pulling the faster flowing fluid towards the slower flowing fluid near the wall.



As the air flows through the gap between the impeller and inlet cone, it will tend to stick to the sideplate. The airflow from the inlet cone will then tend to flow toward the air at the impeller sideplate and bend through 90° to fill the impeller.

Impeller

The impeller comprises a sideplate, blades and a backplate. The impeller is connected to a central shaft via a hub.



Sideplate

The sideplate channels the flow through the blade passages and prevents the air that is fed into the impeller from spilling outward into the casing. Sideplates can either be conical or parallel with the backplate. The conical sideplate offers a more aerodynamic solution, however the parallel sideplate is significantly cheaper to manufacture. A parallel sideplate can be sufficiently aerodynamic, provided that the Coanda effect is utilised effectively to bend the flow around the 90° corner.

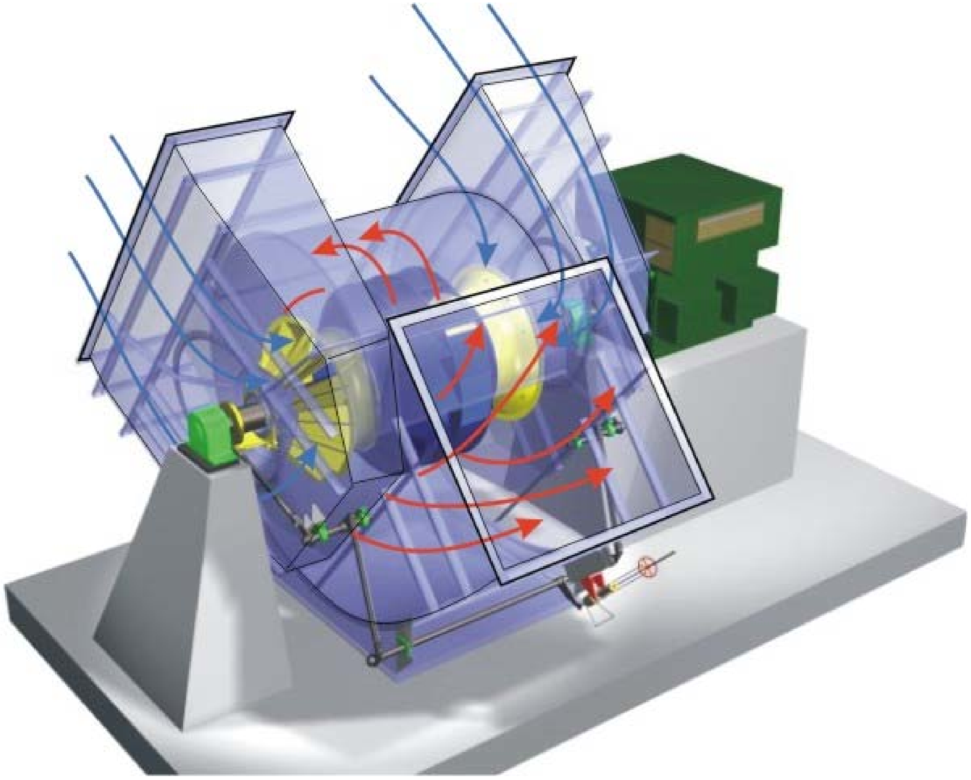
Blades

The blades supply the kinetic energy to the airflow and as such are an extremely important design feature. There are a number of aerodynamic tradeoffs that must be made when designing the form of the blades, including the number of blades and the shape of the blades. To maximise the kinetic energy applied to the air, a large number of blades should be used. However fluid friction effects may be minimised by reducing the number of blades.

The shape of the blades has an effect on how effectively the air will fill the blade passage and how much kinetic energy is transferred from the impeller to the air.

Casing

The impeller casing performs the function of collecting the air that leaves the impeller and pointing it in the required direction, the casing also serves to transform up to 90% of the dynamic pressure at the impeller periphery, into static pressure at the casing outlet. In a centrifugal fan the casing is scroll shaped, this allows a reduction in the velocity of the flow from impeller outlet to the casing outlet.



The blue arrows show the flow through the inlet boxes, whilst the red arrows indicate the flow through the casing.

Efficiency and losses

As with any real life system, losses will occur within a centrifugal fan. That is the electrical power input into the motor is not present in the air at the fan outlet. Energy cannot be destroyed, so power is dissipated within the fan.

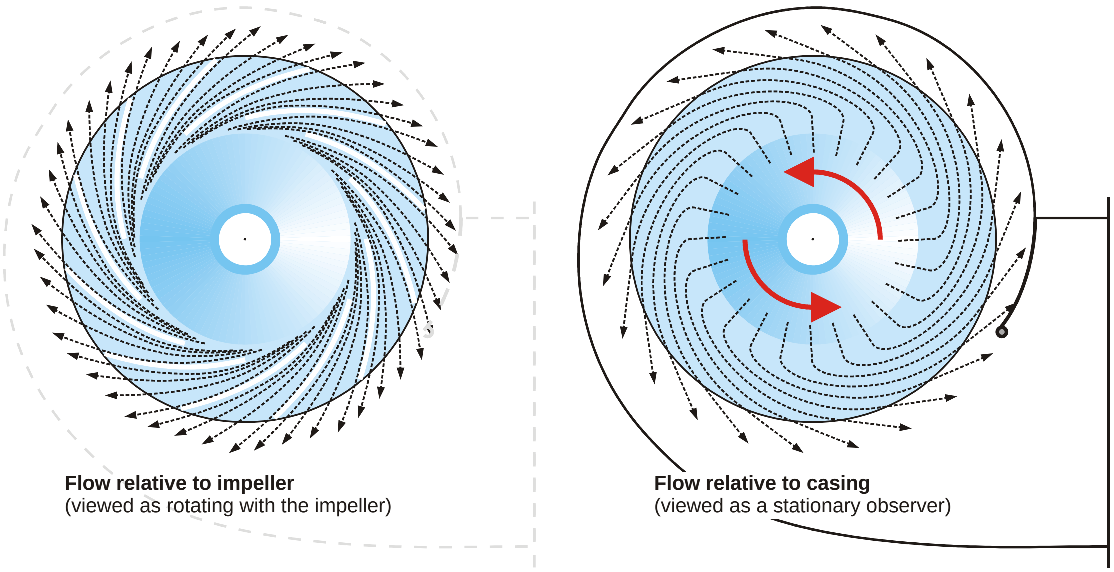
Total efficiency - The total efficiency is the ratio of the theoretical air power to the shaft power. The air power is a measure of the amount of power added to the air in the fan and may be calculated at a particular point by multiplying the fan's volume flowrate and total pressure. The shaft power is the power applied to the shaft, which is measured accurately under test conditions.

Static efficiency - The static efficiency may be determined from the total efficiency and the ratio of the fan static and total pressures.

An impeller's efficiency is greatly effected by the style of the impeller and the shape of the blades, a streamlined blade passage can greatly increase an impeller's efficiency. For some applications, high velocities and volume flowrates are desirable despite the penalty in efficiency.

Velocity triangles

The rotational velocity of the air at the blade tips gives an indication of the amount of energy that has been applied to the air within the impeller and is also indicative of the volume flowrate that can be attained through the impeller.



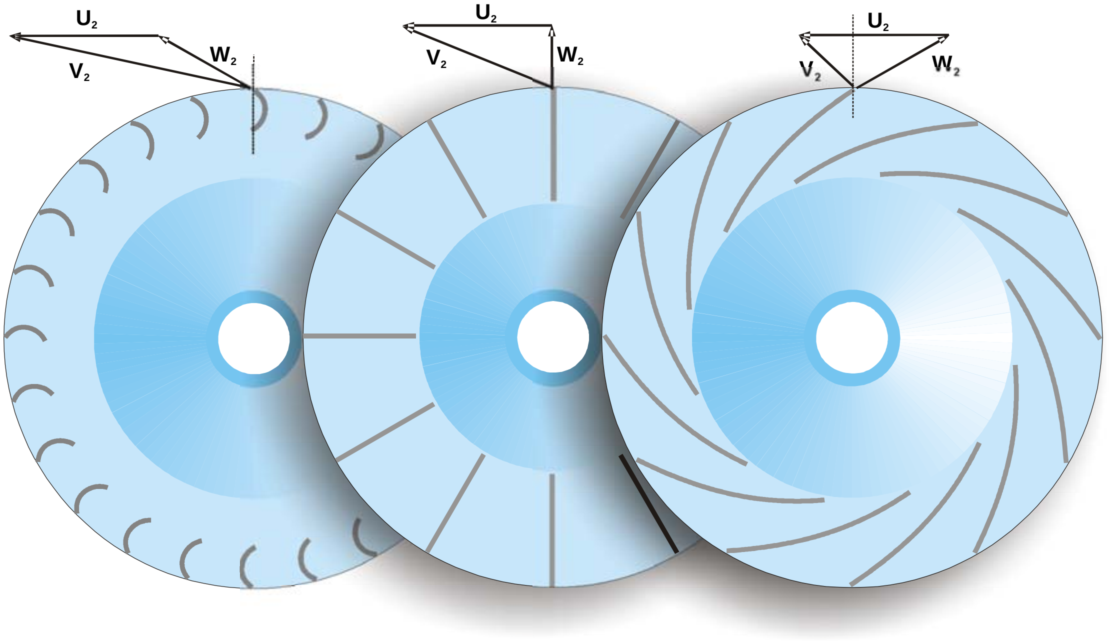
Flow relative to impeller
(viewed as rotating with the impeller)

Flow relative to casing
(viewed as a stationary observer)

W is the relative air velocity – this is the velocity of the flow relative to the impeller. The relative velocity at the impeller outlet is in the same direction as the blade tips.

V is the absolute fluid velocity – this is the velocity as viewed by a stationary observer

U is the linear rotor velocity, which is always tangential to the circumference of the rotor.



Forward Curved Radial Backward Curved

Radial-tipped Blade

From the velocity diagrams, it can be seen that a radial bladed impeller produces a high absolute velocity at the blade tip, which would imply that a radial impeller supplies a large amount of angular momentum to the air. However, radial blades are in fact fairly inefficient due to the turbulent flow through the blade passage.

Some radial tipped impeller blades have their leading edge curved forward into the airflow, allowing a smoother flow of air into the blade passage. There will be significantly less turbulence in this case, providing a much more efficient impeller.

Backward curved blades

The blade tip velocity triangles indicate that the absolute velocity at the blade tip is low compared to other impeller types. However the backward curved blades offer a streamlined blade passage for the air to pass through. The blade passage acts as a longer diffuser than a radial blade passage. This prevents separation of flow at the blade surfaces, hence the air is diffused more efficiently. The power characteristic for this style of blade is non-overloading.

The amount of rotational energy that is applied to the air is less than with other impeller types, however the aerodynamic losses are much reduced with this style of impeller. A backward inclined flat plated impeller will produce tip velocities of the same form as those shown, although the flow through the blade passages will be slightly less efficient, since the length of the blade passage is slightly reduced.

A backward inclined aerofoil style blade offers a further improvement to efficiency. The aerofoil blade is not used for its ability to create lift, as is the case in an axial fan.

The aerofoil offers improved aerodynamics compared to a flat or curved plate particularly at the leading edge of the blade where the air enters the blade passage. The air will flow more efficiently into the passage, maximising the flowrate and minimising disturbances. The aerofoil blades offer the added advantage of being more resistant to bending stresses, since stiffeners may be incorporated into the blades and the second moment of area for an aerofoil shape is significantly increased.

For a given duty the aerofoil bladed impeller offers the highest efficiency of all of the impeller types.

Forward curved blades

The absolute velocity at the blade tip on a forward curved fan is larger than for the other blade types, thus enabling these types of fan to move large volumes of air. For a given duty, this type of fan shall have the smallest impeller and overall installation size making it an attractive option where space is limited. However this type of impeller does require a large number of blades, making it difficult and expensive to manufacture.

However the high velocities mean that the skin friction across the blades will be high. The flow turns through a large angle over the short length of blade passage, which causes high amounts of turbulence in the flow. Hence significant amounts of energy will be dissipated within the blade passage itself.

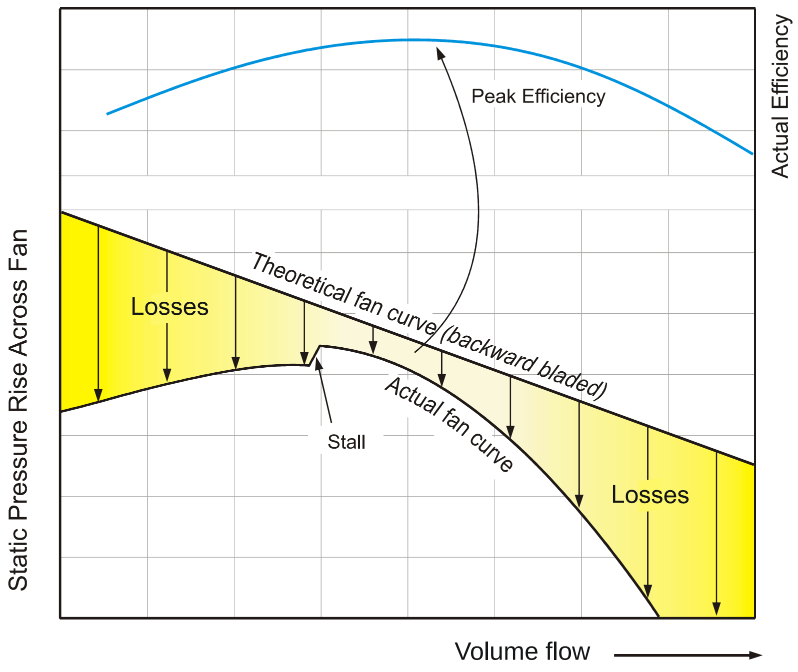
Where a large number of blades is used on an impeller, the blades will be very close together. Thus skin friction will be significant, with the fluid shear stresses at the blade surface effecting the majority of the flow. Wide blade passages would be unable to turn such a large volume of air and severe reverse flow regions would occur. Hence a high number of blades is required to turn the flow on a forward bladed impeller.

Due to the poor efficiencies, high cost to manufacture and weak mechanical strength, Howden do not normally supply this type of impeller.

Performance Curves

The performance of a fan is defined in terms of pressure and volume flowrate. The pressure and volume of a fan have a fixed relationship to each other and may be represented as a fan characteristic curve by plotting volume flowrate along the x-axis and the fan total pressure along the y-axis.

General form of a Pressure – Volume Curve



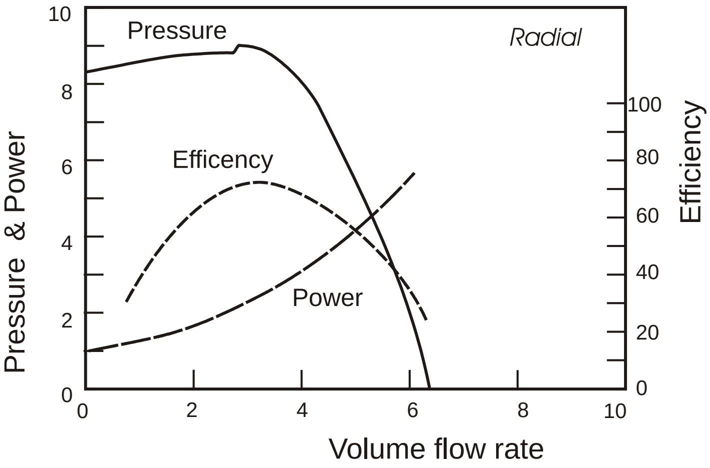
The theoretical characteristic for a fan is a straight-line, however rotational losses, friction and incidence will reduce the actual pressure that is attainable. Incidence is the difference between the fluid and blade angles at the impeller inlet

The losses due to friction increase with mean velocity squared thus the friction losses increase with flowrate. At the peak efficiency, the fluid and blade angles closely match i.e. incidence is zero. Either side of this point, significant losses occur due to the incidence, the losses increase sharply as the incidence increases. Thus the characteristic has a largely negative slope to the left of the peak and a positive slope to the right.

A fan can be operated safely at a range of points along the characteristic curve, however for maximum efficiency the operating point should coincide with peak efficiency.

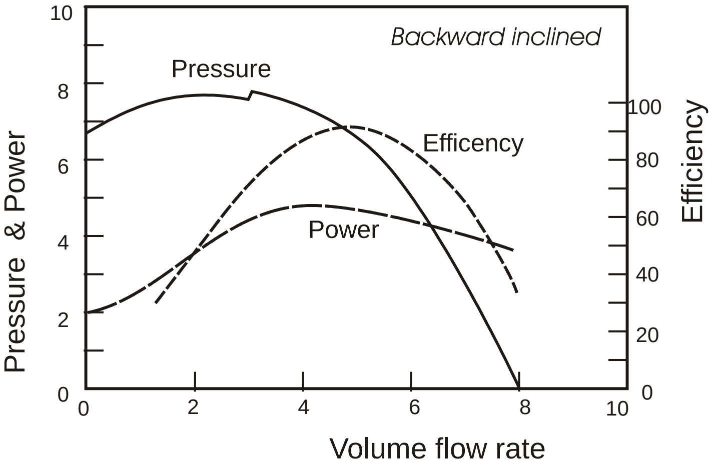
The stall of the fan is characterised by the dip in the curve on the left-hand side. The stall of a centrifugal fan is not particularly severe since the centrifugal forces still force the air through the impeller, However stall should be avoided for normal operation. The stall of a centrifugal fan is explained in more detail in the next section.

Radial/Radial tipped impeller



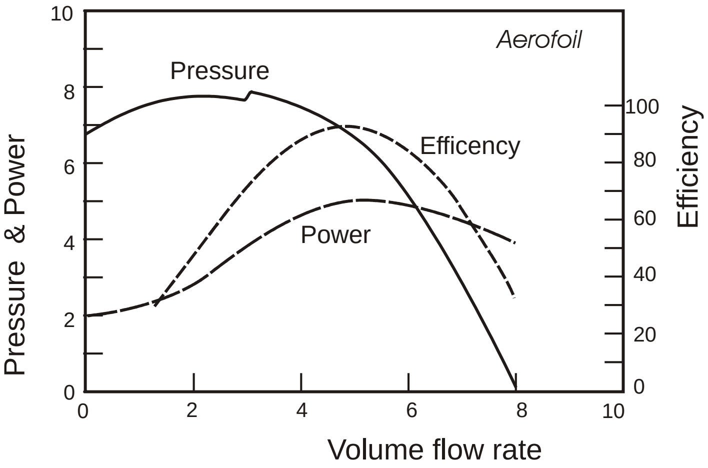
This type of impeller develops the highest total pressure of any of the centrifugal impeller types, for the same impeller diameter and running speed. This is due to the high tip velocities that are produced. However the inefficiencies in the flow mean that the attainable flowrates are low and the pressure drops off rapidly at modest volume flowrates. The stall characteristic is steady and does not cause any particular problems with this style of impeller.

Backward inclined plate impeller



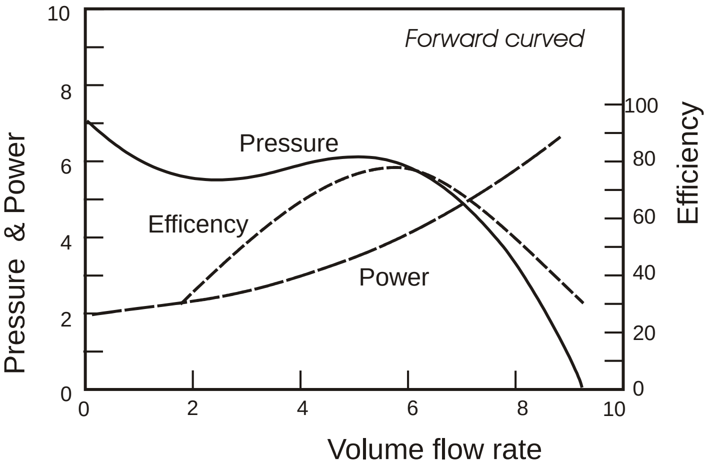
This impeller style develops a lower peak pressure than the radial impeller but offers a significantly higher volume flowrate for the same impeller diameter and running speed. The stall characteristic is similar to that for a radial bladed impeller.

Backward inclined aerofoil impeller



For the same diameter and running speed this style of impeller produces significantly lower pressures than the plate bladed impeller. However this impeller style can offer large volume flowrates in the operating range.

Forward curved impeller



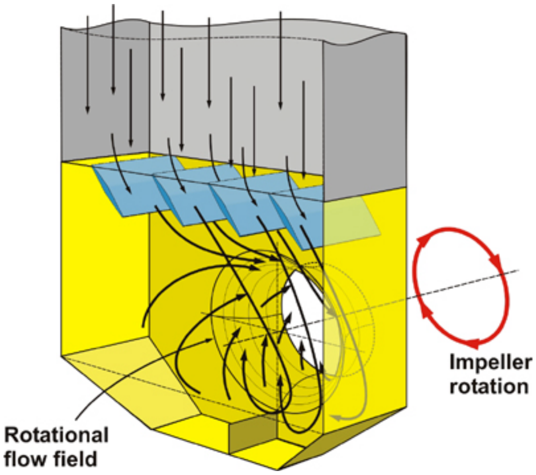
The forward curved impeller produces very high pressures compared to other centrifugal fan types with the same impeller diameter and running speed. Only the radial style of impeller is capable of producing a higher peak pressure. The high tip velocities ensure that the volume flowrate for this type of fan are very large.

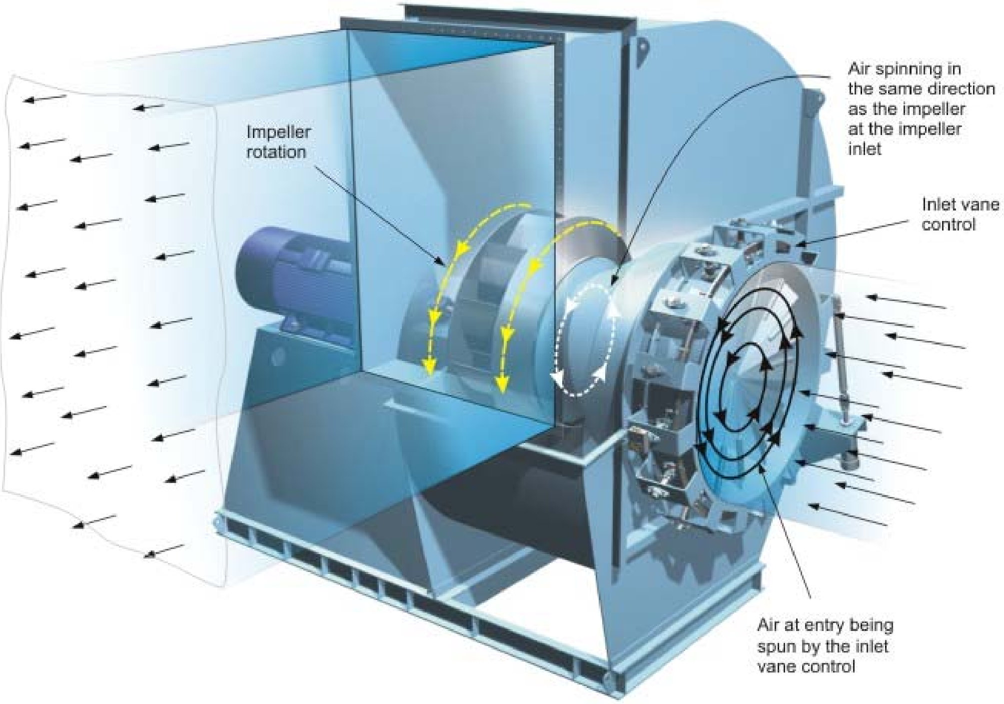
There is a large dip in the left side of the characteristic curve, this indicates a severe stall. Operation in the region of stall should be avoided with this type of fan.

Part load/inlet louvre dampers/radial vane control

When a centrifugal fan is running and the system resistance curve is fixed, the fan will produce a fixed volume flow. However it is sometimes desirable to operate a fan in a part-load condition.

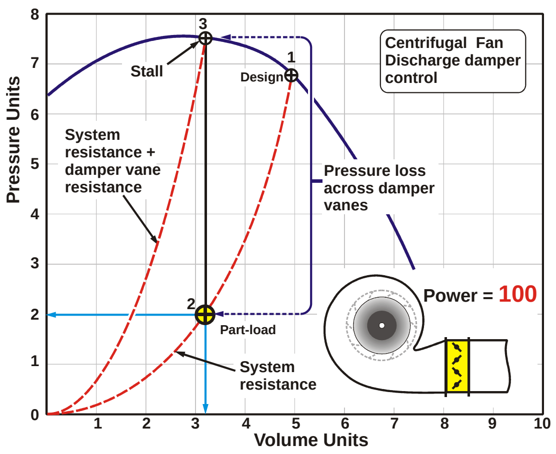
This effect can be achieved by the use of inlet louvre dampers or radial vane control. Both inlet louvre dampers (shown left) and radial vane control (shown below) can be adjusted to pre-spin the air in the direction of impeller rotation; this has the effect of reducing the performance capability of the fan. It is also possible to pre-spin the air in the opposite direction to the rotation of the impeller to increase the performance of the fan, however this is only effective up to a vane angle of around 10°.

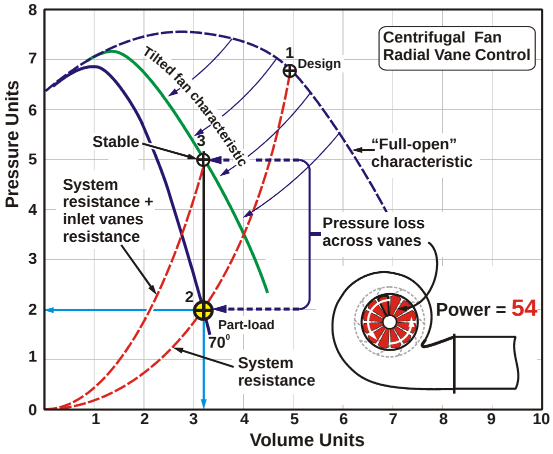




With radial vane control the guide vanes are positioned directly in front of the impeller eye and therefore produce a more uniform and efficient spin. Inlet louvre dampers are fitted into an inlet box. The style of vane control that should be used depends on the conditions that the fan will be operating as well as restrictions on space.

Closing the guide vanes will leads to a drop in both the pressure and volume flowrate, causing the fan to operate at a point further down its system resistance curve.



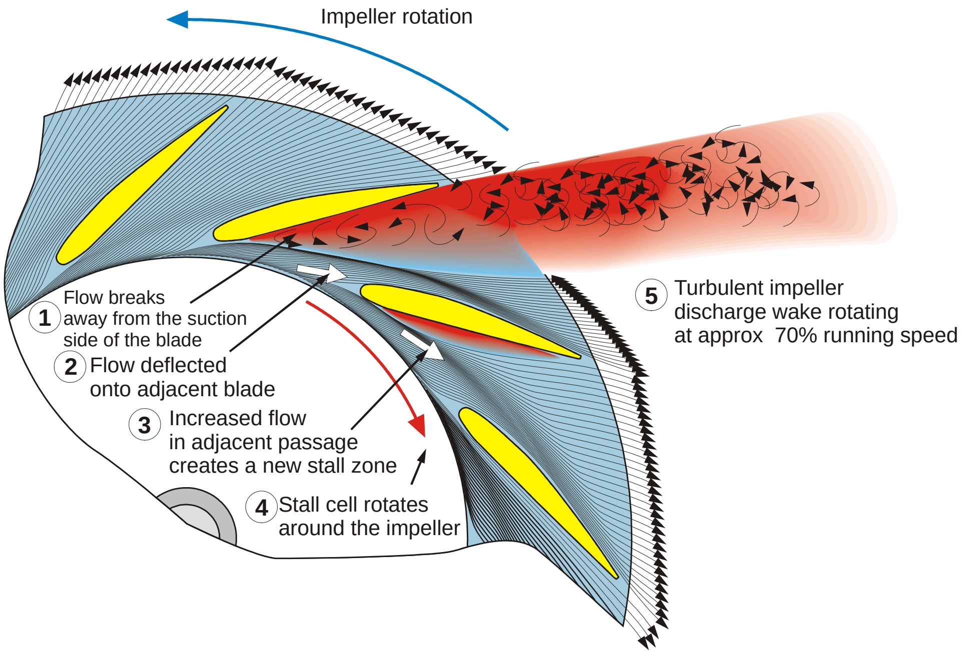


Controlling the volume flowrate by using inlet guide vanes is often preferable to using outlet dampers. Reducing a fan's volume flowrate by closing outlet dampers will increase the fan pressure, in this case the operating point of the fan will move close to the stall. Whereas controlling the flowrate by the use of inlet guide vanes will reduce the fan's power requirement, as well as reducing the pressure rise through the fan. The losses across inlet guide vanes are considerably less than those across the inlet damper. The use of inlet guide vanes can therefore offer a power and cost saving.

Stall characteristics

Centrifugal fans usually have a step in their pressure –volume curve, this point indicates the onset of an aerodynamic stall, known as rotating stall.

The onset of stall will occur on one blade at a time. The stall at one blade will then divert an increased airflow into the neighbouring blade passage, which will then consequently cause the next blade to stall. The blades will then stall one at a time until the entire impeller is in the stall condition.



The stall on a centrifugal fan is not as dramatic as with the stall on an axial fan, due to the fact that a centrifugal fan does not rely on aerodynamic lift to produce pressure. The pressure remains fairly constant as the stall progresses and the volume flowrate decreases. The more severe aspect to a centrifugal fan stall tends to be the increased low frequency noise that is generated causing the casing, ductwork and impeller to vibrate. If large pressure pulsations are sustained then fatigue failure may occur in the impeller, casing and ductwork.

Although operating the fan at stall does not cause a significant drop in the pressure generated, operating a fan in stall for prolonged periods of time must be avoided.

Centrifugal Fans in action

What are the different styles of impeller used for?

Radial – can cope with large volumes of gasborne solids in the flow and as such are suitable for applications where particles are present. Although the fan efficiency is low, the blades are stronger than the other centrifugal fan models. As a result of the simple flat blade geometry, radial impellers can accommodate simple flat plate bolt-on wear protection.

Forward curved – the relatively small blade cross section results in a weak design, which is unable to operate at medium to high tip speeds. Since the blades are weak and the efficiencies are low, this style of fan is rarely used for large-scale industrial applications. The compact installation means that the forward curved fan is often used in domestic heating systems and air conditioning units.

Backward Inclined Aerofoil – often used for heating, ventilation and air-conditioning systems. Due to the high efficiency, this style of fan is used for large-scale industrial applications where large power savings can be made. The fan can be used for low, medium or high-pressure systems. The fan is generally used in large sizes up to around 4-metre diameter, and may be used for non-erosive duties in most industrial applications. For light erosive duties partial liners may be added to the blades or the top skin of the blade may be made slightly thicker.

Backward Inclined Plate – this fan is used in heating, ventilation and air-conditioning applications. The fan is also used for industrial applications. The fan is suitable for erosive duties when sacrificial liners can be added to the blades to increase fan life.