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Radial Thrust in a Single Volute Centrifugal Pump

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Abstract: **The main function of a centrifugal pump is to create Kinetic energy in a liquid. The amount of energy given to the liquid corresponds to the velocity at the edge or vane tip of the impeller. The faster the impeller rotates / revolves or the bigger the impeller is, then the higher will be the velocity of the liquid at the vane tip and the greater energy imparted to the liquid. The kinetic energy of the liquid coming out of an impeller is resisted in a volute (Part of the pump casing is specially designed to collect and direct the flow of water as it enters and leaves the impeller), which is engineered with an increasing flow area to maintain the liquid velocity. Bernoulli's equation holds good as loss of kinetic head in a volute is compensated by increase in pressure head. Also, increasing cross sectional area accommodate more water in the casing. As the velocity of water leaving the impeller equals the velocity of flow in the volute, loss of head due to change in velocity of flow is eliminated by spiral / volute form of casing. Eliminating loss of head due to change of velocity of flow in the volute increases the efficiency of the pump.**

When the fluid mass is rotated in concentric circle, it is called cylindrical free or forced vortex or circulatory flow. The cylindrical vortex is superimposed over the radial flow in order to get the resulting vortex known as spiral vortex.

When a fluid mass is rotated about a vertical axis at a constant speed by some mechanical means, which imparts a constant torque on the fluid mass, every particles of it has the same angular velocity, ω, and the fluid moves as if it were a solid. This type of motion is known as a forced vortex or rotational vortex or flywheel vortex. Rotation of liquid inside the impeller of a centrifugal pump is an example of forced vortex because there is always an expenditure of energy and the fluid mass is subjected to radially inward acceleration. Vanes are made of spiral shape to enable water to have both circulatory i.e. flow in circular motion and radial flow i.e. flow involving a change of distance from the axis of rotation inside the impeller.

The motion of liquid in volute (spiral casing) of a centrifugal pump is an example of spiral vortex. The whole fluid mass rotates without any external agency and rotates either due to fluid pressure itself or the gravity or due to rotation previously imparted energy. The free vortex motion is also called potential vortex or irrational vortex. In free vortex motion, the velocity is in tangential direction i.e. velocity of whirl. While in radial motion, the velocity is in radial direction.

Since in free vortex motion, no energy is imparted to or extracted from the fluid, total head at any point is constant throughout. Thus the energy change occurs in the two main parts of the pump.
Impeller: it is a rotating part that converts driver (Motor, Engine, Turbine etc.) into kinetic energy.
Casing: it is a stationery part that converts kinetic energy into pressure energy.

Casings are generally of two types: volute (Single and Double) and circular. Single volute pump has single lip, which is very easy to cast. It is usually used in small low capacity pumps where as double volute design is impractical due to relatively small size of volute passageway, which makes obtaining good quality commercial casting difficult. Pumps with single volute design have higher radial loads on account of unequal pressure distribution while double volute has dual lips 180^0 apart, resulting in balanced radial loads. Most centrifugal pumps are of double volute design. Circular casing produces low heads but high capacity. Diffuser type casings, in which the diffusers are provided in between the impeller and casing. After excursion of the liquid from impeller outlet it passes through the diffuser so due to that the liquid is not directly collapsed on the casing so there is not back jerk taking place and thus the radial forces are balanced.

The hydraulic radial load is due to the unequal velocity of the fluid flowing through the casing. The unequal fluid velocity results in a non-uniform distribution of pressure acting on the circumference of the impeller. The radial load is most influenced by the design of pump casing. In a theoretical situation at best efficiency point (BEP), the volute casing has a uniform distribution of velocity and pressure around the impeller periphery. Radial thrust can be minimized by making double volute casing or by providing the diffuser (vaned channels more than two) type casing.

In conclusion, the high-pressure liquid is continuously flowing all over the circumference of the impeller and also gets entrapped inside the clearances between impeller and casing / casing cover. This high-pressure liquid exerts pressure on the outlet passages and shrouds of the impeller resulting in generation of two forces, one in lateral and another in longitudinal direction with respect of shaft axis. The force generated in lateral direction is due to dissimilar pressure generation in volute called radial thrust. While another one generated in longitudinal direction is on account of different areas of impeller exposed to trap pressurized liquid called as axial thrust.

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RADIAL FLOW (FIG-1):

The impeller of a centrifugal pump consists of two plates called shrouds, between which are fixed a number of vanes. An opening, called "eye", is provided at the center through which water enters and leaves the periphery. This arrangement produces radial flow. Impellers with shrouds are slightly less efficient due to the drag of the liquid on the shroud. The most common type is a "radial flow" impeller where the liquid makes a 90^0 turn as it passes through the impeller.

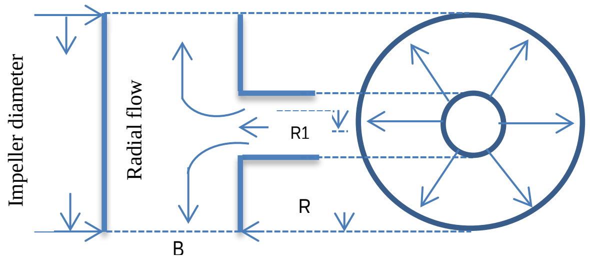


FIG-1

Flow area = $2\pi RB$

Flow, $Q = A \times V_r = 2\Pi RBxV_r$

Q, B are constant, V α (1/R)

In constant flow conditions,

Q= Constant, A α 1/V (α = Proportional)

If the pump is running at B.E.P (Best efficiency point),

V = Constant and A α Q i.e. the quantity of flow.

B = Distance between two circular plates = Width of the impeller.

RADIAL THRUST (FIG-2 A & 2 B):

The force exerted by pumping liquid perpendicular to the direction of the axis of the pump is called radial thrust. Most favorable condition for the pump performance requires constant average velocity in the volute casing and is found at and near the BEP because the pressure is same in all volute section around the impeller and this is the most desirable condition for the impeller discharge. Radial thrust is a function of head, Impeller diameter, Vane width & pump specific speed (Ns). Radial thrust reaches their lowest intensity close to BEP flow. But they are never balanced (FIG-3). The actual low point moves closer to BEP as Ns increases. This unbalanced radial thrust increases quickly as operation moves to the left of BEP and typically reaches its maximum value at shut off head. This may not be a problem with low specific speed pumps that operate at lower flows and heads but, problematic with higher head pumps having large vane width.

FIG-2A

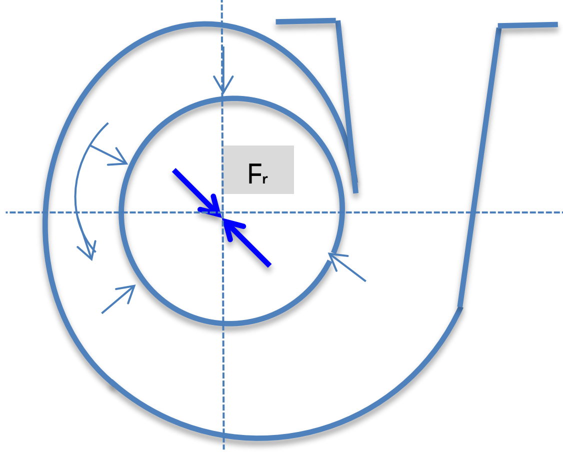
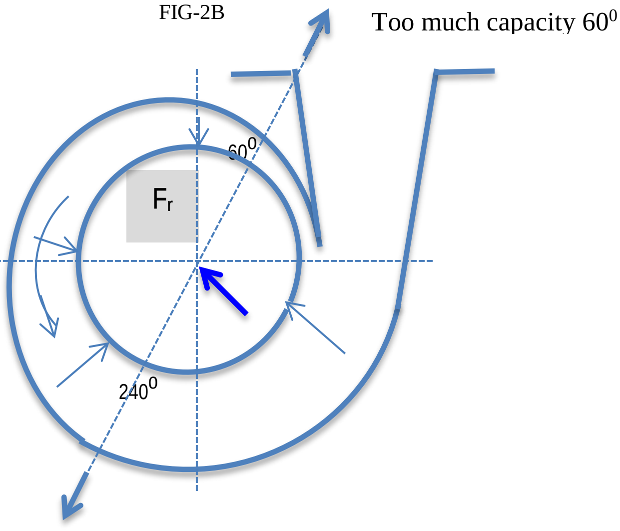


FIG-2B



ENERGY GRADIENT LINE:

The pressure distribution in the volute casing, the resultant of all radial forces acting on the impeller, and the reversal of its direction can be easily explained by the energy gradient variations along the liquid path from the impeller periphery / outlet to the discharge nozzle.

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SINGLE VOLUTE:

In single volute pump, casing pressures are uniform at the design capacity and there is no radial reaction (FIG-2A). Pressures are not uniform at reduced capacities in a single volute pump-giving rise to radial reaction Fr (FIG-2B). When a centrifugal volute type pump is operating at its best efficiency point, the bending forces are evenly distributed around the impeller. If the pump discharge is throttled from the BEP, then the fluid velocity is changed result in increase in pressure at approximately 240^0 from the cutwater in the direction of shaft rotation. If the pump capacity increases because of a lack of sufficient head, then this change in flow will cause an increase in pressure in the opposite direction or at an approximately 60^0 from the cutwater. Francis vane impellers (the most popular shape) deflect at approximately 60^0 and 240^0 measured from the cutwater, in the direction of shaft rotation. Radial vane impellers deflect at close to 90^0 and 270^0. Axial flow impellers deflect close to 180^0 and 0^0 from the cut water

DOUBLE VOLUTE:

Designed actually two single volute designs combined together. The total throat area of the two volutes (double volutes) is same as the single volute design. For diffuser type pumps, the number of vanes in the diffuser casing should divide the volute area of a single volute pump. Double volute is designed because pump is being operated off the pump's BEP. Double volutes usually develop residual thrusts of between 10 % to 20% of the thrust developed by a single volute.

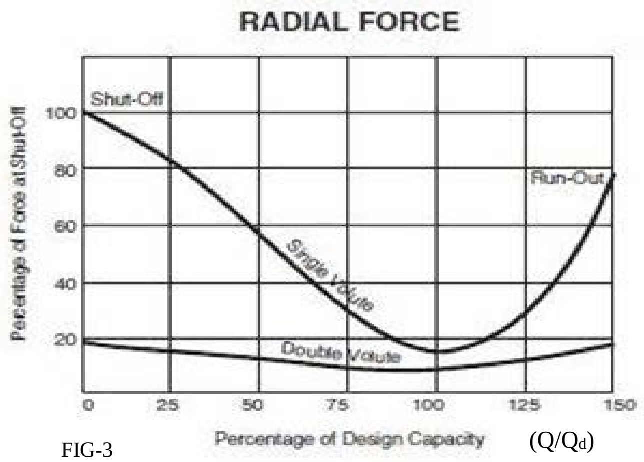


FIG-3

EFFECT OF RATIO OF FLOW RATE (FIG- 4):

If $Q / Q_d < 1$,
For steady flow, Area X Velocity = Constant.
At 60^0, less area results high velocity and hence low pressure.
At 240^0, low velocity results high pressure and hence high radial force.

$Q / Q_d > 1$, the force is usually in opposite direction, but it is impossible to achieve.
At 240^0, low pressure results high velocity.
At 60^0, high pressure results high radial force due to less flow area.

Q = Qd i.e. at BEP, Pressure X Velocity = Constant
Velocity constant results pressure constant and hence, no radial force on impeller.

EFFECT OF CASING GEOMETRY (FIG-5):

Angle, θ_v, increases with increase in the Ns.
K = L $\sin\theta_v$, L is a coefficient depends on variation in a geometrical pattern of the pump.

FIG-4

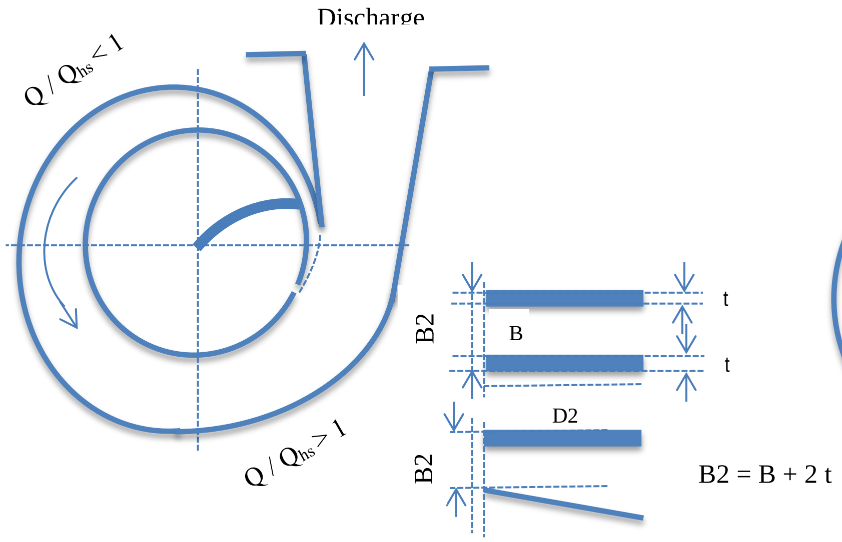
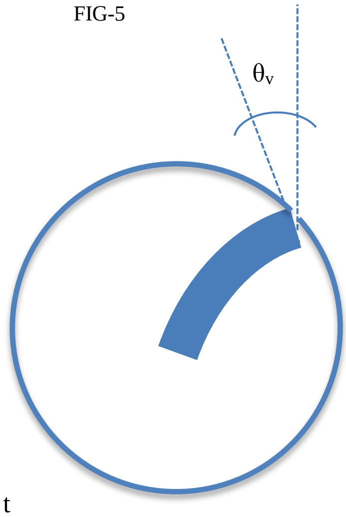


FIG-5



RADIAL THRUST CALCULATION:

Radial force is similar to those existing in a straight, thin rod under tension while tangential force are similar to those occurring around the circumference of a thin tube subjected to internal or bursting pressure. Factors affecting radial thrust are:

The size of the pump
Shut off head
Geometry of the casing
$Q / Q_d (= Q_{hs})$

Radial thrust can be calculated as:

$F_r = P X A = (H X S.G / 2.31) X D_2 X B_2$

$= (H X S.G / 2.31) X D_2 X (B + 2t)$

But, Fr depends on specific design of casing and hence, Fr = K X (H X S.G / 2.31) X D_2 X B_2

Where, K is a coefficient, which depends on specific speed, Ns (= $NQ^{1/2} / H^{3/4}$)

K = Values varies from 0.09 to 0.38. Higher value of 0.6 has also been observed at shutoff head.

Considering capacity factor,

Fr = Kq X K X (H X S.G. / 2.31) X D2 X B2]

OR

[Kq X K X (H X S.G. / 10.2) X D2 X B2]

Whereas, Kq = $[1-(Q / Q_d)^2]$

When, Q = Q_d , Kq = 1 and Fr becomes zero at BEP.

When, Q = 0 (Shutoff head condition), Kq becomes maximum and hence Fr is maximum.

Hence, the radial thrust is maximum at shutoff condition.

This equation applies to radial flow - not to axial flow or to positive displacement pumps. In mixed flow pumps, the thrust acts at some angle from the shaft centerline so it has to be resolved to its radial and axial components.

EFFECT OF RADIAL FORCES:

A radial thrust grows exponentially when a centrifugal pump operates to the left of its BEP, resulting in significant shaft deflections which may result shaft breakage due to fatigue failure of the shaft material, quick seal failures, reduced bearings life (L_{10} fatigue life of bearing is a function of cube of the radial load), worn out bushings and rings.

Pumping a high specific gravity fluid also have substantial effect on the radial load.

Also, a hydraulic phenomenon called "rotating stall" sets-in, which is essentially a back-flow, leaving the impeller eye, and progressing backwards, resulting in violent piping vibrations, pressure pulsations, and wear-out of the components. The problem becomes worth especially when a hydraulic parameter called "suction specific speed" (Nss) is high. Shaft failure mostly occurs in double suction pumps due to large bearing span. In every case, the shaft failure found due to pump operating at partial capacities.

CONCLUSION:

Operational measures: To improve bearing life in a single volute pump:

1. Radial thrust increase with increased deviation in Q/Qd i.e. Pump to be operated as close as to the BEP.
2. Adding a bypass line from the discharge header to the suction pipe to prevent impact of radial load on shaft when running too far off of the best efficiency point of the pump. However, this will reduce the overall pump efficiency for the resulting net flow rate.

Shaft design measures: For long life of shaft

1. A shaft material with a high fatigue / endurance limit should be used. (Note: shrinling the impeller on the shaft reduces the endurnace limit)
2. Threads in the middle portion of the shaft should be avoided.
3. The key seat should have proper fillet to avoid stress concentration.

Casing design measures:

1. Radial clearance between the impeller and casing (I.e. Casing diameter minus impeller diameter) can affect the radial load only upto a certain point.
2. Radial thrust factor, K, increases with increase in specific speed, Ns and hence increase in volute angle, θ_v.
3. Subdivide the casing into two volute shaped passages with their tongues / cutwater located at 180^0 apart.
4. Remachining of the part of the volute adjacent to the volute tongue to make the casing volute concentric with the impeller axis will reduce significantly the radial load being generated by the fluid having high specific gravity

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NOTATION:

Q = Flow rate of the pumping liquid
Q_d= Flow at design.
Q_{hs} = Flow at shutoff head.
Q_{bep} = Flow at BEP
B2 = Width of impeller opening at d2, inches
D2 = outer diameter (OD) of impeller, inches
t = Thicknes of shroud at outlet.
H = Developed head at the flow point, feet
SG = specific gravity of liquid
F_r = Hydraulic radial thrust load, pounds
Kq = Capacity factor
K = Radial thrust factor
A = Projected area of the impeller.
ω = angular velocity
Ns = Pump specific speed
θ_v = Angle between the volute curve and the impeller periphery.

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