Design of Spiral Casing of Francis Turbine for Micro Hydro Applications

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Abstract. Spiral casing is an important component of Francis turbine for even distribution of kinetic and potential energy of water so as to achieve the required reaction for better performance of the runner. Optimal design and analysis of spiral configuration is challenging, especially when the turbine is operating in a low head range due to the necessity of a large cross-sectional area of the casing to accumulate the large flow. The main objective of this study is to design the best configuration of cross section of spiral casing which have a very minimal pressure loss and can provide required inlet flow condition for stay vanes. For this, spiral casing configurations following free-vortex theory with different cross sections i.e. circular, trapezoidal and square are designed and analysed numerically. Pressure, radial and tangential velocity distributions are compared for different cross section of spiral casing suitable for micro hydro applications. Considering the ease of manufacturing, flexibility of dimension adjustments and comparable performance with that of the circular spiral casing, trapezoidal casing is found to be an appropriate alternative for such applications.

Keyword: Micro Francis Turbine; Spiral Casing; Free Vortex; Trapezoidal cross-section; Secondary Flow.

1. Introduction
Hydraulics of fluid flow through Francis turbine is a complex phenomenon. Study and analysis of fluid flow behaviour in such turbine components is a challenging task. Out of different components of Francis turbine, flow through spiral casing is of great importance for optimum turbine’s performance. Spiral casing forms water passage between penstock and guide vanes providing even distribution of water to stay vane, guide and runner. Water enters the spiral casing from one end and exit circumferentially along the radial direction toward the runner. Spiral casing provides even distribution of kinetic energy and pressure energy so as to achieve required reaction for better performance of the runner. It has to increase circumferential or swirl and radial components of the axially incoming water from the upstream and to distribute it evenly through the periphery of the stay ring [1]. In addition, vibrations may be induced in the turbine if the design of spiral casing is not optimal. Spiral casing with polynomial cross sections are found to be suitable for the turbines operating in low head and high discharge. The aim of using these polynomial section shapes is to diminish the overall dimensions of the spiral casing with a suitable ratio of height to width and to fabricate them easily [2]. Hydraulic loss in spiral casing and distributor must be reduced for improvement of overall efficiency of turbine. Sometimes, these losses are very crucial and may amount to twice the loss in the runner. Various experimental studied conducted by Kurokawa & Nagahara [3] suggest that these losses depend on secondary flow generated by the flow curvature and viscous forces. In addition, the study performed by Kurokawa and Nagahara [3] on different configuration of spiral casing i.e. accelerated, decelerated
& free vortex concluded that the optimum configuration can be achieved by reducing the tangential velocity in a spiral casing. Flow structure and the head loss in the free vortex type spiral casing of a reaction turbine with was studied by Maji and Biswas [4] using a finite-element method. This study was mainly focused on distribution of velocity and pressure as well as behaviour of secondary flow inside circular cross section casing. Their study concluded that for a better performance evaluation and further improvement of hydraulic turbines, knowledge about the internal flow field of spiral casing is needed as very strong secondary flow is evolved on the cross-stream planes which reduce efficiency of spiral casing. Ahmed Alnaga et al. [5] in their work of optimal design of turbine distributor concluded that reduction in spiral casing surface increase efficiency of turbine. Comparison of elliptical configuration of the spiral casing with bell mouth type of stay ring with circular cross section was performed by J.Desai et al. [1]. Their study concluded that elliptical configuration of the spiral casing with bell mouth type of stay ring assembly shows better distribution of the radial velocity and less flow separation with overall better efficiency. Lanjin Zhanga et al. [6] studied hydraulic characteristic of cooling tower Francis turbine with different spiral casing and stay ring and concluded that decreasing stay vane numbers or even cancelling it with strong stay ring give better flow in spiral casing which leads to less hydraulic loss. Numerical simulation of fluid flow through various configurations like decelerated, free vortex, accelerated and spiral casing with different aspect ratios (AR) based on cross section was studied using finite element method by P. R. Nakkina et al. [7][8]. Observation of strong secondary flow on cross stream plane of spiral casing with decrease of static pressure from outside wall to distributor exit was made. Also, decelerated flow type casing was found to be better among all three configurations.

In this paper, free vortex types spiral casing configuration with different cross section i.e. square, trapezoidal and square are designed and analyzed numerically. Main focus is to design spiral casing and choose best the configuration of cross section for micro Francis turbine with minimal pressure loss which provide required inlet flow condition for stay vane as well as easy for manufacturing. The inlet velocity requirement of micro Francis turbine is very low due to large flow and low head. So, the dimension of spiral casing is comparatively big. To overcome this problem, guide vane and stay vane are combined together in required proportion and fixed so as to control the inlet velocity condition of the vane. The spiral casing is designed to match this velocity distribution using an iterative process. Pressure, radial and tangential velocity distributions are studied for different cross section of spiral casing.

2. Design of casings

Uniform distribution of flow in runner is achieved only when flow is uniform in vanes. Spiral casing provide uniform flow in vanes. The design of casing is dependent on the flow and pressure condition of runner as listed in Table 1. A certain circulation must be formed for proper incidence angle of water around the vane. Among accelerated, deceleration and free vortex type of spiral casing free vortex is chosen for simplicity, in which the design is based on the law of constant velocity moment, i.e. $C_{u}R = C_{t} = \text{constant}$

| Parameters        | Values |
|-------------------|--------|
| Nominal Head, H   | 16 m   |
| Nominal Flow, Q   | 0.1 m$^3$/s |
| Rotational Speed, N | 1500 rpm |

The outlet tangential velocity is taken as equal to the inlet tangential velocity of the vane. Required inlet flow condition of spiral casing is chosen so as to match the outlet tangential velocity using an iterative process. The inlet flow is transformed to an inward radial ($C_{m}$) and tangential/peripheral ($C_{u}$) flow. Tangential flow is responsible for generation of required circulation for proper reaction ratio for runner.
2.1 Square Cross Section
The spiral casing is divided in sections and dimension of each section is calculated based on the respective flow and tangential velocity. Tangential velocity is assumed to be constant along $R_o$ (See Figure 1 and 2).

\[ C_u = \frac{Q}{B_y \cdot R_o \cdot \ln \left( \frac{R}{R_o} \right)} \quad \text{(1)} \]

\[ C_m = \frac{Q}{A} = \frac{Q}{2 \cdot \pi \cdot R_o \cdot B} \quad \text{(2)} \]

Where $A$ is area of cross section and $B$ is height of vane.

These equations are used to calculate the radius $R$; with the help of this radius and radius of inlet of vane, dimensions of each section are calculated.

2.2. Circular Cross Section
Flow in each section of spiral casing is determined from the fact that constant water flow must be provided from spiral casing. Dimensions of all the section is calculated using iterative process. The radius of each section $r'$ is determined with the help of circulation $C_t'$. To ensure exact circulation strength, the iteration is carried out until there is match between required vortex at inlet of vane and computed vortex at spiral casing.

\[ C_t = \frac{Q}{2 \cdot r^2 \int_{\phi_0}^{\phi} \left( \frac{\sin^2 \phi}{R_T - r \cdot \cos \phi} \right) d\phi} \quad \text{(3)} \]

\[ C_u = \frac{Q}{R \cdot 2 \cdot r^2 \int_{\phi_0}^{\phi} \left( \frac{\sin^2 \phi}{R_T - r \cdot \cos \phi} \right) d\phi} \quad \text{(4)} \]

2.3. Trapezoidal cross section
The design of trapezoidal spiral casing is adopted from a past study [2]. The inlet cross section is determined by using average velocity given by Equation 5

\[ C_0 = K_c \sqrt{H} : 0.7 < K_c < 0.8 \quad \text{(5)} \]
\[ A_o = \frac{Q_o}{C_o} = a_0 b_0 - n_0^2 \tan \delta \] (6)

Where \( 1.75 < \frac{a_o}{b_0} < 1.85 \) and \( \delta = 30^\circ \) for symmetrical shape

- \( A_o \) is area of spiral casing inlet
- \( C_o \) is average velocity at inlet
- \( K_c \) is velocity coefficient
- \( Q_o \) is flow at inlet

Dimension of other cross section of spiral casing are determined by assuming section area decreasing method from inlet to trailing section taking parabolic curve rule.

\[ a_o = k_n \sqrt{n_o} \] (7)

\[ n_i = \left( \frac{a_i}{k_n} \right)^2 \] (8)

\[ A_i = a_i b_i - n_i^2 \tan \delta \] (9)

\[ b_i = 2n_i + B \] (10)

\[ R = R_o + a_i \] (11)

Where

- \( k_n \) is coefficient of parabolic distribution
- \( A_i \) is area of intermediate section
- \( a_i, n_i, \) & \( b_i \) are dimension of intermediate section

### 3. Numerical Model

The computational domain consists of spiral casing with vanes, runner and draft tube. Spiral casing, vanes and draft tube are meshed using unstructured grid consisting of tetrahedral elements while the runner is meshed using turbo grid consisting of hexahedral elements. Same domain of vane, runner and draft tube is used for all configuration of spiral casing as shown in Figure 6. Total number of mesh elements for circular, square and trapezoidal configurations are 17085509, 10010902 and 10705514 respectively which is selected for simulation after mesh independence test so as to ensure that there is minimum influence of grid number on computational results as shown in Figure 7 and 8.

![Figure 4. Trapezoidal section of spiral casing](image)

![Figure 5. Analysis zones in cross section of spiral casing](image)

![Figure 6. Computational domain for (a) Circular (b) Square (c) Trapezoidal cross-section](image)
Numerical solution is carried out using ANSYS CFX 15.0 which is based on Reynolds-averaged Navier-Stokes Equations of conservation of mass and momentum described as

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0
\]  
\[\rho \left( \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + S
\]  
\[\frac{\partial (-\rho u_i u_i)}{\partial x_i} = \frac{\partial \left( \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right)}{\partial x_i}
\]

Where, the variables have usual meaning.

Figure 7. Meshing for the circular cross-section computational domain

Figure 8. Meshing independence test for circular cross section

Numerical solution is carried out using ANSYS CFX 15.0 which is based on Reynolds-averaged Navier-Stoke Equations of conservation of mass and momentum described as
Flow through the turbine is considered to be incompressible, viscous and fully turbulent. Total pressure at spiral casing inlet based on nominal head and nominal mass flow rate at draft tube outlet is used as boundary condition for simulation. Effect of walls on boundary layer flow is captured with smooth flow of 8 layers of inflation with growth rate of 1.15. Runner is considered as rotational domain with 1500 rpm while all other components are stationary. K-epsilon turbulence model is used for initial solution as well as comparative study as it needs less computational effort. Also, due to robustness, reasonable accuracy and economy this model is very popular for much application. In this study, K-epsilon model is used looking at economy, computational effort and easiness for comparison study of this turbulence model.

4. Result and Discussion

4.1. Comparison with previous study
There are many similar studies that are focused on the flow behaviour, head losses as well as the secondary flow in spiral casing. Most of the studies are focused on free vortex type spiral casing with circular cross section while some of the studies are focused on accelerated and decelerated type as well. The tangential velocity and pressure distribution in V-V section (illustrated in Figure 5) at θ = 90° is compared with the result of study done by P.R Nakkina et al.[7] [8] in Figure 9. The normalized tangential velocity and normalized pressure distribution show good agreement with the result obtained by Nakkina. Normalization of tangential velocity and pressure in this comparison is carried out by maximum tangential velocity and maximum pressure in V-V plane at 90° section angle respectively.

It can be observed that velocity near wall in this study is not captured accurately due inadequate number of mesh in the boundary layer near wall. The pressure distribution in present study is constant due to less pressure fluctuations.

The main function of spiral casing and vanes is to provide required flow condition for runner. The tangential velocity distribution is one of the important parameter and must be uniform at the vane outlet. For validation of the study, comparison of these parameters at vane outlet with previous study is carried out in which tangential velocity is reduced to dimensionless term by nominal head ‘H_n’ at inlet of spiral casing and pressure ‘P’ is normalized by pressure at spiral casing inlet ‘P_in’.

\[
C_{\text{ured}} = \left(\frac{C_x}{\sqrt{2gH_n}}\right) \quad (15)
\]

\[
P = \frac{P}{P_{\text{in}}} \quad (16)
\]

![Figure 9](image)

**Figure 9.** Comparison of values at V-V at θ=90 degree cross section (a) normalized tangential velocity : \( C_\theta \) (b) normalized pressure: \( C_p \) (Reproduced from [7] [8], Copyright 2013-2016 P.R Nakkina et al.)
The reduced tangential velocity distribution of current study is compared with CFD result experimental study carried out by B.S Thapa et al. [9] using Particle Image Velocimetry (PIV) technique as show in Figure 10. It can be observed that the trend of tangential velocity distribution at vane outlet in current study is comparable with the experiment and CFD carried out by Thapa.

![Figure 10. Comparison of normalized tangential velocity obtained from PIV and CFD with present study at vane outlet (Reproduced with permission from [9])]({})

### 4.2. Comparison of different configuration of spiral casing

Fluid flow behaviour along with tangential velocity, radial velocity and pressure distribution of different configuration of spiral casing is studied. Radial velocity and tangential velocity at vane outlet are determined in order to predict the performance as well as find best configuration of spiral casing. Comparison of parameters are carried out in V-V, H-H, G-G plane shown in Figure 5 which represent the variation of flow parameters in vertical direction, radial directions and exit of casing.

Static pressure contour at horizontal mid plane of the trapezoidal and circular casing is shown in Figure 11. Pressure at inlet of trapezoidal cross section is lower than other types of circular spiral casing, however the distribution of pressure is similar and required reaction ratio is achieved using trapezoidal spiral casing. The pressure in trapezoidal casing is low due to increase in velocity of fluid at inlet of the casing as circular to trapezoidal transition exists near inlet section.

![Figure 11. Static pressure contour at mid (a) trapezoidal (b) circular spiral casing](a) (b)
Secondary flow behaviour at different cross section of all configurations is show in Figure 12. Secondary flow is present due to curvature effect, the continuous reduction of a cross-sectional area in a circumferential direction of the spiral casing, the no-slip boundary along the walls and the opening at the exit in a circumferential direction [8]. It can be observed from Figure 12 that the secondary flow is not significant at inlet cross-section of the spiral casing. However, as fluid moves further due to the imbalance between radial pressure gradient and centrifugal force, secondary flow increases. Among the three configurations of spiral casing, secondary flow in circular and trapezoidal are comparable as well as less than in the case of square spiral casing. The intensity of secondary flow is high in 90° and 270° cross section, so comparison of velocity and pressure distribution were carried on these sections of three configurations.

![Figure 12](image)

**Figure 12.** Behavior of secondary flow on cross stream planes at a) θ = 0° b) θ = 90° c) θ = 180° d) θ = 270° in (i)circular (ii) trapezoidal (iii) square  spiral casing

![Figure 13](image)

**Figure 13.** Distribution of (a) normalized static pressure (b) radial velocity (c) tangential velocity in section H-H for different configuration of spiral casing at (i) θ=90° (ii) θ=270°
In spite of the difference, the vane outlet condition is comparable. In trapezoidal, the dimension in radial direction is made small which is the cause of decrease in overall pressure in the mid horizontal. Decreasing the casing dimension can increase the tangential velocity which can induce turbulence and secondary flow if the velocity is very high. In this case, it can be observed from Figure 12 that there is no significant secondary flow observed due to the decrease in dimension of trapezoidal casing.

Pressure, tangential velocity and radial velocity distribution in section H-H at 90° and 270° turn cross section are show in Figure 13. It can be observed that decreasing the dimension in radial direction as in trapezoidal spiral casing, there was not a considerable change in the radial velocity distribution. However, slight increase in the tangential velocity and decrease in pressure at vane inlet can be observed. There is sudden rise in tangential velocity near the wall of the spiral casing due to wall effect. This rise of velocity is high in case of trapezoidal casing which is due to sudden decrease of dimension in H-H plane. The distribution of velocity is even after flow passes the wall and follows same trend in all configuration of the casing.

Radial velocity distribution at vane outlet is similar for all configuration of casing; however the tangential velocity distribution is different. Figure 14 shows the distribution of tangential velocity along vane outlet. It can be observed that for all cases, there is fluctuation of tangential velocity obtained from numerical study while the analytical tangential velocity is constant. In case of numerical study, viscous effect and frictional losses in wall cause fluctuation in radial velocity. Also, CFD over predict wakes and analytical results are ideal results without any viscous and frictional effect. It can also be observed that the trapezoidal casing give the best distribution of tangential velocity among all configurations of casing under study.

![Figure 14. Tangential velocity distribution at vane outlet](image)

5. Conclusions
In this paper, spiral casings with trapezoidal, square and circular cross sections were designed and numerically compared. No significant secondary flow was observed in circular and trapezoidal casing. However, in square spiral casing, the secondary flow was higher than circular and trapezoidal casings due to the effect of flow separation at the corner of the exit side. Decreasing the dimension of casing in radial direction without change in the area of section has no significant effect on the radial velocity. However, it was found that the tangential velocity increases with the decrease of dimensions. This increase in tangential velocity does not affect the overall performances of spiral casing if casings have
large flow and low head i.e. low velocity. Nevertheless, for spiral casing of high head and low flow, the increase in tangential velocity might be critical and may induce secondary flow and increase head loss in spiral casing.

Although the square spiral casing showed the better distribution of pressure and velocity in H-H plane, the tangential velocity distribution at the vane outlet was lowest and did not match with analytical value which is caused by the flow separation at the exit of casing. It was illustrated that for micro Francis turbine where spiral casing dimension becomes big due high flow and low head condition, trapezoidal spiral casing with free vortex configuration could be a better option, due to the ease of manufacturing.

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