

Pressure Drop Analysis of Turbine Housing Model with Circular Sliced Pipe for Micro Hydropower Generation

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Abstract – Energy independence is a government program aiming to meet society's energy needs evenly. Steps to increase energy independence in the new and renewable energy sector include hydro-energy generation. One of the important components of a hydro generator is the penstock pipe and turbine housing, which channels water and then pushes and drives (spins) the turbine with the flow of water to produce electrical energy. The turbine housing flow design innovation must provide a function as an optimal fluid conductor by minimizing the resistance that occurs when fluid flows towards the turbine housing and rotates the turbine optimally. The scope of this research includes analysis of the phenomenon of energy loss flowing in circular pipe slices in hydroelectric power plant turbine housings with influencing factors such as friction, turbulence, and flow resistance, as well as measuring the pressure drop in circular pipe slices. The model developed is a circular slice bend with angles of 180 degrees, 270 degrees, 360 degrees, and 450 degrees, taking into account the optimal curvature ratio (R/D) of 3.5. Based on previous research, 90-degree wedge bends with many slices ($n_{90\text{-degree}}$) 4 to 6 or ≥ 4 and pressure drop coefficient (C_{pd-th}) obtained 180-degree (0.333 – 0.200), 270-degree (0.445 – 0.277), 360-degree (0.527 – 0.339), 450-degree (0.587 – 0.390) with a bend length L, an elevation reduction angle ϕ and a 1.5D upstream-downstream elevation difference to avoid contact between the upstream and downstream bends. The results obtained from this research are the slice modules that can be used and the resistance coefficient values that arise from the slice modules. The more slices selected according to the angle of inclination chosen, the smoother the resulting circular bend shape and the lower the resistance value, but the work will be more difficult. The most optimal slice module is the number of slices that allow its implementation, and the resistance coefficient is small. By knowing the optimal resistance coefficient value, the resulting pressure drop can be predicted to maximize the thrust to rotate the turbine.

Keywords: Pressure drop; turbine house; direction flow; turbulent flow; circular.

Introduction

Energy independence is a Government program through the Ministry of Energy and Mineral Resources that aims to evenly meet energy needs throughout Indonesia. Existing potentials are developed with an emphasis on new and renewable energy potential. Energy needs must begin to focus on increasing the development of new and renewable energy with the intention that natural conditions and global warming that occur suggest efforts to slowly stop fossil energy production, which causes air pollution and global warming (Vinca et al., 2021).

Through this government program, the world of higher education is obliged to participate in research and development that supports sustainable energy development. To support increasing independence in new and renewable energy, this research discusses hydro-energy generation. The potential for hydroenergy resources in Indonesia is enormous, from the potential of rivers in the highlands to main irrigation networks, which have energy-absorbing points with significant differences in height that can be utilized for hydro generation on both micro to large scales.

Hydro generators are one of the important components in generation, including penstock pipes and turbine houses, which function to channel water and move turbines to produce electrical energy. As an important component and driving force, the turbine housing design innovation must provide optimal fluid conductor function, namely minimizing the resistance that occurs when fluid flows towards the turbine housing and rotating the turbine optimally with minimal resistance. Power is generated by the rotation speed of the turbine due to the push of the speed of water or fluid against the turbine in question (Graciano-Uribe et al., 2021).

The rotation and current of the fluid flowing and turning the turbine will be corrected due to the resistance that exists on the conducting walls [of the penstock pipe], the angle of direction change, and the rotation of the flow that occurs. The greater the difference in height or head available, the more power will be produced, especially by changes in direction, wall roughness, and direction of rotation of the flow. The description and illustration above are conditions that must be considered when calculating the amount of pressure drop that occurs. The more carefully the considerations are taken into account, the resulting pressure drop will be corrected. A decrease in pressure in the penstock pipe is a phenomenon where the water pressure in the pipe decreases along with the flow of water from the source to the hydropower turbine. This decrease in pressure occurs due to friction between the water and the inner surface of the pipe, as well as changes in flow velocity (Abduh et al., 2020a; Çelebioglu, 2019; Zeghadnia et al., 2015).

Several factors that influence the pressure drop in the penstock pipe include the longer the penstock pipe (Hilbočan et al., 2022; Kueny et al., 2014; Rahul Kumar Garg & Arun Kumar, 2019), the greater the pressure drop that occurs due to friction between the water and the pipe wall; pipes with larger diameters tend to have smaller pressure drops than pipes with smaller diameters, due to lower flow velocities; pipe wall thickness can also affect pressure drop, pipes with thicker walls tend to have smaller pressure drops due to lower resistance to flow; Cleanliness and surface conditions in pipes can also affect pressure drops, scale or deposits in pipes can increase friction and cause greater pressure drops (Abduh et al., 2020a; Basappa Meti & Nagaraj Sitaram, 2016; Çelebioglu, 2019).

Factors that influence include the geometric design of the snail house, including the shape, size, and length of the water flow channel, which can influence the pressure drop; proper design can minimize energy losses due to friction and changes in flow velocity; high water flow velocity or turbulence in the snail house can cause greater pressure drops, proper geometry, and flow design settings can reduce unwanted turbulence and pressure drops; the cleanliness and condition of the surface in the snail house can also affect the pressure drop, scale or sediment attached to the surface in the snail house can increase friction and cause a greater pressure drop; Like in a penstock pipe, the height difference between the start and end points of the water flow also contributes to the pressure drop in the snail housing, the greater the height difference, the greater the pressure drop that occurs (Basappa Meti & Nagaraj Sitaram, 2016; Çelebioglu, 2019; Latif et al., 2022).

Pressure drop at pipe bends is a phenomenon that commonly occurs in fluid flow, as described above. It is important to account for pressure drops when designing a pipe system, especially if the system has bends or significant changes in the flow direction. Proper analysis can help in selecting appropriate pipe sizes and minimizing energy wasted due to pressure drops. Numerical methods such as the Darcy-Weisbach equation or friction factor can be used to estimate pressure drops in complex pipe systems (Jha, 2020; Lakshmiraju & Cui, 2007; Putra et al., 2022; Sheikh et al., 2022).

The simulation was built using software applying the finite volume method to solve the Navier-Stokes equations as a flow model. The simulated water velocity profile is then validated against the analytical solution velocity profile (power law) for turbulent flow in a pipe. Analysis of energy loss in the penstock has been carried out to determine the causes of energy loss in the penstock, which is characterized by the loss coefficient. A very large value will have an impact on reducing the potential electrical power of a micro-hydro system (Adhikary et al., 2015; Graciano-Uribe et al., 2021; Hilbočan et al., 2022; Latif et al., 2022; Nigussie et al., 2017; Xu et al., 2021). The total length of the penstock induces variations that influence changes in the electrical power of the micro-hydro system. The shorter it is, the greater the potential electrical power of a micro-hydro system (Çelebioglu, 2019; Xu et al., 2021).

The scope of this research study covers several things, including an in-depth analysis of the energy loss phenomenon that occurs in the slice circular pipe inside the hydro generator turbine house. This includes understanding the factors that influence energy loss, such as surface friction, flow turbulence, and changes in flow velocity, developing numerical or experimental models to simulate fluid flow behavior, and measuring

energy loss in slice circumferential pipes. This will enable in-depth analysis of various operational conditions and pipe designs, optimizing slice loop pipe designs to reduce energy losses.

Materials and Methods

This research is a development of previous research that has been ongoing and published in several international publications. Starting from research on fluid flow in bending pipes that are not curved, it was then developed for other needs that are still and very related to previous research. The data that has been obtained from previous research is then developed and projected into different forms and models but is an inseparable part of the previous model. The data and objects used in this research are pipes made from steel or HDPE with dimensions of diameter (D), bend radius (R), and bend angles of 180, 270, 360, and 450 degrees, with the number of slices (n) and the angle of each slice (θ), starting and ending angle changes ($\alpha=\theta/2$), and angles after the beginning and before the end ($2\alpha=\theta$), angle of change elevation (ϕ), as so the viscosity and type of fluid flow.

The model development aims to provide alternative options and recommendations in determining the shape of the penstock pipe bend or turbine house model that adapts to the conditions of the hydropower generation land to be built, especially about the direction of flow from the penstock pipe inlet to the tile-race. Because a fluid flow through the penstock pipe or turbine housing will experience a slowdown due to the shape or geometry of the curve or circle formed by the pipe, the estimated magnitude of the deceleration must be detected and known so that when planning the penstock pipe or turbine housing the pressure drop can be estimated, occurs due to the shape of the pipe. In this way, the goals and objectives to be achieved in this research can be obtained.

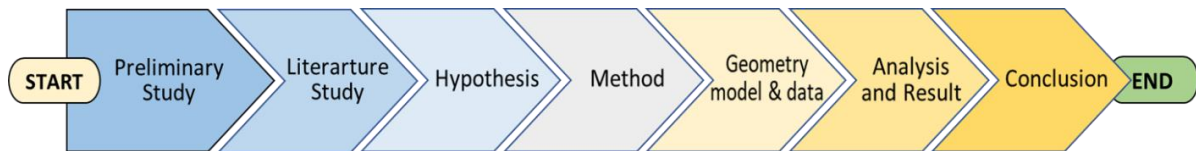


Figure 1. Research process.

Based on previous research (Abduh et al., 2020a, 2020b, 2020c), the size of the slice angle (θ) is greatly influenced by the number of slices (n), and the number of slices has special requirements that depend on the size of the bend angle. If the magnitude of the bend angle is beta (β), To obtain an effective deceleration coefficient value, the n value has the following conditions (applies to all bend angle models):

$$\text{Amount of slices (n)} \geq 2 * \left(\frac{\text{angle of bend } (\beta)}{90\text{-degree}} \right) \quad (1)$$

In this study, the elevation change angle (ϕ) is taken into account when the bend angle is large ($\beta > 180\text{-degree}$); if the magnitude of the bend angle ($\beta < 180\text{-degree}$), the elevation change (ϕ)=0.

$$\theta = \frac{\text{angle of bend } (\beta)}{n}; n = \text{equation (1)}; \alpha = \frac{\theta}{n}; Li = \frac{R \sin \theta}{\cos \alpha} \quad (2)$$

The hypothesis developed regarding the deceleration or decrease in pressure that occurs in the penstock pipe or turbine housing is influenced by two things: friction between the pipe wall and the flowing fluid and changes in direction caused by each angle of the connection slice. (Abduh et al., 2020a; Çelebioglu, 2019; Vollestad et al., 2020).

The model was developed with circles forming angles of 180-degree, 270-degree, 360-degree, and 450-degree, also taking into account the curvature ratio (R/D) 2, 3, and 4. This takes into account several related aspects, namely location conditions and ease of assembly both on the penstock pipe and on the turbine housing. The circular bend model developed can be seen in Figure 2 below.

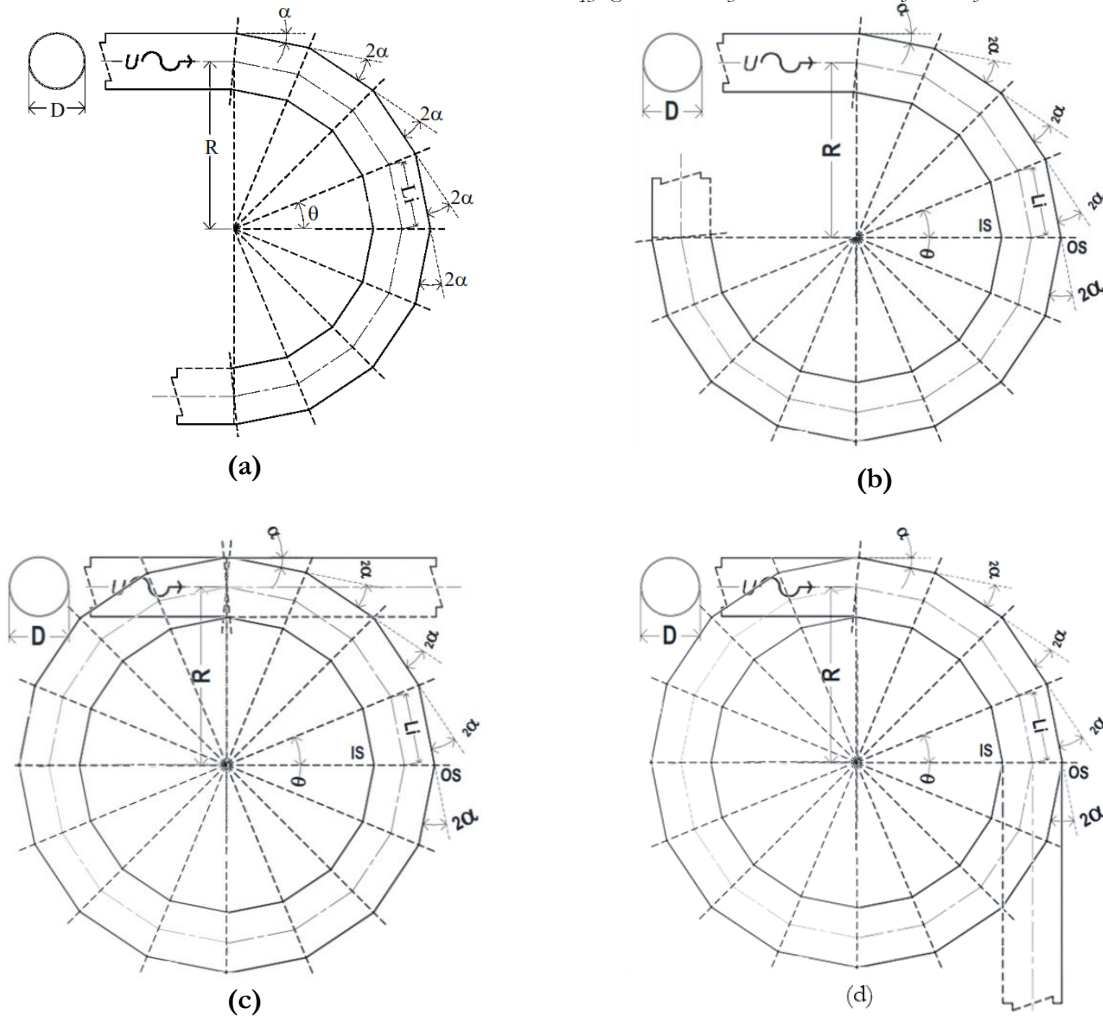


Figure 2. Research model geometry (a) 180-degree circle bend model, (b) 270-degree circle bend model, (c) 360-degree circle bend model, (d) 450-degree circle bend model.

Based on the geometry of Figure 2. above and data from physical model measurements on 90-degree bends, the model is then developed for different circular angle conditions by considering the number of slices (n) with the conditions imposed above, and then analysis can be carried out. This model is a follow-up to the goals and objectives to be achieved according to the hypothesis of this research. Following the research roadmap developed from previous research, the basic equation used in this discussion is the equation obtained from the results of previous research on 90-degree slice model bends (Abduh et al., 2020a) which is then validated with a physical model in the laboratory, pressure drop coefficient (C_{pd}) as described below.

$$C_{pd} = \omega * \left[f * \left(\frac{nLi}{D} \right) + \left(1 - \cos^2 \alpha * \cos^{(n-1)} 2\alpha \right) \right] \quad (3)$$

In circular bends with a 180-degree bend angle, to facilitate the derivation of the formula, changes in elevation angle are still taken into account because the fluid flow is considered to be turning around and decreasing in elevation downstream. This includes following location conditions when elevation changes occur. In circular bends with turning angles of 270 degrees, 360 degrees, and 450 degrees, changes in elevation angle must be taken into account because the downstream pipe of the circular bend will intersect with the upstream pipe or circular pipe bend (turbine house).

Results

A circle or circular bend (a full circle) with a 360-degree angle is a series of 4 activities of a 90-degree bend. The flow deceleration or pressure drop that occurs is considered to be identical to the 4 times deceleration that occurs at a 90-degree turn due to fluid friction with its viscosity against the pipe walls and changes in flow that occur at each intersection. Friction on the pipe wall is the accumulation of the total length of the pipe wall's circumference at each slice. The number of direction changes that occur is the accumulation of the number of slice connections according to the number of slices (n) used.



Figure 3. Modeling laboratory: 90-degree slice bends

Completing the pressure drop coefficient in the case of the penstock pipe and turbine housing requires correction of several things related to changes in the elevation of the ring pipe and related elements. In circular bends with 180-degree, 270-degree, 360-degree, and 450-degree angles, elevation changes are calculated based on the pipe diameter (D) and bend radius (R). If a full circle or 360-degree angle = 2π and so that the upstream and downstream pipes of the turbine house do not touch, the total elevation change is $\geq 1,5D$. The length of the elevation change path (L) and the angle of change in elevation (ϕ) are:

$$(L) = 2\pi R * \left(\frac{\text{angle of bend } (\beta)}{2\pi} \right); \text{ and } (\phi) = \tan^{-1} \left(\frac{1,5D}{L} \right) \tag{4}$$

If the elevation of the downstream side pipe is below the upstream side pipe, then the influence of the slope angle of the elevation change will reduce the resistance value. In contrast, if the elevation of the downstream side pipe is on the upper side of the upstream side pipe, then the influence of the slope angle will increase the resistance value.

Based on the geometric shape presented in this research, as shown in Figure 2, equation (4) must be adjusted because the angle of the circular bend formed is > 90 degrees. This adjustment reduces the number of slices used, a multiple of the number of slices in a 90-degree slice turn. The equation for reducing the number of slices used is described as follows: if $\pi = 180\text{-degree}$ $90\text{-degree} = \pi/2$, the equation for reducing the number of slices becomes the following.

$$\text{Number of slices } (n_\beta) = n_{90\text{-degree}} * \left(\frac{2\beta}{\pi} \right) \tag{5}$$

In the equation above, π is a semicircle or 180-degree angle, and β is the magnitude of the turning angle. If it is decided that the location of the downstream side pipe is below the upstream side pipe, then the change in elevation will not affect the pressure drop coefficient equation but will affect the fluid pressure if initially there was only pressure due to flow velocity, then in the downstream part, there will be pressure due to the flow velocity + pressure due height difference ($P = \rho * g * 1,5D$, with D: pipe diameter; theoretical of flow velocity (U) = $\sqrt{2gh}$, with h: total head). Thus, the amount of total pressure/energy (E_{th}) What happens upstream and downstream of the turbine house is as follows.

$$\text{Upstream: } E_{th-us} = C_{pd-th} * \left(\frac{U_{us}^2}{2g} \right) \quad (6)$$

$$\text{Downstream: } E_{th-ds} = \rho * g * 1,5D + \left[C_{pd-th} * \left(\frac{U_{ds}^2}{2g} \right) \right] \quad (7)$$

With U_{us} : upstream flow velocity, and U_{ds} : downstream flow velocity, and ρ : fluid density, and g : acceleration of gravity, and then C_{pd-th} : coefficient of pressure drop in the turbine housing. Equations (6) and (7) above are the total energy remaining due to the pressure drop in the turbine house due to the slowing of wall friction and changes in flow direction due to the circular bending geometry as in the figure above.

According to the simulation result of the laboratory, the model has been done as 90-degree slices bend; data from observations and measurements in the laboratory have been carried out in a series of analyses and development of empirical models, analysis of the relationship between parameters including the residual variance test (NSE), determination test (R^2), correlation (r), quantity test (MAE), accuracy test (RMSE), then the selected equation becomes equation (3). This equation was then developed based on the geometry of the turbine housing model, as shown in Figure 2. The model accuracy test results were NSE = -0.632 to +0.994, MAE = +0.021 to +1.699, and RMSE = +0.031 to +1.817.

Based on initial equation validation (Abduh et al., 2020a) with the results of physical modeling in the laboratory, which produces variance, determination, and other values as above, then produces a coefficient correction factor, namely $\omega = 1.3784 n^{0.2077}$ for $R/D=2$; $\omega = 1.2996 n^{-0.296}$ for $R/D=3$; and $\omega = 1.4095 n^{-0.357}$ for $R/D=4$, further as in Table 1 below.

Table 1. Coefficient correction factor for pressure drop of various curvature ratios and number of slices

Curvature ratio (R/D)	ω based on the number of slices (n)									
	1	2	3	4	5	6	7	8	9	10
1	1.64	2.68	3.33	3.78	4.14	4.44	4.70	4.93	5.13	5.31
	60	00	10	80	90	90	70	30	50	90
2	1.37	1.59	1.73	1.83	1.92	1.99	2.06	2.12	2.17	2.22
	84	18	17	83	55	98	49	30	56	37
3	1.29	1.05	0.93	0.86	0.80	0.76	0.73	0.70	0.67	0.65
	96	85	88	22	71	47	06	23	82	74
3.5	1.33	0.76	0.84	0.73	0.66	0.60	0.55	0.51	0.47	0.44
	10	20	40	90	20	20	30	30	80	70
4	1.40	1.10	0.95	0.85	0.79	0.74	0.70	0.67	0.64	0.61
	95	05	22	93	35	35	37	09	33	95
5	1.70	1.21	1.77	1.82	1.88	1.93	1.98	2.02	2.07	2.10
	90	70	10	90	40	70	30	90	00	90

According to Table 1, the pressure drop correction value with the number of slices from 2 to 10 at a curvature ratio (R/D) of 3.5 has the optimum correction factor value. The result of the simulation model according to the 90-degree physical model is shown below.

Based on Table 2. above, because the model development uses the results of the physical model on the bend of the slice model 90-degree ($n_{90\text{-degree}}$), it must adapt to the dynamics of research results in these conditions. The simulations carried out in the table above as a whole refer to the optimum conditions in the range ($n_{90\text{-degree}}$) 4-6 and correction (ω), and optimum curvature ratio (R/D). In this simulation, the roughness coefficient value used (f) 0.0003; it depends on several things, including the type of fluid flowing, the viscosity of the fluid, and the roughness of the pipe walls following the Moody diagram (Çelebioglu, 2019; Vollestad et al., 2020), because the flow tends to be turbulent, it can also be used Colebrook-White equation;

$$\frac{D}{\sqrt{f}} = -2 \log \left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re \sqrt{f}} \right) \quad (8)$$

with Re (Reynold number) and ε (absolute roughness). Number of slices used (n_{β}) is a multiple of the bend angle (β) according to Eq (5).

Table 2. Analysis and simulation model for the coefficient of pressure drop in turbine housing (D=0.5 meter)

n 90- deg.	Optimum		Friction (f) if it	<—Geometry of design—>					Analysis of Pressure Drop			Notes
	ω	R/ D		β	n_β	θ°	α°	Li	δ_a	δ_b	C_{pd-th}	
4	0.7 390	3 .5	0.0003	1	8	22.5	11.2	0.6828	0.003	0.45	0.333	The friction (f) value depends on the Moody diagram, and this simulation model for optimum condition (correction factor and curvature ratio)
				80					5	28		
				2	12	22.5	11.2	0.6828	0.004	0.60	0.445	
				70					5	92		
				3	16	22.5	11.2	0.6828	0.006	0.71	0.527	
				60					5	56		
4	20	22.5	11.2	0.6828	0.008	0.79	0.587					
50					5	19						
5	0.6 620	3 .5	0.0003	1	10	18	9	0.5475	0.003	0.38	0.253	
				80						29		
				2	15	18	9	0.5475	0.004	0.52	0.345	
				70						93		
				3	20	18	9	0.5475	0.006	0.62	0.417	
				60						57		
4	25	18	9	0.5475	0.008	0.71	0.474					
50						21						
6	0.6 020	3 .5	0.0003	1	12	15	7.5	0.4568	0.003	0.33	0.200	
				80						29		
				2	18	15	7.5	0.4568	0.004	0.45	0.277	
				70						93		
				3	24	15	7.5	0.4568	0.006	0.56	0.339	
				60						58		
4	30	15	7.5	0.4568	0.008	0.64	0.390					
50						22						

The circular bend model in the turbine housing that has the best performance is the design model whose analysis results show a small resistance coefficient value (C_{pd-th}). If the resistance value is small, the resistance that occurs is small too, and the energy working is maximum, so the power produced from hydropower generation is also maximum.

Discussion

Turbine housing models, especially for mini or micro hydro turbines, tend to use products from small manufacturers, so the manufacturing model tends to use a slice model. This slice model is made in an unstructured and patterned way so that the resistance caused is not measured, and the slice pattern is also not uniform. This condition causes differences in the energy produced because the obstacles that arise are challenging to predict. Of course, extra rigorous thinking is required to get a clear picture that can be used as a hypothesis in the study concept.

In the research and study, approaches are needed to model the behavior in fluids that flow through such media. Many experts have used various modeling approaches to obtain satisfactory results. As science and technology develop, related research continues to be carried out by experts. Of course, this will continue and will not stop because science always continues to develop dynamically to achieve deeper thinking and provide benefits to human life.

Based on Table 2, it can be explained that the value of the resistance coefficient obtained from a circular bend in a pipe, turbine housing, or something else is significantly influenced by the change in direction that occurs. The fewer slices are used, the more extreme the angle of change in direction is, so the value of the drag coefficient is higher. Likewise, if the number of slices used is greater, the drag

coefficient becomes smaller because the change in direction occurs more gently. Hence, the function value of the angle of change in direction causes obstacles to become smaller.

Two things that influence the value of the drag coefficient when turning a circular slice are friction on the slice walls and changes in direction. However, the dominant influence occurs because changes in direction appear at each slice connection in the circular bend model. As shown in Table 1, the greater the number of slices used (n) in the circular bend, the smaller the resistance coefficient value will appear, but in reality, using a large number of slices will be difficult in the fabrication process. Of course, the best choice is to choose a moderate number of slices (n), meaning that the number of slices used is as large as possible but is still possible in the fabrication process.

Furthermore, based on Table 2, a simulation can be carried out with various pressure height conditions for a hydropower plant when planning a penstock pipe or turbine housing with circular slice bends, as presented in Figure 2. The simulation concept describes the conditions of a power generation system, which can be used as a simulation illustration to resemble the potential conditions that exist around us. This can be explained clearly as shown in Figure 4 below (Mohammad Mashkour, 2018; Putra et al., 2022; The Pacific Power Association (PPA) & The Sustainable Energy Industry Association of the Pacific Islands (SEIAPI), 2020).

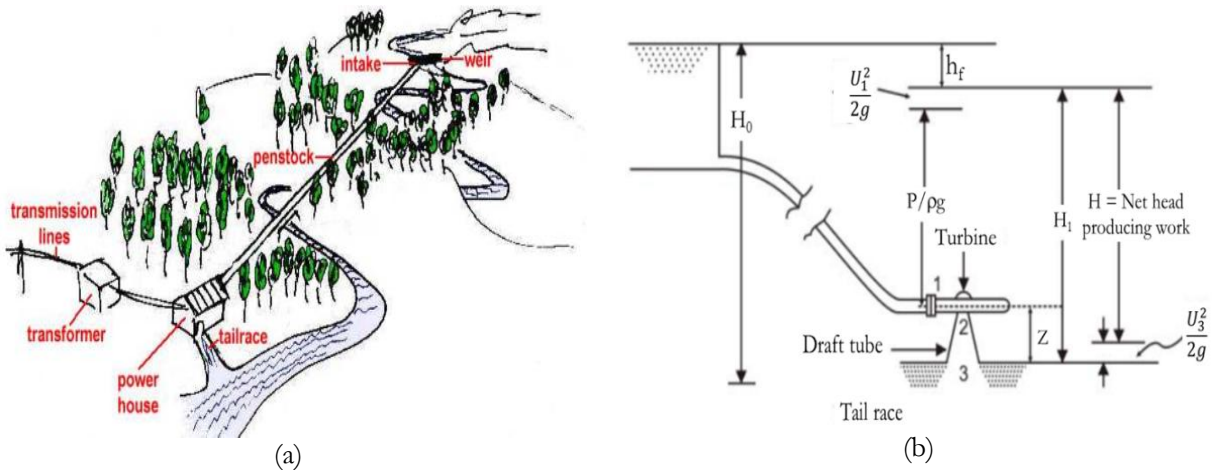


Figure 4. Hydropower Generation System (a) layout concept, (b) head (Mohammad Mashkour, 2018).

A hydropower generation system, as described in Figure 4 above, simply explains that according to the Bernoulli equation, the effective pressure height of a power in a hydropower system is the amount of energy that works in the form of pressure and resistance consisting of potential energy, kinetic energy (velocity), and the decrease in energy due to resistance. The two energies that arise are interconnected, potential energy is very dependent on the height difference (head) of the water, while kinetic energy arises due to the flow velocity which is influenced by the difference in water level. In Figure 4 part (b), the energy scheme that arises (Mohammad Mashkour, 2018):

$$H = \frac{P_1}{\rho g} + \frac{U_1^2}{2g} + z - \frac{U_3^2}{2g} = H_1 - \frac{U_3^2}{2g} = (H_0 - h_f) - \frac{U_3^2}{2g} \quad (9)$$

This research on pressure drop is a small part of the system but has a big influence on turbine performance.

The pressure reduction coefficient in the turbine housing is the pressure reduction in the kinetic energy scope and will affect the working flow velocity so that the energy generated follows the remaining pressure due to the deceleration that occurs. The results of this research state that the optimal condition of the model presented refers to a curvature ratio (R/D) of 3.5, with the slice model being able to adjust according to the conditions. The more the number of slices made, the resistance value will decrease, but keep in mind that the number of slices in this circular turning model must still make it easier to fabricate so that accuracy will be maintained.

From the results of model simulations using four models with a diameter of 50 cm, a curvature ratio (R/D) of 3.5, and trying a friction coefficient (f) = 0.0003 and with the number of slices on the slice scale $n_{90-degree}$ 4, 5, 6 (n_{β} according to multiples) the results obtained from the simulation are described in Table 2. Based on the model in Figure 2, the four models represent different requirements conditions in the powerhouse, primarily due to the upstream and downstream directions. These four models have an optimum pressure drop at a curvature ratio (R/D) of 3.5, with several slices still feasible for fabrication. The recommended effectiveness is related to fabrication feasibility with the number n . Each model is effective with several slices, as shown in Table 2.

Conclusion

Hydroelectric power plants are one of the important components in energy generation, producing electrical energy. As an important component of innovation, the turbine housing must provide optimal fluid conductor function, minimize resistance when the fluid flows, and rotate the turbine optimally with minimal resistance. So far, turbine housings have tended to be made with irregular slice models, making it difficult to predict the resulting resistance. This has led to unmeasured water pressure and problems in calculating the effective pressure generated. Due to these issues, the phenomenon of energy loss flowing in circular pipe slices within the turbine housing, along with the influencing factors, has been studied. The developed model includes circular slice bends with angles of 180 degrees, 270 degrees, 360 degrees, and 450 degrees, considering an optimal curvature ratio (R/D) of 3.5. Based on previous research, 90-degree wedge bends with many slices ($n_{90-degree}$) 4 to 6 or ≥ 4 and pressure drop coefficient (C_{pd-th}) obtained 180-degree (0.333 – 0.200), 270-degree (0.445 – 0.277), 360-degree (0.527 – 0.339), 450-degree (0.587 – 0.390) with a bend length L , an elevation reduction angle ϕ and a 1.5D upstream-downstream elevation difference to avoid contact between the upstream and downstream bends. This model was obtained by considering optimum conditions; the pressure drop coefficient will be smaller if the number of slices increases, but this will make it difficult at the fabrication stage. The recommended optimum pressure drop coefficient values are provided in full in Table 2. Further research is needed to compare and validate the results with variations in pipe diameter on a field scale.

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