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Optimizing Hydro Power Turbines in Order to Secure the Passage of Fishes in Khuzestan province

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Abstract

Nowadays, it is important to consider environmental issues, as ecological problems and their severe effects are intensifying in Iran, particularly in Khuzestan province. The environmental effects of hydroelectric plants are highly regarded due to their significant impact on an extensive area. Lack of safe path for fish passing through the turbines is one of these damages. In order to deal with these challenges, researchers are trying to optimize hydro power turbines. In this optimization, old runners were replaced. Meanwhile, conditions of fish passing through the turbines and fish survival have been improved. Considering the existence of six hydroelectric power plants in Khuzestan province, it would be possible to conduct optimization or constructing studies with a fish-friendly approach for the safe passage of fishes to slightly reduce the extent of environmental damages.

Keywords: hydro power turbine, fish-friendly turbine, optimization of hydro power turbine

1. Introduction

Benefits of hydroelectric power are frequently faded by environmental contrasting. One of these challenges is the mortality of fishes which pass through the turbine (especially, fishes that are migrating upstream to downstream and vice versa). However, fish mortality would be reduced by optimization of turbine passage conditions. On the other hand, improving the quality of water passing through the turbine (such as increasing dissolved oxygen) and the power plant operating conditions are of paramount importance ~~priority~~. Studies show that any of rapid pressure drop factors (e.g. cavitation), the high head, low efficiency of turbine and pressure variation (the difference between the acclimation pressure upstream of the turbine and the exit pressure within the draft tube zone) could be the cause of their mortality and damage [1- 3]. However, the impossibility of observing, identifying the damage area of fish and its mechanisms have caused problems for expressing the causes of fish mortality. Studies also show that peripheral speed is higher in the runner entrance of Francis turbines (wicket gates and blades) and greater wicket gate opening would lead to more fish morality rate. The mortality rate does not change by variation in the operating head of Francis turbines (at 12 meters and 120 meters, mortality rates are equal). Results concerning the effective role of hydraulic head in the fish mortality are contrary to the popular belief. However, the clearance between blade tips and discharge ring in a Kaplan turbine (where the fish could be caught) is so important. Mortality rate is 20% on average in Francis turbines, 12% in the Kaplan turbines and 9% in bulb turbines [2, 3].

In 1996, U.S. Department of Energy (DOE), Northern Research and Engineering Corporation (NREC), the Electric Power Research Institute (EPRI), Alden Research Laboratory Inc., Voith Hydro Inc. and several industry partners began a multi-year effort to develop 'fish-friendly' turbines for hydro-electric projects that are greater than 90% efficient and reduce fish mortality to 5% or less. Before 2009, numerous studies supported by DOE, EPRI and industry collaboration, were conducted to validate the theoretical concept of the turbine. Studies included: CFD modeling, use of a one-third-scale test facility to evaluate the turbine biological and engineering performance, additional conceptual turbine development efforts (in 2006), and laboratory experiments that examined the relationship between turbine blade leading edge geometry and fish injury/survival after blade strike [4]. The research produced two turbine designs. The first, designed for large rivers, is currently being tested in the Columbia River. The second, designed for smaller rivers, is called the Alden/NREC turbine and features a helical-shaped runner with only three blades. Up to 98 percent of fish survive passing through the Alden turbine [2, 5].

With the Alden and minimal gap runner turbine, Voith hydro is the leading developer and supplier of fish friendly turbines. The Alden turbine rotates more slowly than conventional turbines and has only three blades, whose shape minimizes the shear force, the pressure change rates and minimum pressure within the water passage. Fish can thus pass through the turbine much better. Depending on the fish species, the survival rate of adult animals is 98 to 100 percent. The American research laboratory developed the innovative runner concept, and Voith hydro optimized it: low collision-induced fish mortality, optimum number of blades and guide blades, improved hydraulic profile of individual components, reduced rotation speed, excellent water flow geometry, which supports downstream fish passage [6, 7]. The Voith team also made extensive use of CFD analyses of all aspects and components of Kaplan and Francis turbines. The team used their experience and CFD tools to further their studies and to develop an understanding of turbine flow velocity and pressure distributions and how these may lead to fish injury. Independent investigations of basic turbine flow physics and issues dealing with low dissolved oxygen and ways to mitigate it were also conducted. The design concepts provided here can be used for both rehabilitating existing turbines as well as new turbines in order to improve their compliance with the new age of environmental awareness and safe fish passage. These new concepts would also benefit the hydropower plant in more ways. The Vioth team believes that incorporating the suggested design modifications would result in a more efficient operation; more generated power, and reduced operation and maintenance costs. The Voith team produced new fish-friendly design criteria for Kaplan and Francis turbines that can be incorporated in units during rehabilitation projects or in new hydroelectric facilities. These include the use of advanced plant operation, minimum gap runners, placement of wicket gates behind stay vanes, among others. The Voith team will also provide design criteria on aerating Francis turbines to increase dissolved oxygen content. Detailed reviews of the available literature on fish mortality studies, causes of injuries to fish, and available biological design criteria that would assist in the design of fish-friendly turbines were performed. This review identified a need for more biological studies in order to develop performance criteria to assist turbine manufacturers in designing a more fish-friendly turbine [2, 3 and 8-12].

2. Injury Mechanisms

Mechanisms of injury and mortality of fishes depend on their passing zone through the turbines; fishes entered in different zones of turbine system are damaged due to the duct geometry and flow characteristics. For example, mortality of the fish passing through a zone near the turbine hub is approximately 5% over the fishes passing through the middle zone of runner. Fishes passing through the surrounding zones of blades are also dealing with damages such as the blade strike and local effects of fluid flow. Zones of specific damages to the passing fishes are shown in Fig. 1. According to this, the mechanism of damage can be classified into four categories: mechanical, pressure, shear and cavitation [1-3, 7]. Mechanical damages include strike, abrasions and grinding. Abrasion damage is dependent on flow discharge, velocity, number of turbine blades, spacing between them and the geometry of the flow passage. Damage due to grinding occurs when the fishes are moving in small clearness (gaps of sizes close to that of the fish) within the turbine system [1, 2]. In the process of strike, fishes get damaged by colliding with components of turbine system and the probability of a fish dying is variable. The amount of damage depends on several factors such as fish size, number of blades and the space between them, turbine speed, flow velocity and discharge. Researchers indicated that the mortality increases with runner peripheral velocities. High head turbines have smaller units and high rate of pressure change per unit time, while low head turbines have large units and lower rate of pressure change per unit time. Survival of fishes totally depends on the pressure change inside the turbine system and damage due to the pressure change depends on rate and amount of change pressure and the type of fish. It is believed that fishes are more sensitive to the pressure decreases than pressure increases [2, 3, 8].

Pacific Northwest National Laboratory researchers (Richland, U.S.) found that higher discharges tend to increase mortal injury rates from exposure to low pressure, in Kaplan turbine. Also depth of fish acclimation is a significant factor in the prediction of passage mortal injury due to rapid pressure change. The majority of pressure nadirs occurred immediately below the runner blades, with the lowest values in the gap at the blade tips and just below the leading edge of the blades. Such information can help engineers focus on problem areas when designing new turbine runner to be more fish-friendly than existing units [13]. The created cavitation is another factor affecting fish passing through a turbine. The collapse of bubbles in the water can result in noise, vibration, pressure fluctuations, erosion damage to solid surface and loss of efficiency or flow capacity; each of these factors can lead to mortality increase. Cavitation can also make high-pressure shock waves or high-velocity micro jets. Studies show that mortality caused by cavitation is about 2 to 6% and mortality caused by pressure change is about 19% [2, 3].

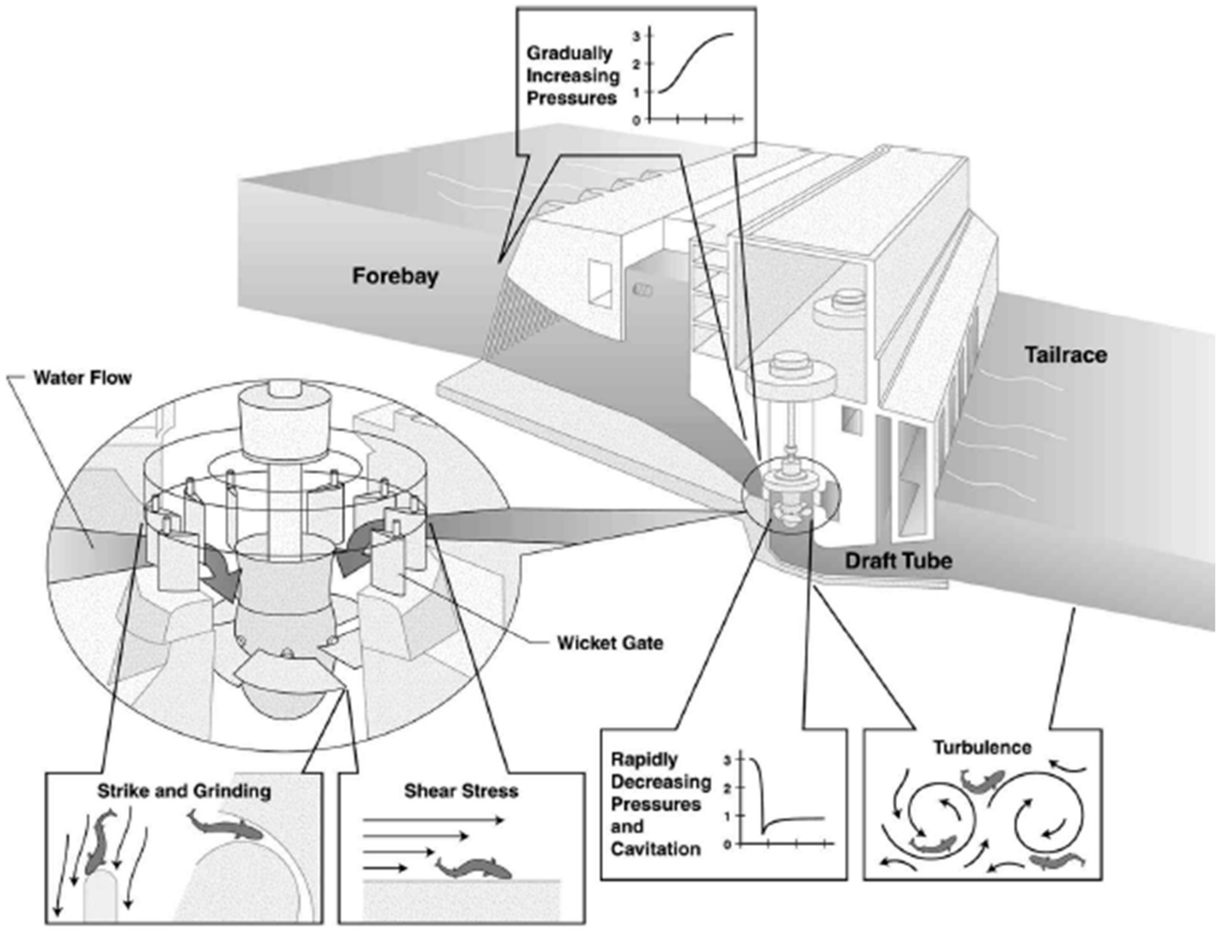

Fig. 1. The occurrence mechanism of certain injuries to fishes passing through the turbines [3].

In addition to the aforementioned factors, the shear stress is another reason for fish mortality. In the flow field, shear stresses are a result of the change of velocity with respect to distance or the rate of deformation of the fluid. Shear stress zones are also associated with vortices within the flow field. The highest levels of shear stress have been seen in the blade leading edge, vanes and gates. The amount of damage caused by shear stress depends on the fish species, size and manner of entering to the shearing zone. Vortices in the draft tube swirl also have associated shear stresses and may be a primary source of shear stress damage to fish in Francis turbine [2].

3. New Design Concept for Existing and New Turbine

As it was noted, investigations into fish passage conducted by research institutions and manufacturing companies have been carried out separately. The first category (research institutions) has resulted in designing a new runner. In optimizing the designed runner, several factors are considered: preventing flow separation in order to minimize the losses and turbulence, avoiding the pressure reduction to less than the specified amount, minimizing damage potential of fishes by balancing factors such as head, the blade shape, runner diameter, number and length of the blades (each of these factors can affect the peripheral velocity of the runner) and minimizing zones of high shear stress.

A commercially available screw/centrifugal pump impeller was selected for initial evaluation; the selected impeller was based on performance comparison of six different pump models. The chosen single-bladed impeller had a long leading edge, a large flow passage, and hardly any gaps, and has been proven safe for the transport of fish and vegetables with minimum damage. Biological data from this and other studies conducted at Alden Research Laboratory Inc. showed this pump to be effective and safe to transport live fish. An impeller model with the highest operating efficiency was chosen for the initial evaluation; an important parameter in selecting the initial geometry is for the new runner to be competitive with efficiencies of existing turbines.

During the preliminary design stage, the pump impeller performance in the turbine mode was analyzed. Peak electrical efficiency reached 79% at 1000 cfs, 96ft of head, and the rotor diameter was about 22.2 ft. A new design was needed because this efficiency was well below the desired value of 85%, and the efficiency was reduced drastically when the unusually large rotor diameter was made smaller. This meant a new runner design had to be developed, and two- and three-bladed runners were compared with the large pump impeller operated as a turbine (Table 1). Although in DOE research Case 3 was chosen for further analysis because of the lower number of blades, Case 2 may be used if a smaller diameter runner is desired.

Table1. Preliminary design of the new runner [2]

Case	Design Description	Number Of Blades	Runner Diameter [a] (ft)	Runner Length (ft)	Rotational Speed (rpm)	Head [b] (ft)	Overall Efficiency [c] (%)
1	Scaled up Impeller as a Turbine	1	22.2	10.8	61.2	96	79
2	New Turbine Design	3	16.2	12.3	73	84	90
3	New Turbine Design	2	17.5	13.3	68	85	89

[a] Runner diameter at best efficiency
[b] Head between scroll case inlet and tail water
[c] Efficiency includes estimates for draft tube and scroll case losses
For case 3 the overall efficiency would be reduced by about 1% with a 30% reduction in runner diameter

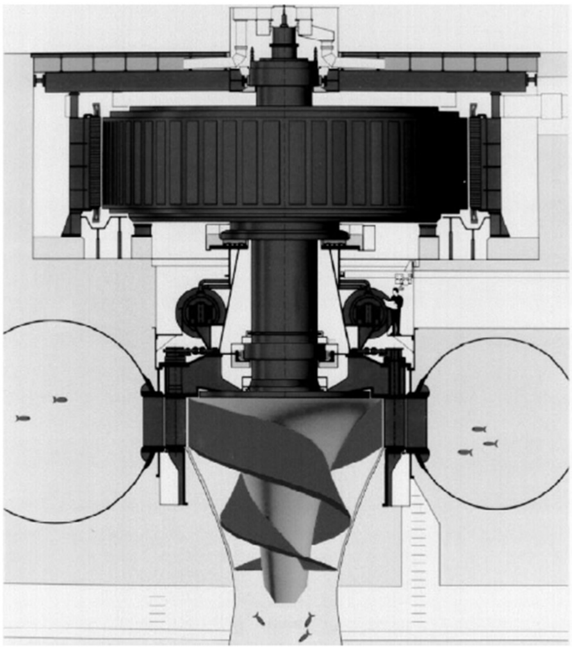

Fig. 2. The new runner design with two blades [2]

Fig.3. Manufactured fish-friendly turbine with three blades [14]

According to economic considerations, the final design is a runner which has a vertical shaft and three-bladed runner. Turbine efficiency is 90 %. The efficiency and the power output of this turbine are lower than other types of traditional turbine. The investigation of velocity distribution near the blade shows that the flow is proceeding in the downstream direction and does not separate from the blade between the hub and the shroud surface. In the new design, pressure distribution and its decrease from runner inlet to exit were found to be reasonably in uniform. In these turbines, cavitation is not expected anywhere in the runner. New runner CFD analysis indicates its good performance based on design criteria and the fish does not get damaged in the passage [2]. This new design of runner is shown in Figs. 2 and 3. Fish-safe hydroelectric turbine design reduces fish death, protects endangered species and allows migrating fish to pass downstream safely [14].

On the other hand, the manufacturer does not pay attention to the fish-friendly issue in designing commercial hydro turbine, while efficiency and economic considerations dictate the aim of the design. Thus, for the competition of fish-friendly turbines with traditional turbines, they tried to optimize the efficiency of this power generating turbine providing a safe fish passage and minimize maintenance and rehabilitating costs.

Manufacturing companies used several tools with multiple fish sensors to understand the physical, path and passage conditions and measurement the pressure. These sensors measure physical conditions and fish passage with a high accuracy [8]. The objective of the investigation conducted by the manufacturer is optimization of the turbine components (such as blades) to reduce the fish injury. The entrance edge of stay vane is one of the most important places, as the head or flow changes, the angle of flow will have minimum effect of the amount of guide vane opening. Therefore, the optimization should be in such a manner that provides the possibility of local velocity reduction and gradually increases it. In addition to the entrance edge, issues like lack of alignment and minimum distance between the stay vanes and wicket gate, manner of blades profile (including geometry items), design manner of blade tip, overhang of wicket gate can also be some of the damage resources in turbines [9].

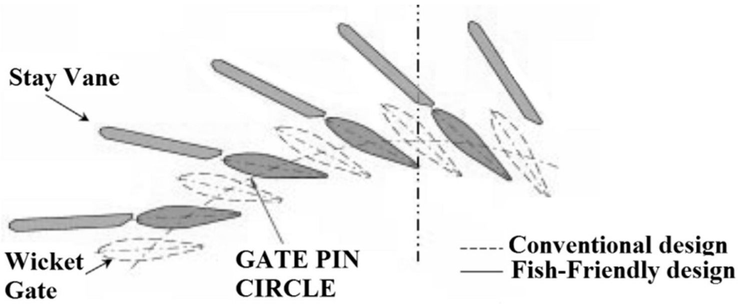

Fig. 4. Proper positioning of wicket gates against the stay vanes [2]

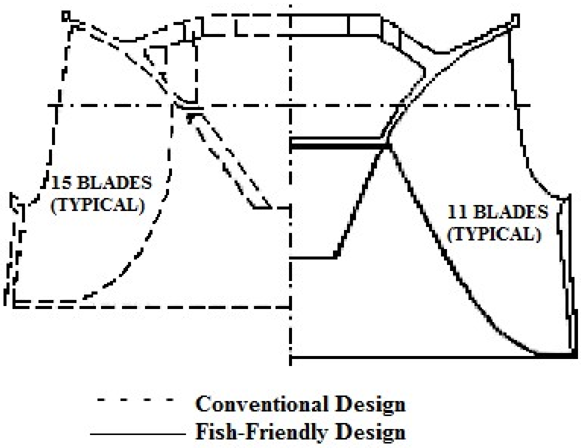

Fig. 5. The Ultimate design with reduced number of blades of Francis turbine [2]

Typically, stay vanes and wicket gate alignment and optimize manner depend on the project information and the performance range, respectively. The design of a turbine with fixed blades (Francis) is easier in comparison with Kaplan turbines (with variable blades) in which flow and head are important. In advanced design of the guide vane, the pressure gradient decreases and the velocity profile is optimized based on mechanical considerations (such as the head and torque of guide vane). On the other hand, CFD technique can be used to optimize the placement of stay vanes and wicket gates and minimize fluid turbulence and mechanical strike caused by different gate opening. Figure 4 shows the proper placement of wicket gates against the stay vanes. In this position, efficiency is maximized and the risk of strike is minimized. Roughness of welding surfaces is another damage factor. It is possible to reduce the risk of fish abrasions by polishing the welding surfaces (such as a stay vane of turbine, wicket gates, and cone of draft tube). In places where speed is low, it is not necessary to smooth surfaces, as this may increase the costs. Draft tube piers are among the places which their smoothness is important. With regard to structural reasons, it is not possible to remove draft tube piers, as piers design of draft tube must be completely smooth (round nose), so that it reduces the risk of strike and flow separation. On the other hand, Francis turbines using fewer blades have reduced probability of strike, while they have increased the size of the flow passage; the risk of damage caused by abrasions may also be minimized. A low number of blades reduce the probability of strike and maximizes the size of flow passage, which also minimizes the probability of abrasion damage of fish. A lower number of blades result in having longer blades to maintain the same capacity, power production and minimize cavitation (Fig. 5) [2].

4. Alden turbine development: pricing

The Alden turbine is, by design, lower in power density than conventional turbines. The larger, more slowly rotating equipment leads to a relatively more expensive turbine-generator solution. For the site conditions at a comparable prototype site, sizing for a conventional Francis unit gives a 13-bladed, 2.5-meter-diameter runner with an rpm of 189.5. Sizing for a conventional Kaplan turbine gives a five-bladed, 2.7-meter-diameter runner with an rpm of 276.9. During the Alden turbine development, a detailed cost study was performed to determine the equipment, installation and commissioning cost. Tables 2 and 3 provide a comparison of the installed equipment price for the Alden turbine vs. conventional hydro turbines and sizing for specific head and flow. The prices are normalized relative to the Alden turbine. The relative pricing does not include civil work. The larger size and slower speed of the turbine allows for a higher setting relative to the tail water. For the prototype design, the Alden distributor centerline is 5 feet above tail water, while the conventional Francis centerline is anticipated to be set 2 feet above tail water. The conventional Kaplan centerline is set the lowest, falling 16 feet below tail water. The higher setting of the Alden turbine may result in less excavation and lower civil costs. Therefore, true costs comparison of project components may be less for an Alden unit than conventional Francis or Kaplan units (Table 4) [4, 15].

Table2. Relative Equipment Pricing [16]

	Alden Turbine	Conventional Francis (same Power)	Conventional Kaplan (same Power)
Turbine Cost	1	0.5	0.55
Generator Cost	0.8	0.65	0.65
Installation and Commissioning Cost	0.25	0.25	0.25
Automation/Balance Of Plant Cost	0.25	0.25	0.25
Relative Costs	2.3	1.65	1.7
Premium of Alden		39%	35%

Table3. Sizing for Specific head (92 ft) and flow (1500 cfs) [16]

		Alden Turbine	Conventional Francis	Conventional Kaplan
Reference Diameter (mm)	$D_{ref.}$	3900	2510	2650
Maximum Power (MW)		13.6	13.6	13.6
Rotational Speed (rpm)	$N_{nom.}$	120.0	189.5	276.9
Number of Runner Blades	Z_2	3	13	5
Survival Due to Strike for an 8" Fish		98%	<50%	86%

Table4. True Cost Comparison [15]

ALDEN	<	Conv. Turbine	+	Fish Passage	+	Lost Energy

5. Applicability to other hydro sites

Although the turbine was hydraulically and mechanically designed for a target site condition, it represents a new turbine family with a range of head and flow applications. Figure 6 shows the anticipated turbine application range. The region, labeled "current application," spans 75 to 100 feet of net head and represents the head range covered by the current design. The larger region, labeled "modified current application," can be accomplished through appropriate sizing and design modifications to the turbine. This region spans from 30 to 120 feet of net head. At 120 feet of net head, stress limitations of the current design limit applicability. It is anticipated that future design modifications to the turbine can extend the operation above 120 feet of net head. Below 30 feet of net head, turbine application switches to large bulb units [4, 15].

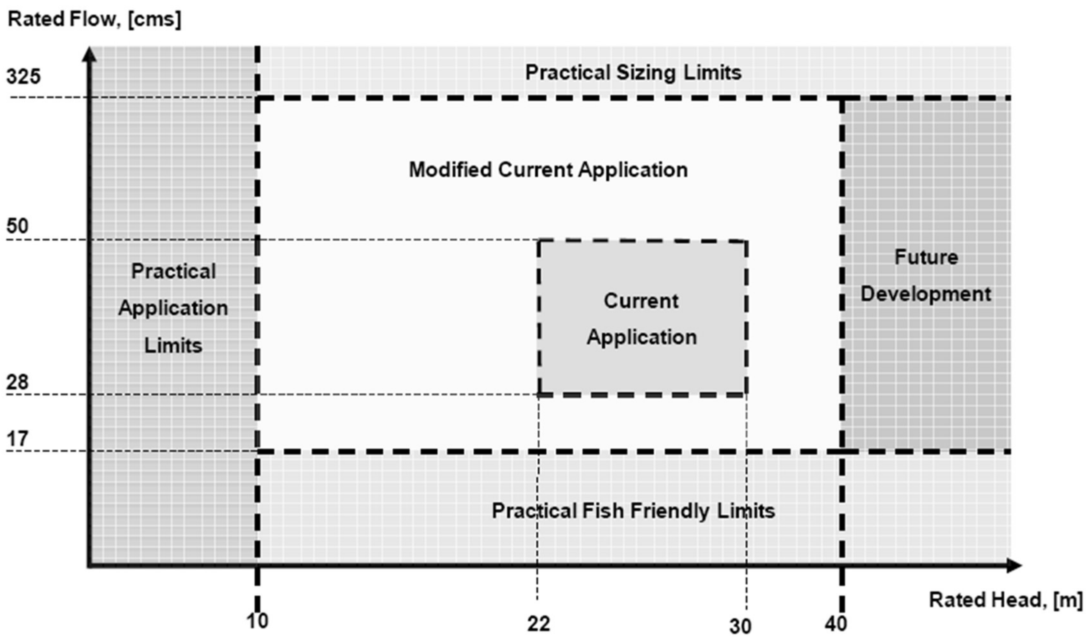

Fig. 6. Alden Turbine Application Chart [15]

6. Conclusion

Due to the importance of environmental issues in the hydroelectric power plants, one of the new programs of designers is developing hydro turbines in order to optimize the fish passage through the turbine along with increasing their overall efficiency. The Energy Department and Alden turbine first started working together to design a fish-friendly turbine in 1996. Results from the initial biological analysis at Alden's Holden, Massachusetts research facility were unprecedented, with anticipated survival rates nearing 100 percent for nearly 40,000 species of fish. In 2009, the Energy Department supported EPRI to continue development of the Alden design for eventual deployment at commercial scale. Energy Department funding enabled a critical round of testing and developmental engineering at the Voith Hydro Hydraulic Test Stand Facility in York, Pennsylvania. Those trials yielded results that exceeded expectations: at peak performance, an Alden turbine should convert about 94 percent of the water's energy into usable electricity, comparable or superior to the efficiency of traditional turbines; the overall wildlife survival rate should be over 98 percent, up from 80-85 percent for a traditional turbine. The successful demonstration and testing of this innovative fish-friendly technology over the course will be a crucial step toward moving the turbine closer to commercial deployment [17]. This program contains three steps [18]:
1) 2013: Adapt turbine engineering design to site, preliminary installation design, turbine manufacture and delivery,
2) ~2014: Installation
3) ~2015-16: Performance testing

According to availability of six hydropower plants in the Khuzestan province, their optimization studies and construction studies of new hydroelectric power plants in the province, fish-friendly studies regarding available or under construction turbines are very important, as current situation has made serious damages to the environment and fish migration process. It is possible to develop these studies regarding that some local companies have attempted to design hydro power turbine.

Therefore, this research area would be aboriginal using conducted studies in other countries (regarding securing the passage of fish); the turbine can be optimized based on the safe pass of fish or new design can be proposed in collaboration with hydropower plants exploiting companies in Khuzestan and based on the design requirements of each plant, existing fish and its passage conditions in the turbine. On the other hand, it is possible to suggest new designs in order to use them in construction projects in collaboration with KWPA and consulting companies associated with this kind of studies. As it was mentioned in the previous sections of this study, experimental methods and computational fluid dynamics software are useful in this regard.

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