Review of air turbines for wave energy conversion

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***Abstract* - The development of air turbines for wave energy conversion has been in continuous evolution starting from conventional turbine to self-rectifying turbine and still in progress. The turbines applied to harness wave energy via a pneumatic type system is called oscillating water column which either has a reaction or impulse principle of operation. The reaction turbines are simple in construction but possess weaknesses such as high rotational speed, less efficiency and narrow operating range. Favorably, the impulse turbines feature low rotational speed, high efficiency and wider operating range which made it inefficient. Recently developed self-rectifying impulse turbines too substantiate these features. In this paper, a review of various types of impulse turbine along with a comparative study has been presented. As a result, self-rectifying axial impulse turbine with linked pitch-controlled guide vanes and self-rectifying radial impulse turbine with active-pitch-controlled guide vanes are found to be predominant in terms of wide operating range of flow coefficients at useful efficiencies. A review of bidirectional flow turbine and a comparison with impulse turbines & reaction turbines have also been reported.**

***Keywords* - Oscillating water column, bidirectional air flow, self-rectifying turbine, Wells turbine, impulse turbine, renewable energy.**

I. INTRODUCTION

In the era of ever increasing dependence for energy, the depletion of hydrocarbon based fuels has raised a major concern, and hence a huge demand for sustainable energy devices is the need of the future [1]. To protect our environment, renewable energy sources such as solar, ocean, wind are finding its growing application. Many researchers are finding out ways to harness the energy from these sources in an efficient way [2]. Ocean provides a vast option for the supply of energy. The wind tides over the ocean, hydropower electricity generation, salinity gradient, capturing the alternating waves by point absorbers are some of the common means that the ocean provides [3, 4, 5]. The unpredictability of wave motion, the extreme weathers, the randomness of the waves, loss to aquatic life are the primary disadvantages and factors for the lesser output from these devices [6]. Ocean wave energy is considered as an abundant and promising renewable power resource in many countries especially countries in Europe and Asia [7].

Oscillating water column (OWC) is a pneumatic type wave energy conversion technology being exercised in fixed as well as floating type wave energy devices. The principle of OWC is simple wherein the free water surface contained in a duct or chamber, which is submerged in water, oscillates under the action of waves. This oscillation compresses the air which is trapped above the free water surface inside the duct and in turn it forces the air to flow through a turbine that drives an electrical generator [8, 9]. In simple terms, wave energy is initially converted to pneumatic power in the form of bidirectional air flow, which is then converted to mechanical energy through a turbine for generating electricity. Air turbines for an OWC based energy device have been developed since the 1940s [13]. Impulse turbine is suitable for pneumatic type wave energy conversion as it operates with higher pressure drop for higher incident wave energy density. It is well known that an impulse turbine works on the principle that the force from the impulse of the fluid on the blades and the reaction caused due to the flow deflection by the blades rotate the turbine. Guide vanes (GV) of an impulse turbine align the flow in desired angle. They also alter the flow velocity converting the pressure energy of the fluid into kinetic energy which is then transferred to the blades.

In fact, the first air turbine employed for the wave energy conversion was a simple impulse turbine with flow rectification valves [10, 11]. Valve rectification system intended to rectify the bidirectional flow produced by the OWC device and hence producing a unidirectional flow through the turbine. But, it introduced flow losses, design complications and maintenance difficulty in the system [12-14]. This became the cause of development of a turbine which operates in a bidirectional flow without need of flow rectification. Such turbine is called as a self-rectifying turbine which rotates in a single direction in spite of a bidirectional or reciprocating nature of air flow produced by OWC device [12-16]. Though the patents of self-rectifying turbine were filed in the early 1970s [17-22], Wells turbine became the widely used self-rectifying turbine after its invention in 1976 [23-28].

Wells turbine is the simplest and economical turbine for wave energy conversion. In contrast, Wells turbine has inherent disadvantages such as poor starting characteristics, narrow operating range of flow rates at acceptable efficiencies, high speed operation accompanied by noise and high axial thrust [12, 13, 14, 29]. Hence, various alternatives of air turbine for wave energy application have been proposed for improving the starting and running characteristics of the turbine [29-36].

Impulse turbine is found to be predominant in comparison to Wells turbine [12, 16, 29 and 37-39]. Different configurations of impulse type have been studied as it shows good characteristics for both unidirectional and bidirectional flows. Badhurshah and Samad studied the turbines for bidirectional flows and admitted that the impulse turbines have high efficiency in comparison to Wells turbine, which is one of the reaction turbines [40]. The objective of this paper is to study the optimum design characteristics, efficiency and operating flow coefficient range of turbine types that have been proposed by various authors and to arrive at an identification of most desirable impulse turbines for energy conversion.

II. CLASSIFICATION OF TURBINES

Hydro-turbines are devices that can convert the hydraulic pressure into usable mechanical energy, which can be converted to electrical energy using an electric generator. The power available at the shaft of the turbine is given by

$$P = \eta \rho g Q H \quad (1)$$

Where, η, ρ, g, Q, H is the hydraulic efficiency of turbine, density of water, acceleration due to gravity, volume flow rate through the turbine, pressure head across the turbine, respectively. On the principle of operations, turbine are generally classified into two main types namely impulse turbines and reaction turbines. In case of an impulse turbine, the rotor runner is open to air, high jet(s) of fluid make an impact on the runner of the turbine, thus rotating the turbine, it is to be noted that the atmospheric pressure of the fluid before hitting the runner and post hitting of the runner is almost the same. In case of a reaction turbine, the turbine remains immersed in water enclosed in a pressure casing, the pressure gradient created over the blades due to the flow, creates a lift and causes the runner to rotate [7]. The classification of air turbines is shown in Fig. 1.

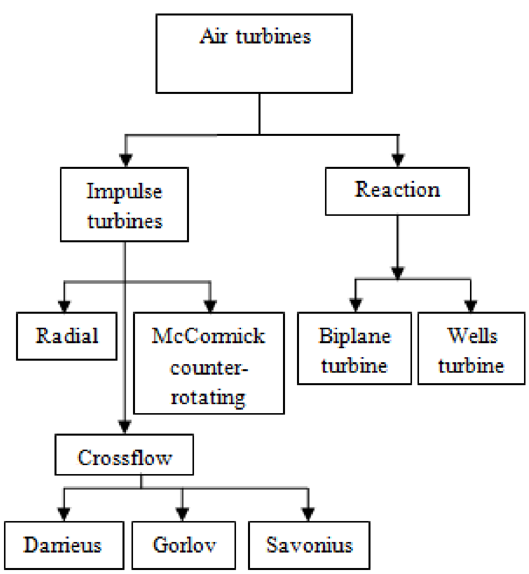

Fig. 1. Classification of air turbines

III. WELLS TURBINE

A Wells turbine essentially consists of rotor having untwisted blades of symmetrical aero foil cross-section, which are 90^{o} radial to the flow which is shown in Fig. 2. Axial turbine is extensively used because of its simplicity for operating in both unidirectional and bidirectional flows but it produces axial thrust which causes fatigue loads on the bearings. Radial turbine is beneficial because of their low manufacturing cost, lack of axial thrust, the high torque obtained due to the radial configuration and their ruggedness [41, 42]. Unfortunately, the radial turbine induces a high damping on the OWC device [42]. The symmetrical cross section facilitates equal performances in either direction of flow.

The performance of wells turbine depends on Solidity, Reynolds number, Hub to tip ratio, tip clearance, blade profile. The performance of wells turbine can be improved by modifying the guide vanes, end plates and by swinging the rotor blades according to performance parameters [40].

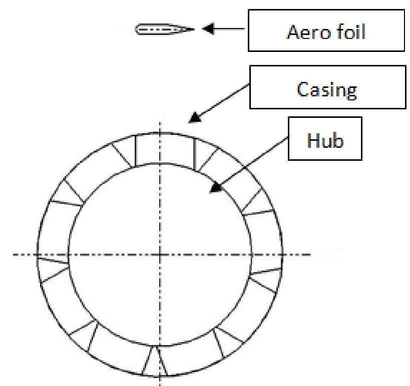

Fig. 2. Wells turbine

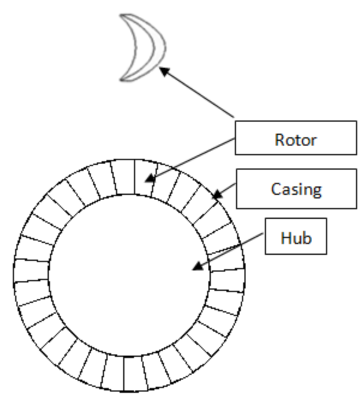

Fig. 3. Impulse turbine

IV. IMPULSE TURBINES

Impulse turbine can be broadly classified on the basis of direction of air flow through it into two versions namely axial and radial. Based on accompany of flow rectification system, impulse turbine can be either unidirectional or self-rectifying. An impulse self-rectifying turbine may have guide vanes on either side of the rotor. Further, the nature of guide vanes like fixed, self-pitch-controlled and link mechanism indicate the type. The simple impulse turbine is shown in Fig. 3.

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V. AXIAL IMPULSE TURBINES

A. Unidirectional turbine

A simple conventional unidirectional turbine as shown in Fig.4 (α is incident angle), which was applied for the first OWC device [10, 11] along with a system of non-return valves for flow rectification. Takao *et al* [14] acknowledged that the peak efficiency of the conventional turbine is higher than that of the self-rectifying turbine, despite such a system is complicated and difficult to maintain. They achieved optimization of the unidirectional turbine geometry for developing a high-performance generator through experimental investigations of different rotor profiles and guide vane setting angles with a straight line-circular arc guide vane profile. As a result, they noticed that the best guide vane setting angle is 20° and the best rotor profile has the width of the passage at the mid-chord is much greater than that at entrance which itself is greater than that at exit. This turbine is evident to have efficiency which is 25% more than that of Wells turbine.

Unidirectional axial impulse turbine has been employed in both fixed and floating type OWC based wave energy plants [43-46]. Numerical simulations on twin unidirectional turbines have been found to be most suitable for the Indian fixed wave power plant as reported by Jayashankar *et al* [43] and for the floating wave power device, backward bent duct buoy (BBDB) as reported by Dudhgaonkar *et al* [46] as part of wave energy program conducted by National Institute of Ocean Technology, Chennai. These reports advocate twin unidirectional turbine topology for achieving high turbine efficiency over a broad range of flow coefficients when the turbine is made to rotate at different speeds using a variable speed generator [46, 47] effecting an efficient conversion in all types of wave climate.

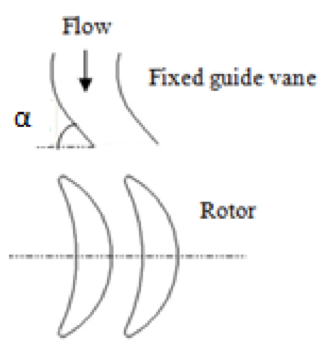

Fig. 4. Unidirectional axial turbine

B. Turbine with self-pitch-controlled Guide vane

Kim *et al* [29] proposed an impulse turbine with self-pitch-controlled guide vanes to obtain enhanced efficiency and low speed operation besides self-rectifying feature of the turbine shown in Fig. 5. Guide vanes on upstream and downstream of the rotor are pivoted to the hub so that they can move on their own according to the aerodynamic moment induced by the oscillating flow. Turbine tests [31, 39, 47-50] have been carried out to study the effect of rotor, guide vane geometry and other parameters on the characteristics of this turbine. The profile of the guide vane used is a straight-circular-arc type (mono-vane type) whereas the rotor blade profile is elliptic. This impulse turbine showed no apparent stall region in the characteristics, which ensures better starting characteristics than that of Wells turbine.

Setoguchi *et al* [39] reported that this turbine possesses wider range of flow coefficients having high values of efficiency, lower operational speed and noise reduction in comparison to Wells turbine. They observed that the behavior of guide vanes in the reciprocating flows is in relation with the axial flow velocity and a gradual decrease in downstream guide vane angle as a result of inappropriate movement of downstream guide vane in a reciprocating flow reduces the efficiency of diffuser action. In order to alleviate this, tandem splitter type guide vanes has been tried out instead of mono-vane type [31, 48]. It is observed that poor efficiency of the impulse turbine resulted also due to a higher pitch-chord ratio of the guide vane [47].

Setoguchi *et al* [48] experimentally investigated the performance for different types of turbine blade rotors with different blade inlet angles and two types of guide vanes such as splitter type and mono-vane type. They used the circular-arc-elliptic blade profile and observed that both types have high efficiency if blade inlet angle is 60°. Further, the efficiency of mono-vane type is proved to be higher by about 10% than that of the splitter.

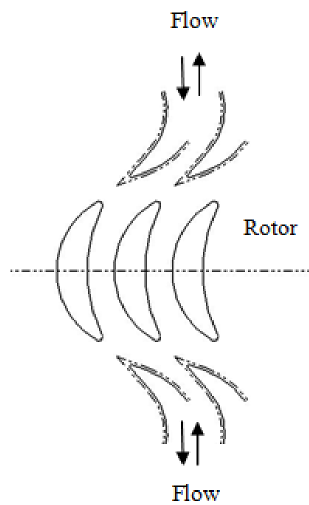

Fig. 5. Axial turbine with self-pitch-controlled guide vane

C. Turbine with self-pitching linked guide vane

Setoguchi *et al* [32] aimed to improve the performance of the impulse turbine with self-pitch-controlled guide vanes by the use of links as the downstream guide vanes did not work as a diffuser properly. In this turbine, a link mechanism is implemented between upstream and downstream guide vanes, which are set on the outer casing with the help of pivots so as to control the movement of downstream guide vanes in the course of altering axial flow velocity [32, 51]. The aerodynamic moment produced by the upstream guide vanes while acting as a nozzle may be utilized to move the diffuser action of the downstream guide vanes which act as a diffuser [32]. It is found that a high-efficiency in impulse turbines can be achieved by connecting the guide vanes with links [32, 51-54]. These links can be moved to change the incident flow angle with respect to the rotor blade angle and thus widening the operating range.

From the article [32] it is clear that the peak efficiency of this turbine is nearly two times greater than that of a turbine without link. Setoguchi *et al* [51] found the performance of the impulse turbine with self-pitching linked guide vanes to be better in comparison to the various forms of Wells turbine and McCormick turbine. This turbine is proved to have about 6% more efficiency than the impulse turbine with self-pitch-controlled tandem guide vanes [32]. It was also evident from the results obtained in the Indian fixed wave power plant at Vizhinjam, India that the link between guide vanes enhances the efficiency of self-pitch-controlled turbine greatly [53]. On the other side, difficulty in maintaining the guide vanes, operational cost and non-linear damping characteristics are the weaknesses of this turbine. Non-linear damping characteristics of a turbine have an important effect in the overall energy conversion [54].

D. Turbine with fixed guide vane

A simple fixed geometry impulse turbine was studied as a suitable self-rectifying turbine for OWC based wave power plants by Maeda *et al* [33]. They proposed an impulse turbine with symmetrically placed fixed guide vanes on either side of the rotor and studied its performance for different sets of guide vanes since the moving parts of the impulse turbine with self-pitching linked guide vanes especially exposed to mist laden air lead to higher maintenance, limited operational life problems and more costs. They found out from the experiments on oscillating flow test rig that if the guide vanes of the turbine are fixed at an optimal angle, the trouble with linked guide vanes will be lessened at the cost of very small loss in performance.

The guide vane profile consists of a straight line-circular arc and the blade profile consists of a circular arc on the pressure side and part of an ellipse on the suction side. According to [33], impulse turbine with fixed guide vanes has peak efficiency if the guide vane angle is 30° and the turbine with optimum design parameters such as rotor diameter of 0.6, hub to tip ratio of 0.6 is superior in running and starting characteristics to Wells turbine under irregular flow conditions [33, 55-59], but it is inferior to unidirectional impulse turbine [43, 46]. The damping characteristics of this turbine are found to be better than that of the turbine with self-pitching linked GV [54, 55].

E. Turbine with active-pitch-controlled guide vane

Since large aerodynamic losses associated with the symmetrical fixed impulse turbine, due to large incident flow angle at the inlet of the downstream guide vanes, an impulse turbine with active-pitch- controlled guide vanes has been proposed [16, 36]. Thiebaut *et al* [36] carried out sea trials on a floating type OWC device with impulse turbine having guide vanes which are moved using two hydraulic actuators. This turbine consists of a rotor and movable guide-vane rows on each side of the rotor. With the help of synchronization, the pair of guide vanes made to rotate simultaneously twice in every wave cycle.

Further, this helps to create enough swirls in the flow reaching the rotor and to reduce the blockage of the flow leaving the rotor by means of upstream and downstream guide vanes respectively [36]. They have reported efficiencies in the range of 30 to 50 %, which are higher than that of turbine with fixed guide vanes. Still the complexity in geometry and expensive systems remain the major concerns.

VI. RADIAL IMPULSE TURBINES

A.Turbine with fixed guide vane

McCormick *et al* [30] proposed the first format of self-rectifying radial impulse turbine which consists of a single-stage type having one row of rotor blades attached to a vertical shaft and two rows of fixed stator blades as shown in Fig.6. A number of radial impulse turbines have been studied for operating at low rotational speed as the efficiency of radial turbines using reaction type rotor blades was extremely low [60, 61]. The comparison of the test results of the counter-rotating bidirectional radial turbine with that of a counter-rotating bidirectional axial turbine tested under the same conditions indicates that McCormick counter-rotating radial turbine [30] performs significantly better than the counter-rotating axial turbine at higher operational pressures ranging from 200 to 500 N/m^2. Turbine power produced by radial turbine, which is a function of rotational speed, is twice that of the axial turbine at this pressure range. The Fig. 6, shows the radial impulse turbine with fixed guide vanes.

Setoguchi *et al* [61] examined the effect of guide vane angle on the turbine characteristics and recommended an angle of 25° as the optimum for both inner and outer guide vanes. Further, the effect of tip clearances of rotor, inner guide vanes and outer guide vanes on performance of this turbine has been analyzed by Pereiras *et al* [62]. They observed the tip clearance effect to be more pronounced in the inner part of the turbine where the flow velocities are higher.

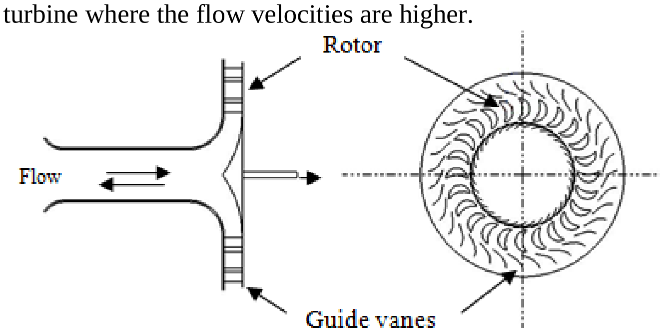

Fig. 6. Radial turbine with fixed guide vane

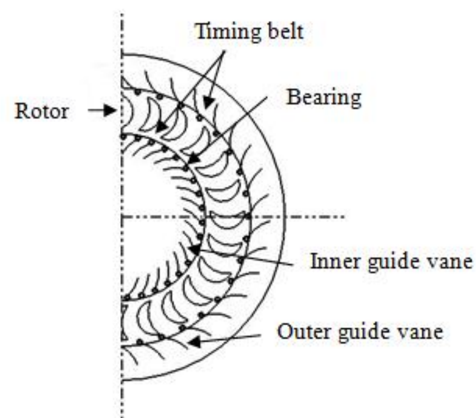

Fig. 7. Radial turbine with pitch-controlled guide vane

B. Turbine with active-pitch-controlled guide vane

Takao *et al* [34] proposed a radial turbine with movable guide vanes (see Fig.7) as the efficiency of radial impulse turbine with fixed guide vanes was not so high due to improper diffuser function of the downstream guide vanes [35, 63]. In this model, the guide vanes are pivoted and controlled by the stepping motors, timing pulleys and timing belts. Experimental investigation of its performance under steady and sinusoidal flow conditions clarifies that the efficiency of this type to be 10% more than that of the radial turbine with fixed guide vanes [63].

VII.COMPARISION OF IMPULSE TURBINES

The performance comparison of axial impulse turbine types has been reported by several articles [43-46, 64-67]. Takao *et al* [64] observed that the efficiency of the axial impulse turbine with self-pitch-controlled guide vanes is higher over a wider range of flow coefficients in comparison with the axial impulse turbine with fixed vanes under irregular flow conditions.

The axial impulse turbines have maximum efficiency at low flow coefficient and their overall conversion efficiency is better than that of Wells turbine because of lower rotational speed for the impulse turbines [64]. Setoguchi *et al* [65] compared various axial types and concluded that under irregular flow conditions, the impulse turbine with self-pitch-controlled linked guide vanes is superior to the fixed guide vane impulse turbine which by itself is superior to the Wells turbine.

Based on the above review, a comparative study of axial impulse turbines and radial impulse turbines in terms of operating range of flow coefficients and efficiency has been presented in Table I, Table II and Table III respectively. The numerical values mentioned for a particular type of turbine are borrowed from the corresponding reported results of the turbine testing or experiments under irregular flow conditions. The differences between impulse and reaction turbines are wide with their parameter which defines the efficiency of impulse and wells turbine (See Fig. 8) [40].

TABLE I. COMPARISION OF AXIAL TURBINES

Type	**Acceptable efficiency for operating range**	**Signification**
Simple unidirectional [8]	35-37% for flow cofficient of 0.2 - 0.9	Highest peak efficiency (57%) at guide vane angle of 20º.
Self rectifying with fixed guide vane [27,37,40,50]	35-38% for flow coefficient of 0.8 - 2.0	Less operational cost, poor performance, optimum parameter is guide vane angle of 30°.
Self rectifying with self pitch controlled guide vane [25,42]	Around 30% for flow coefficient of 0.6 - 1.2	Better performance at 60° blade inlet angle.
Self rectifying with self pitching linked guide vane [26]	30-52% for flow coefficient of 0.4 - 2.1	Best performance, improved peak efficiency,difficult to maintain.
Self rectifying with active pitch controlled guide vane [30]	40-55% for turbine speed range of 400 – 800 rpm	Higher efficiency then fixed guide vane, complex and expensive.

TABLE II. COMPARISION OF RADIAL TURBINES

Type	**Acceptable efficiency for operating range**	**Signification**
Self rectifying with fixed guide vane [54,55]	25-27% for flow cofficient of 0.6 – 1.2	Peak efficiency at guide vane angle of 25º,unfavorable diffuser action.
Self rectifying with active pitch controlled guide vane [28,57]	30-41% for flow coefficient of 0.6 - 2.0	10% higher efficiency than fixed guide vane, higher cost.

TABLE III. DIFFERENCES BETWEEN IMPULSE AND REACTION TURBINES [40]

Parameters	**Impulse turbine**	**Reaction turbine**
Pressure head	Higher (>10m)	Lower (<10m)
Principle of Operation	Driven by jet or impluse of water	Pressure creates rotations
Device location	Free to air	Immensed in water
Mechanism	Simple	Complex
External casing	May be present or absent	Necessary
Part loading	Easy	Difficult
Interference Problems	Does not affect much	Affects lift
Efficiency	Better without Modifications	Poor without Modifications

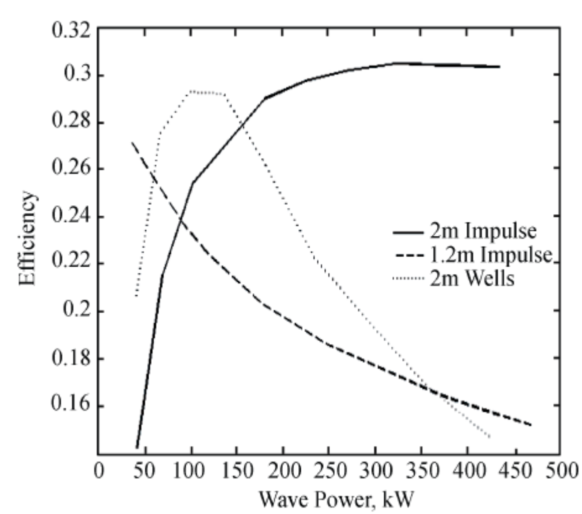

Fig. 8. Comparison of impulse vs. wells turbine [67].

VIII. CONCLUSIONS

A review of various types of impulse turbine considered for wave energy extraction has been reported in this article. The self-rectifying impulse turbines with variable pitch guide vanes regardless of axial or radial configuration possess better performance characteristics such as wide operating range of flow coefficients and high efficiency over those with constant pitch guide vanes. The self-rectifying turbine with self-pitching linked guide vanes is found to be most suitable among the axial types; whereas among the radial types, it is the self-rectifying turbine with active-pitch-controlled guide vanes. Moreover, the axial type has higher peak efficiency apart from less complexity in construction and maintenance than the radial type of impulse turbine.

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