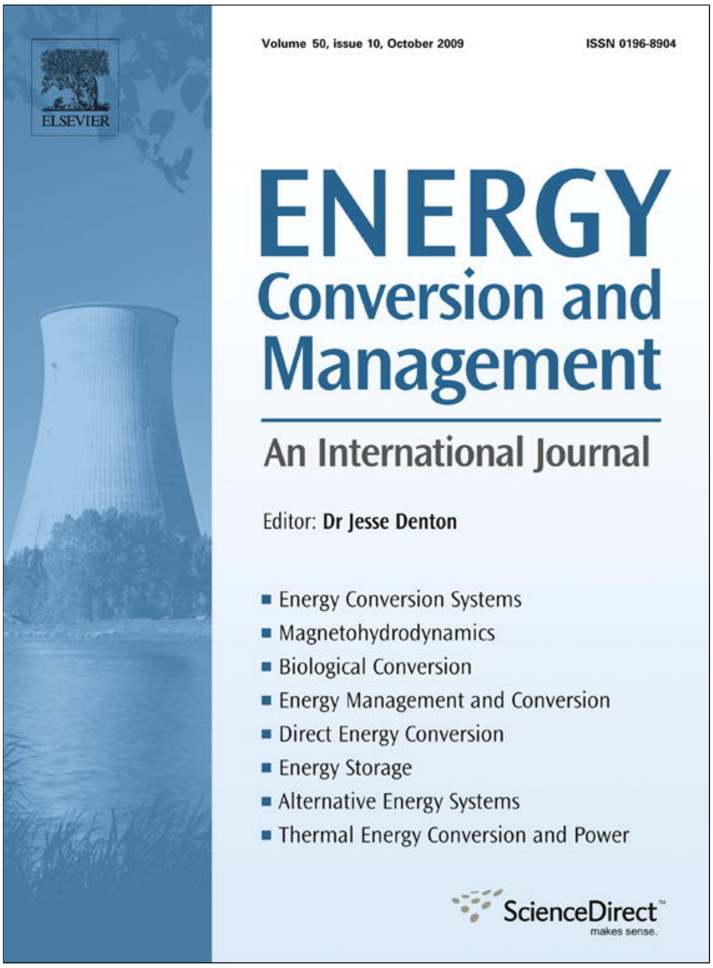
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The effects of improvement of the main shaft on the operating conditions of the Agnew turbine

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ABSTRACT

Agnew turbine is a 45° axial flow Kaplan type micro hydro. The turbine was designed by an ex-lecturer of the University of Glasgow, to operate without guide vanes. Later due to a joint research program between the Iranian Research Organization for Science and Technology (IROST) and the University of Glasgow it was developed to operate under low head and limited flow potentials in Iran. The original design of the main shaft of the turbine was supported by a bearing housing consisting of three bearings outside the main casing, leaving the rest of the shaft, hub and the runner without any supports inside the turbine .Later a suitable support near the runner and inside the casing was designed and installed. Standard turbine tests showed considerable improvements in operating characteristics of the turbine due to these design modifications. This paper presents details of these improvements and the related outcomes.

1. Introduction

Today one of the most important issues that authorities and therefore specialists have to deal with is "the issue of energy production". Hydro power is of the oldest energy resources known to the man which offers a clean, non-polluting and almost endless source of energy. The leading cause of climate change today is the burning of fossil fuels related to energy production, and using hydraulic power is regarded as a viable solution to this ever increasing problem [3,14].

Through the last decades of the twentieth centaury application of micro hydro turbines gained world wide attention. Although they are by no means comparable to large hydro plants in so far as their power production capacity is concerned yet their simple design and relatively simple manufacturing processes, low price per kilo watts, easy installation without requiring heavy construction activities, cheap and easy maintenance, and their minimal or rather non-riverine impacts have made them attractive especially to the countries with ample micro hydro sites [3]. However, one of the most important factors which make micro hydro power much more attractive is their power generation capability versus their minimal environmental negative impacts as compared to those of large hydro plants. Large hydros usually require construction of enormous hydro power dams which their riverine effects make them environmentally harmful; this would in turn make them unfavorable for application [3,8]. Moreover is their important role in decentralized production of power across rural areas for many local applications or even for sale to the national power grid, which would encourage and enable the private sector to enter the energy production programs for the relatively low capital investments required for micro hydro power plants [8].

Facing with escalating energy costs and prices, and diminishing oil resources, and following the Iranian government's programs, ministry of power and ministry of Jihad started programs on installing small and micro hydro power plants [13]. Ministry of Jihad embarked upon a joint venture with Chinese government for establishing micro hydro plants, a number of which are at present operating at different points of the country [10]. Since Chinese have the leading role in the field of micro hydros, the program was quite successful. China started her work on micro hydros in early 1950s with developing four different types of micro hydros [12], and they managed to establish more than 60,000 micro hydro power stations around China during 1990s [11,12]. China is one of the countries in which micro hydro plants have proved to be a good and a viable investment, not only at national levels but as a good source of income through exports. There are also many other developed and developing countries which are benefiting micro hydros. Their presence in the international market has resulted in a competitive atmosphere leading to much more improvement of micro hydro plants [7].

IROST as the main reference research center in Iran decided to undertake research projects to gain the most possible hydro energy of the micro hydro potentials, by designing and developing suitable micro hydro power stations for thousands of micro hydro sites scattered all over the country [13,16]. However, the suitability of a turbine for a certain hydro potential is depended upon a number of different factors, of which the effective head and the flow rate

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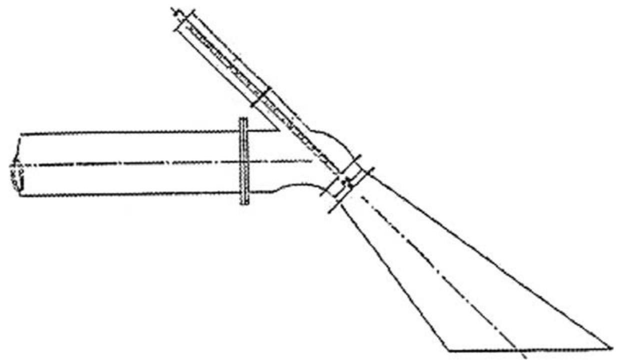

Fig. 1. Schematic view of the turbine.

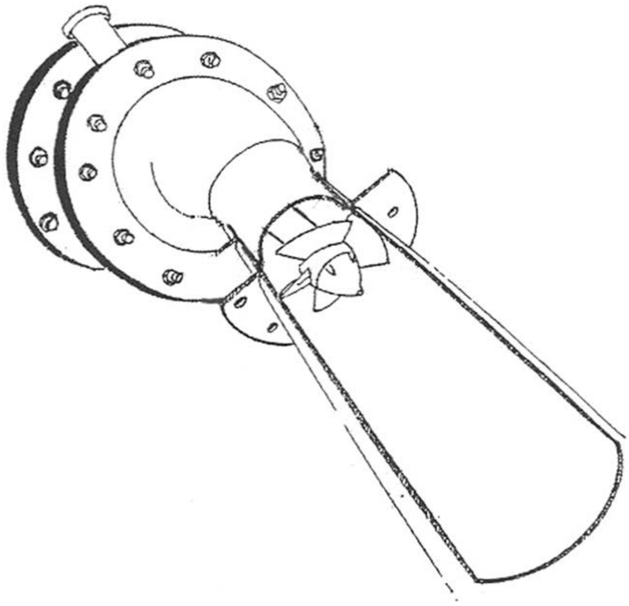

Fig. 3. A cut through section of the turbine.

are of paramount Importance. Generally, different types of hydro turbines fall into one of the two major categories, either reaction turbines or impulse turbines. Each category consists of different types and designs of turbines, which are suitable for a certain range of heads and flow rates. Ramos and Almeida have represented a chart showing operating range of various types of hydro turbines, which can help selection of turbines for given hydro potentials [7]. Also Craig et al. have lead a research work for selection of a suitable turbine for a certain micro hydro site at Minors Millpond in Reynolds, Georgia. In their work they have discussed various types of micro hydro turbines along with required criteria for their selection according to the characteristics of the hydro potential site [9]. A study of available micro hydro potentials in Iran showed that a good percentage of them fall into a category for which axial flow Kaplan type turbines may be recommended [16]. Following this guide line a joint program was undertaken between (IROST) and the University of Glasgow for developing a micro hydro suitable for micro hydro potentials in Iran [5]. Therefore The Agnew turbine was selected as the main subject of this program.

This turbine was originally designed by Mr. Pat Agnew, an ex-lecturer of the department of the mechanical engineering of the University of Glasgow.

Before the start of the joint program, Mr. Agnew and his team had embarked upon production of the turbine and ten units of them were manufactured and installed at different sites in Scotland [1,2]. But due to the lack of government financial supports the program was abandoned without any research on improvement of the turbine. However, the turbine was tested at the British national laboratories and the outcomes showed 62% efficiency as the highest performance of the turbine [2].

However, the joint program consisted of manufacturing and testing a sample of the original turbine design, according to the current standard turbine test procedures [7]. At the later stage an improvement program was defined for the turbine .Since the turbine was originally designed to operate without guide vanes, then the program concentrated on designing a guide blade mechanism which also could act as a support or in fact as a second rest point for the main shaft of the turbine which originally was designed to operate as a cantilever [4]. The same standard tests were then performed on the improved model of the turbine, results of which showed a 23% improvement on the highest performance point of the turbine [5]. However, complete standard turbine curves such as characteristics curves, operating curves etc. were plotted for

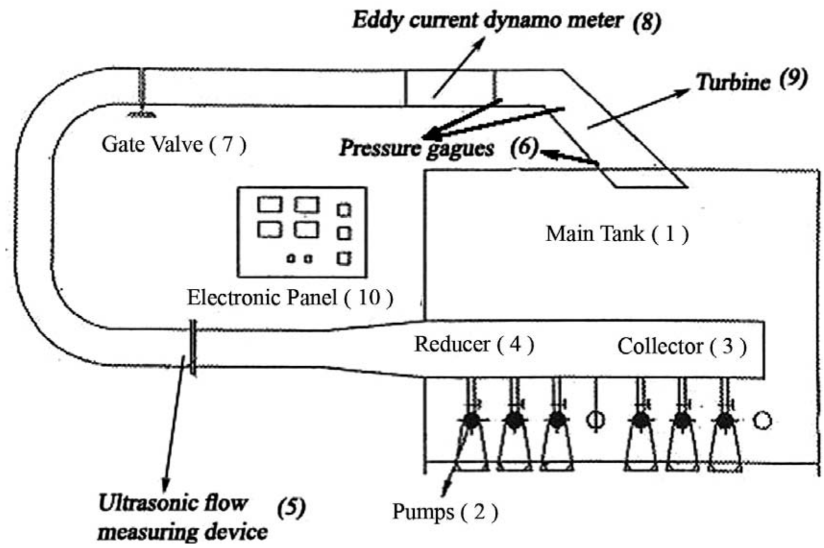

Fig. 2. Schematic view of the test rig.

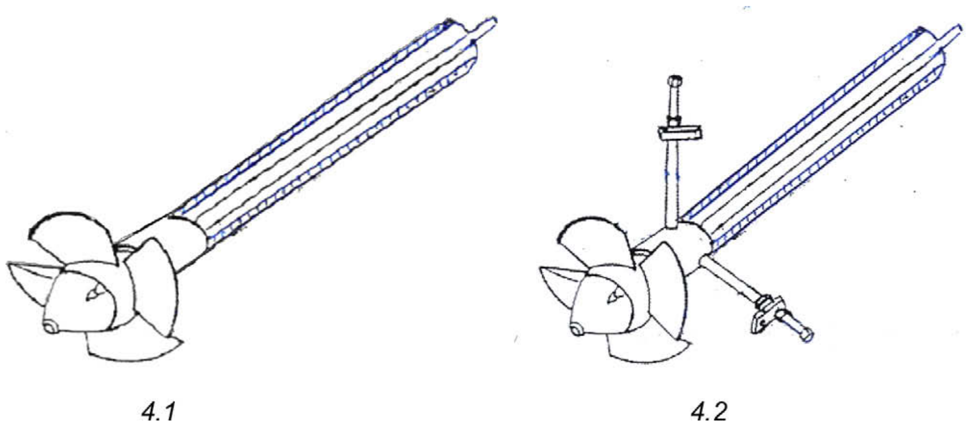

Fig. 4. Views of the main shaft before and after improvement.

results obtained for the turbine before and after improvements [6]. A comparative study of these results showed various aspects of the improvement on the turbine. Fig. 1 shows a cut through schematic side view of the turbine.

2. Test circuit and apparatus

The test circuit design and selection of its elements, and their characteristics such as circularity and cylindricality of pipes, their lengths before and after installation points of measuring devices, required straight run before the entrance to the turbine, etc. were all determined according to the ISO 5167-1980 (E) standards [4]. However, the details of the test rig and its measuring devices are as follows.

A 20 m^3 reservoir provides the water requirements of the test rig. The piping is of 10 in. diameter all through. The collector into which the water is pumped from the reservoir is a 4 m long cylinder of 20 in. diameter, which is connected to the main piping via a 2:1 semi-conical reducer. Six 11-kW electro pumps provide the required water flow for the test rig. Pumps are installed parallel to one another, generating heads up to 24 m and an overall flow rate of 420 m^3/h.

The flow is measured by means of an ultrasonic flow meter in (lit/s) with a precision range of 0.5% for linearity, 0.0015% M/S of sensitivity, 0.25% repeatability, and overall flow measuring accuracy range of 1–3%, manufactured by The Iranian Farasanj Afzar company. The pressure gauges were manufactured by the American Honeywell Co. which were installed at the inlets and outlets of the turbine and the draft tube to measure the effective head on the turbine and the suction head of the draft tube, respectively, in (mbar), accuracy range of these gauges are ±2% given by the manufacturer. A 20 kW eddy current dynamometer was applied to measure the brake force of the turbine in terms of (N). The dynamometer was designed and manufactured at the mechanical engineering research center of IROST. The accuracy of the load cell measuring the brake force of the dynamometer is ±1%, manufactured by the Korean Bong Shin Company. The angular velocity of the turbine is measured in terms of (rpm) by means of a tachometer, using a magnetic induction sensor of ±0.5 accuracy range manufactured by The Iranian Tabriz Pajooh Co. with an overall accuracy range of <0.001%. Fig. 2 shows a schematic view of the test rig. However, the accuracy of the devices and their precision range and their over all effects on the precision of results of the test rig were taken into account according to current procedures when writing the computer software for analyzing the measurements of the measuring devices.

3. The turbine

The Agnew turbine which has been named after its designer, Mr. Pat Agnew, an ex-lecturer at the University of Glasgow is a 45° axial flow Kaplan type micro hydro. Fig. 3 represents a cut through section of this turbine. The main turbine casing consists of a short straight run, leading to a 45° bend, with a reducing cross section. These two parts are flanged together to form a single part. Using the 45° bend in the main casing of the turbine is due to the elimination of application of two 90° bends as usual practice In Kaplan type turbines for guiding the flow of water into the guide vanes system. This would in turn helps eliminating the guide vanes as well as reducing of losses caused due to presence of two 90° bends in the passage of the flow. The main turbine shaft is a circular hollow shaft through which the operating rod passes and holds the runner and blades at one end and a toothed wheel to transmit the power into a gear box via a toothed belt at the other end. It rests on three bearings, two of which are tapered and one is an ordinary ball type. All three bearings are installed inside a housing separated from the main casing by a water tight seal to avoid water entering the bearing housing.

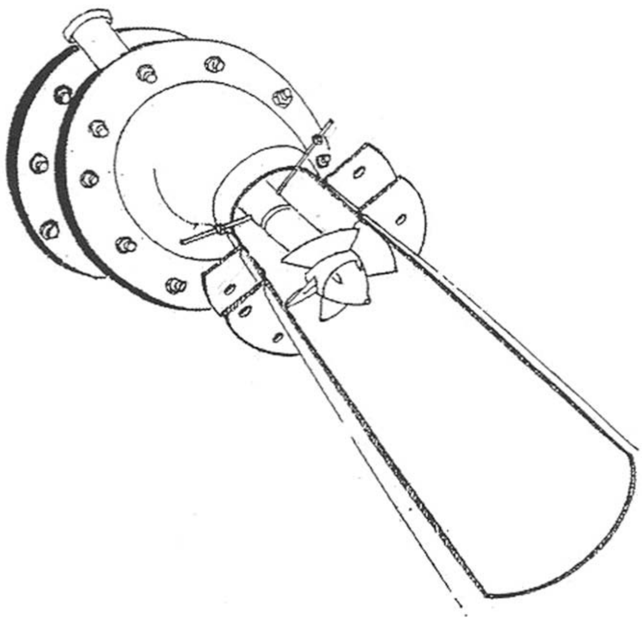

Fig. 5. Cut through schematic view of the turbine and the main shaft after improvement.

The runner consists of four blades and the hub. Blades are set around the hub which houses the blades changing angle mechanism. This mechanism is activated by the operating rod running through the main shaft. A special knot installed on the free end of the operating rod, at the outer end of the main shaft actually activates the mechanism. Turning the knot clockwise closes the blades which would almost shut down the turbine. Anti-clockwise turning of the knot opens the blades, letting easier flow through the runner. The maximum opening angle of the blades is obtained by a 30° rotation of the blade around a radius perpendicular to the main shaft.

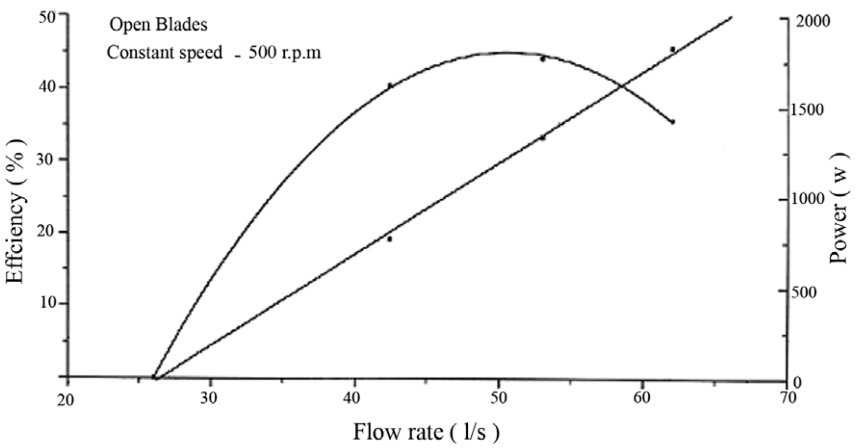

Fig. 6. Operating point before improvement for constant speed 500 rpm for open blades.

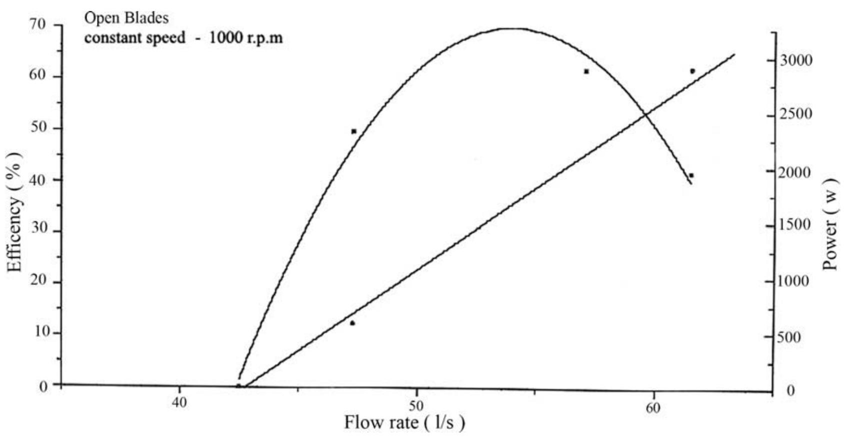

Fig. 7. Operating point before improvement for constant speed 1000 rpm for open blades.

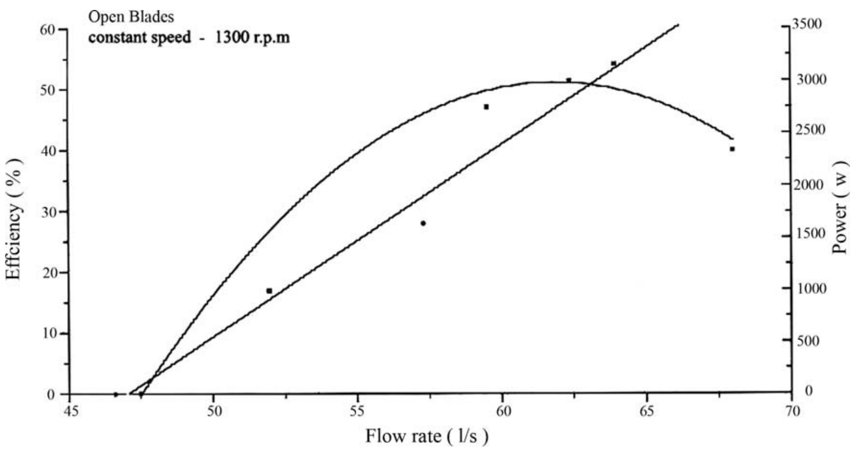

Fig. 8. Operating point before improvement for constant speed 1300 rpm for open blades.

The draft tube is of semi conical shape, cut horizontally in cross section at the larger end so that the end cross section stands parallel to the free water level of the swamp. The smaller end is flanged to the outlet of the main turbine casing.

The original design of the turbine was tested at the British national laboratories and the highest efficiency achieved was 62%. As mentioned earlier due to the lack of financial supports from the government, no research activities were performed on the turbine.

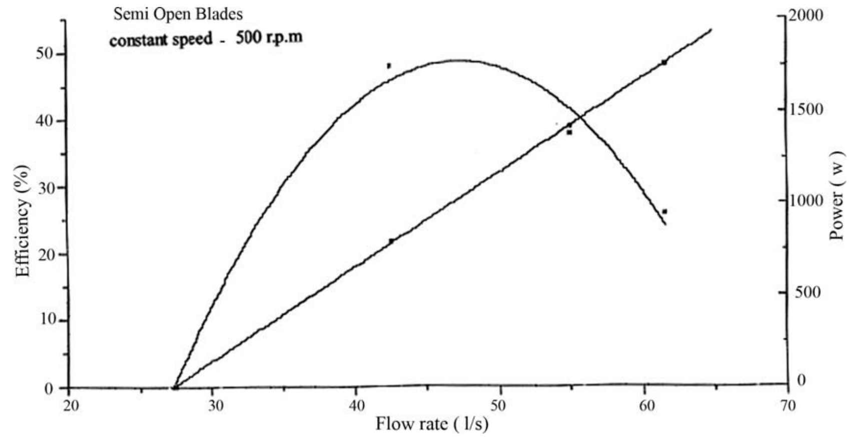

Fig. 9. Operating point before improvement for constant speed 500 rpm for semi open blades.

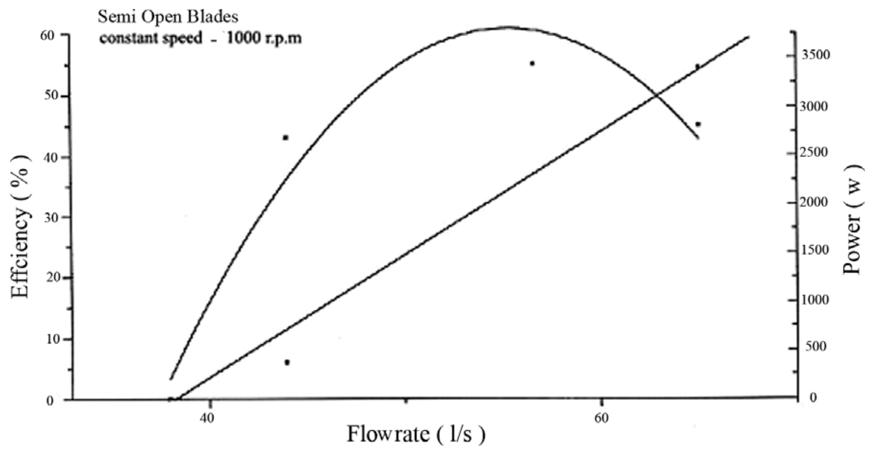

Fig. 10. Operating point before improvement for constant speed 1000 rpm for semi open blades.

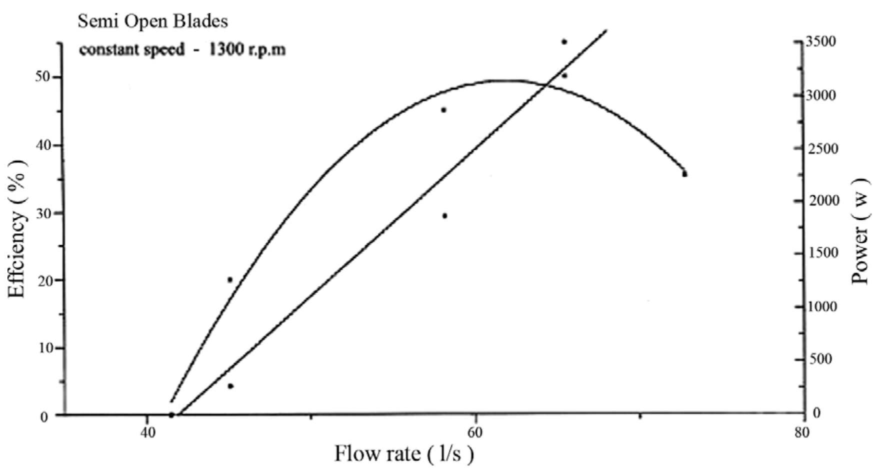

Fig. 11. Operating point before improvement for constant speed 1300 rpm for semi open blades.

When the turbine was selected for working in Iran, studies for improving the performance of the turbine revealed that the design of the main shaft along with the lack of guide vanes could have been major causes for the relatively poor performance of the turbine and

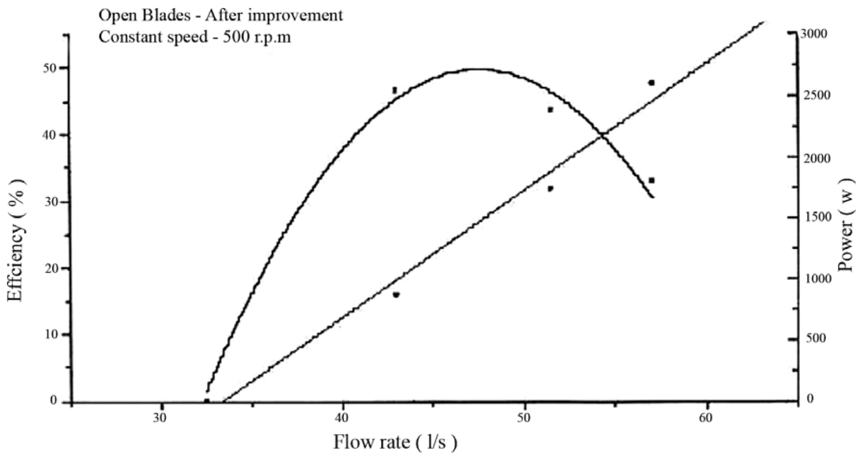

Fig. 12. Operating point after improvement for constant speed 500 rpm for open blades.

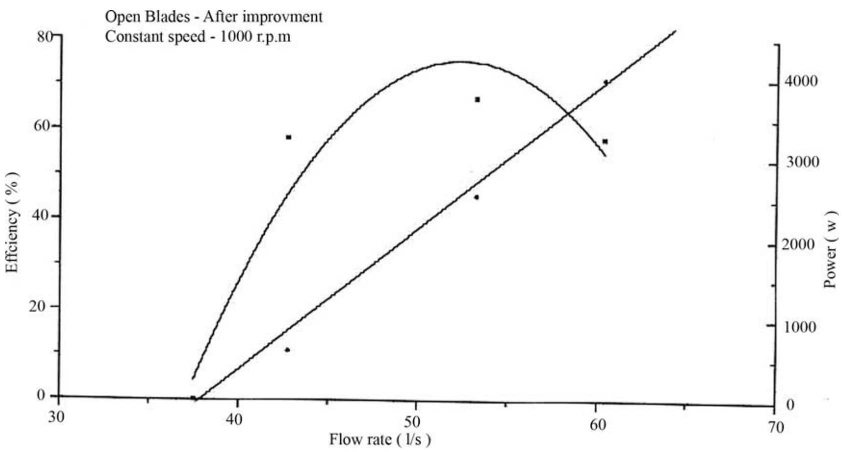

Fig. 13. Operating point after improvement for constant speed 1000 rpm for open blades.

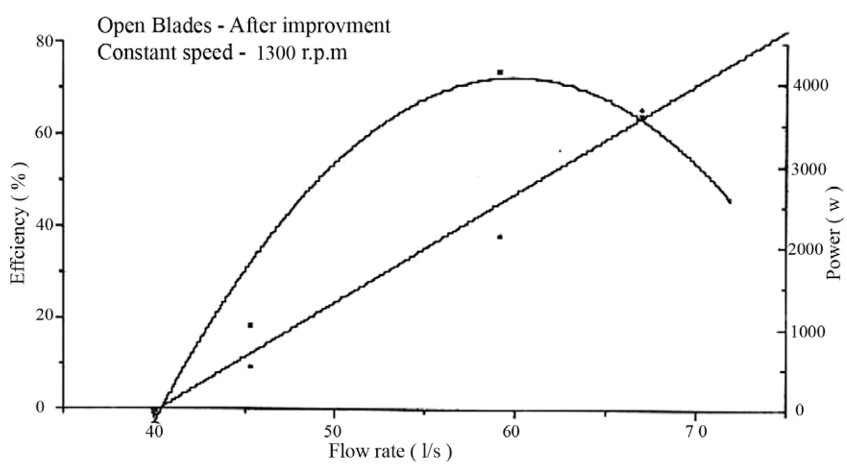

Fig. 14. Operating point after improvement for constant speed 1300 rpm for open blades.

therefore the work began with designing guide vanes and improving the main shaft of the turbine, the effects of which were studied separately.

4. The main shaft

As indicated earlier the main shaft of the turbine is supported by three bearings, installed inside a housing outside the main turbine casing and connected to it. The main shaft subtends 45° to the line of horizon, and holds the hub and the runner assembly. An operating rod passes through the main shaft, which operates the angle of runner blades for changing their angle of attack between 0° and 30° around the radius perpendicular to the main shaft. The 30° blade angle is called "fully open blades" and 15° blade angle is called "semi open blades". However, the unsupported part of the main shaft is left without any rest point inside the turbine cas-

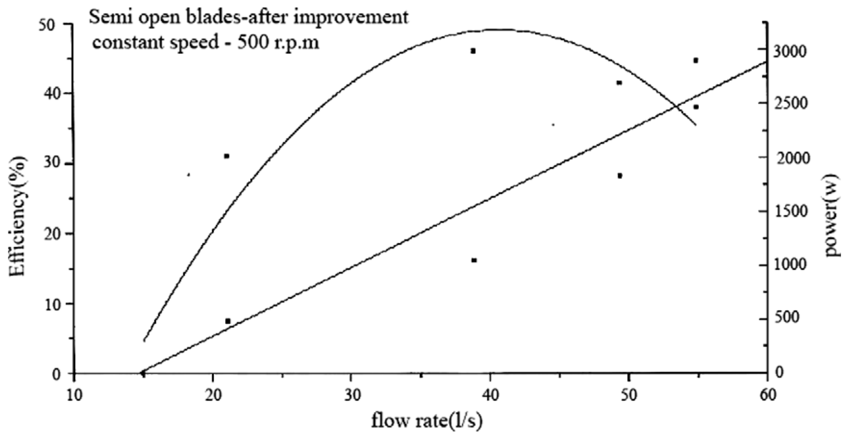

Fig. 15. Operating point after improvement for constant speed 500 rpm for semi open blades.

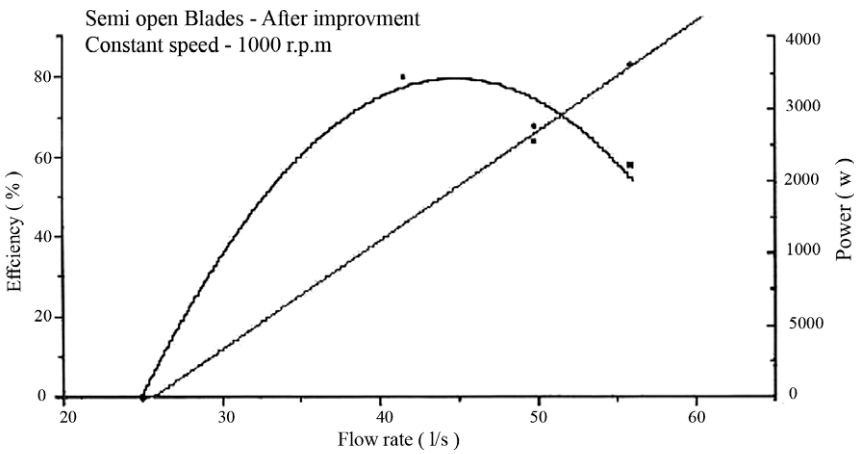

Fig. 16. Operating point after improvement for constant speed 1000 rpm for semi open blades.

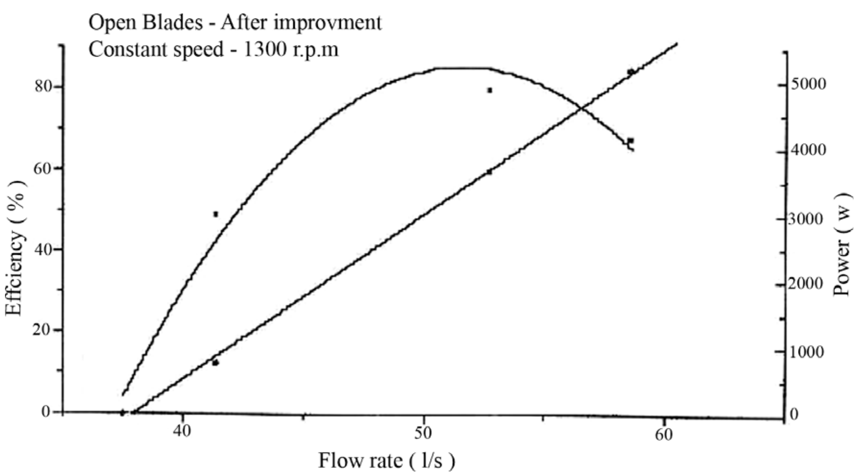

Fig. 17. Operating point after improvement for constant speed 1300 rpm for semi open blades.

ing which should also support the hub, the runner and the mechanism for changing the blade angle installed inside the hub, and the blades. Also it has to withstand effects of large volumes of water passing through the runner. All these factors tend to escalate a lack of stability in turbine's operation, and therefore increase the vibrations at the free end of the main shaft. This would in turn escalate the danger of collision of the runner blades with the turbine casing, causing efficiency drop, noise, and vibrations. Therefore it seemed appropriate to improve the design of the main shaft so that it could rest on a second support inside the turbine casing (4).

5. Improvements of the main shaft

In order to establish a suitable second support for the main shaft, without redesigning and remanufacturing it, an extension to the main shaft was designed and manufactured. This extension was installed at the free end of the main shaft in place of the runner. Instead the runner was installed at the free end of the extension. Fig. 4.1 and 4.2 shows the shaft before and after improvement.

The extension consists of three parts. The outer casing, which is stationary and acts as a second rest point for the main shaft .The inner part, which is actually screwed into the free end of the main shaft and rotates with it. An assembly of a needle bearing and two seals, which operate between these two parts. The outer casing and therefore the free end of the main shaft are held and supported by means of three rods, connecting them to the turbine casing, each rod being separated by 120° from one another. Fig. 5 represents a cut through schematic view of the turbine and the main shaft after improvement.

6. Test procedure

Tests were taken for different settings of the runner blades, namely fully open and semi open, for various flow rates and different heads, according to standard turbine test procedures for both versions of the main shaft, before and after improvement [14].

Generally, turbines in the field must be supplied with natural flow of water (Q) under some head (H). However in a laboratory both Q as well as H are obtained by a suitable pumping unit. The pump draws water from a sump of sufficient capacity, and delivers it under a specified pressure (H) to the turbine.

The pump is started and the delivery valve of the pump is opened fully in order to supply water to the turbine. The inlet valves to the turbine, as well as the turbine gates are opened. The turbine is run for 15–20 min before the readings are recorded. The brake cooling water tap is opened. Allowance for this water is made for the accurate calculations of discharge. The turbine is set for a number of inlet openings, at least four, say 25%, 50%, 75% and 100%. For each inlet opening, the turbine is first run and the break is applied and torque readings along with all other necessary readings are taken until the turbine is at standstill. Not less than six different loadings for a single inlet opening are to be recorded. The head under which the turbine is operating is kept constant as far as possible during the test by adjusting the delivery valves of the pumps or by varying the speed of the driving motor.

7. Formulations

In order to study the outcomes of implementation of improvements on the turbine complete operating and characteristics curves were plotted and compared for the turbine before and after improvement. One of the most important factors which can determine the operating performance of a turbine is its operating point.

Table 1
Percentage improvements for the values of the operating point for open blades.

Constant speed (rpm)	Percentage improvements in characteristics of the operating point for fully opened blades		
	Flow rate reduction (l/s)	Efficiency increase (%)	Power increase (%)
500	16	7.5	52
1000	2	1	60
1300	3.5	7	42

Table 2
Percentage improvements for the values of the operating point for semi open blades.

Constant speed (rpm)	Percentage improvements in characteristics of the operating point for semi-open blades		
	Flow rate reduction (l/s)	Efficiency increase (%)	Power increase (%)
500	7.5	0	65
1000	19	46	30
1300	17	58	50

To obtain these point curves of efficiency and power for constant speed against the same flow rates were plotted. Their intersection point represents the operating point for the specified conditions. To plot these curves the required data were collected and processed as follows [7,14,15]:

$$P_o = \omega \cdot T \cdot \pi/30 \text{ (W)}$$

where ω is the angular velocity (rpm), T is the torque (N m).

Also;

$$N = 2 \cdot \pi \cdot \omega/60$$

where N is the turbine speed (rad/s).

And;

$$P_i = \rho\ g\ Q\ h$$

P_i is the input power (W), g the 9.81 m/s^2, Q the volumetric flow rate (m^3/s), H is the available head (m).

Also; the overall efficiency is given by:

$$\eta t = P_i/P_o$$

8. Results

As mentioned before all the necessary curves were plotted and the relative operating points were obtained. Figs. 6–8 show these plots for open blades, for constant speeds of 500 rpm, 1000 rpm, and 1300 rpm; before improving the turbine's main shaft. Also, Figs. 9–11 show the same plots for semi open blades, keeping all other parameters and test conditions constant. After improvement of the main shaft the same plots were generated for both different blade settings. Figs. 12–17 show the same curves for fully open and semi open blades settings, respectively, after improving the main shaft.

Tables 1 and 2 show comparative percentage improvements in characteristics of the operating point for different blades settings, fully open and semi open, respectively. As it may be observed all the comparative percentage values are of positive magnitude. Therefore, it could be deduced that the operating points of the turbine for any speed and under any conditions have been enhanced due to establishment of the second support and improvements made to the design of the main shaft. Also drastic improvements are observed, especially at higher speeds (closer to the speed required to run electricity generators) when blades are semi open.

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