“Backflow Preventer;” ***Exploiting Patterns of Separated Flow to Increase Power in an Enclosed Hydropower Turbine*, by George F. McBride of PfISH Turbines**

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I. Introduction

George F. McBride, indendent inventor and sole proprietor at PfISH Turbines, Machiasport, Maine, began to develop a new instream hydropower turbine, four years ago. A “Seed Grant” (less than $5,000), from the Maine Technology Institute in 2009, provided initial funding.

Instream hydropower refers to energy obtained by a machine that is submerged in a stream. No dam is involved. The machine might be stationary, anchored in a streamflow, or moving through water, for example, propelled by a boat. It can be of any size. The goal is to have a scaleable, efficient, cost-effective turbine that converts a high proportion of captured current flow into useful power.

Mr. McBride has developed a novel design that uses channels and internal rotors to capture instream flow and generate rotational power (Fig. 1). A US patent application was filed in September 2010 and allowed in its entirety in May 2013. The issue fee has been paid, and the patent is expected to issue shortly (Ref. 1).

II. Background

Up to now, development at PfISH Turbines has focused primarily on internal configuration - what happens inside the machine. The PfISH turbine is designed for a target ambient current of 4 knots (1 knot = 1.15 mph). It comprises two, matching, mirror-image rotors mounted on opposite ends of a rotatable shaft that is transverse to the stream, two spiral channels that surround and enclose the rotors, and feed them with a spiraling inward flow, a common intake funnel that communicates with the two spiral channels and brings new flow in from the stream, and two exhaust channels that carry spent flow axially away from the rotors and discharge it back to the stream (Fig. 2). The rotors take in flow all around their open intake peripheries, redirect it to an axial direction, and harvest power from the flow.

Specifics of PfISH turbine’s internal configuration are well defined in extensive notes, CAD files, and physical models. Observations, videos, and test reports suggest that internal channel components are suitable to operate as intended. A number of prototype variants have been built and tested that produced rotational power.

A problem exists, however, that in all of the instream tests, not enough power is obtained.

For example, in Test Report #3, dated 5/15/2012, representative of test results so far, nineteen power measurements are recorded for the machine propelled by a boat in varying

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conditions of speed, direction and load (Fig. 3). Seven of these measurements were made at travel speeds close to 4 knots, the target of design, for which calculated power flux is 283 watts for the 100 square inch intake opening of the tested machine, and Betz limit (Cp = .59) power flux is 167 watts, (Msmts # 2-3, 6-8, 17-18). But these seven measurements are in the range of 9.1 - 17.8 watts, with an average of only 12.7 watts (Cp = .045).

Clearly, further work is needed.

III. What is the problem?

One important consideration of instream hydropower is that a flowing stream need not pass through the turbine immersed in its path. It can just go around. This contrasts strongly with conditions at a dam, where a stream is bottled up and released only through the dam's turbine passages. If, as the author believes, internal channels of the PfISH turbine are functional in their design, then the problem is getting sufficient water in.

In any turbine, generated power is proportional to new flow coming in. Spent flow at turbine discharge has equal volume as new flow coming in, but less energy and speed. If the energy of incoming flow were to be completely harvested, for example, then spent flow wouldn't even move. Sluggish flow at turbine discharge is additionally impeded by the backwash of the turbine's downstream wake. How can spent flow be speedily removed to make way for new flow coming through?

One must learn how the turbine's shape - its external configuration - interacts with the stream.

IV. "Separated Flow"

Submerged, the PfISH turbine acts as an obstruction in the stream. Where smooth flow encounters an obstruction, it forms a three-dimensional topology of disturbance, a shifting pattern of "separated flow", that varies in shape, location, and intensity with the physical characteristics of the fluid (speed, density and viscosity) and the configuration and size of the obstruction in its path.

Separated flow is considered to include lines of detachment, lines of attachment and the turbulence that persists in an obstruction's downstream wake (Ref. 2). A simple example of turbulence in a downstream wake is the momentary, axisymmetric toroid (donut) ring that appears behind a flat, circular disk obstructing a laminar stream. Images of this and other patterns such as the "horseshoe vortex" of water flowing around a bridge piling, can readily be viewed online (Refs. 3-5).

The wake behind an obstruction has little downstream component of flow, as the author learned years ago, while canoeing in a boulder-strewn stream with an experienced

companion who demonstrated how to exploit rocks' wakes to travel against the prevailing current. The area directly behind each obstructing boulder contained a backwash of water which, if the canoe were well-positioned in it, would draw the canoe right up until it gently bumped the rock from behind. By paddling hard from one backflow to the next, among boulders plentifully arrayed, the paddlers made passage up the fast-moving stream.

By understanding patterns of separated flow that occur around an instream hydropower turbine, the author hopes to find a way to exploit them. His goal is to increase power in the PfISH turbine design and to spur investigations by others to improve the efficiency of instream turbines, generally. An ancillary benefit might be the possibility of closer unit spacing in multiple turbine arrays, or "farms."

V. Two solution attempts

The first attempt to exploit patterns of separated flow was attaching a backflow preventer, a barrier to keep the turbine's downstream wake from getting back at its rear-facing exhaust. The design was based in part on the gills of a Pollock, a streamlined, ocean-dwelling fish, a specimen of which found its way to the author's kitchen one recent evening (Fig. 4). Gills are openings at the fish's sides, near the body's widest part, that contain water channels inside, and blood vessel structures for exchanging oxygen. It is surprising to see that the water channels inside the gill openings are quite, completely open. One can look into either side and see right through the open mouth. There appears no muscle structure, no large fleshy tongue inside that might serve to push water through. Apparently water is drawn past the gills by the stream around the fish as it swims. Bernoulli's equation would apply.

The Pollock's gill channels diverge behind the mouth, directing water out both sides of the fish. The backflow preventer emulated that gill channel shape to direct water out both sides of the turbine, just behind the exhaust channel outlet.

It was assumed that a moving object such as a fish has similar effects of separated flow in quiet water as a stationary object, like a turbine, has in a smoothly flowing stream, though the separated flow patterns likely differ for the different object shapes. Little turbulence inherently follows in a fish's wake (disregarding its self-propulsive thrusts). Its shapely, streamlined body sees to that. But a hydropower turbine need not be streamlined like the fish. It will not be propelled, but anchored in the stream and anchor force is not an issue as muscular exertion must be for a fish. So, behind the channel structure that directed spent flow outwards, the backflow preventer was truncated. The theory was that backflow still exists in the turbine's downstream wake, but is kept out of the way of the turbine's spent flow discharge.

The backflow preventer was built and tested in May, 2013 (Fig. 5). Unfortunately, it did not appear to have much effect, neither substantially increasing nor diminishing the tested power of the machine.

The next attempt was to add a ring of exhaust vanes around the opening between the turbine's exhaust outlet and the backflow preventer (Fig. 6). This idea was inspired by "vane windows" of the author's old truck. It was thought exhaust vanes might draw water through the exhaust channel outlet as vane windows draw air through a pickup truck's cab. It was tested in July, 2013 and, unfortunately, did not have much effect either, except to add more drag on the machine.

VI. Two key tools

One design tool used extensively in developing the PfISH turbine is streamlines modeling. Bent-wire streamlines helped define shapes of smooth, non-obstructive passages inside the machine, and a rotational transformation (a mathematical procedure) rearranged the streamlines representing rotor channels to get the shape of the rotating vanes.

A streamlines model is a mapping of idealized flow. Each streamline represents multiple water "particles" that travel a common path. Physical (wire) streamlines, carefully located and shaped, and appropriately separated from each other, represent desired flow passages as bundled pathways, or "tubes" (Ref. 6). By extracting 3-dimensional position coordinates, the shapes of the channels can be determined. Or the process can be performed virtually, with appropriate modeling software (Ref. 7).

The failure of the first two solution attempts shows that an additional tool must be brought into play, this one to answer, "What drives the flow?" Pressure mapping is that second tool. Flow is movement of water from high pressure regions to low. The term, "pressure field," can be used for the variations of pressure in space involved in fluid flow. A pressure field can be mapped as equipotential pressure surfaces, outlined individually in contours, with implied lines of force that follow a pressure gradient perpendicular to the equipotential surfaces (Ref. 8). A flow is influenced by the pressure field as to its momentum, speed and direction of travel and, no doubt, the presence of flow influences the pressure gradient in its turn.

The three-dimensional pressure field that acts inside the PfISH turbine channels is presumably of interest, presumably complex, and will not be covered here.

VII. What is to be done?

Pressure values at the turbine's openings - intake and exhaust - mark the end points of a pressure gradient inside the machine and set the limits of force available to drive fluid through. Pressure at the intake inlet is easily ascertained. By the formula: $h = \frac{v^2}{2g}$,

velocity head of a 4 knot flow equals about 8.5 inches of water column, and the intake inlet faces into that flow. Pressure at exhaust outlet is not so easy to determine. The patterns of separated flow that surround the machine in the stream have an influence here.

Re-visiting the cofiguration of the backflow preventer, the author notices that it misses one, perhaps key, point in emulating a fish. In the many online images of separated flow, there are some common elements. Flow builds up on the front of the body that it encounters - streamlines are close together there. The flow parts, and goes around the body - with streamlines still adjacent to the body and still close together. Just past the body's widest point, the streamlines typically break away and continue on their way, no longer adjacent to the body. The body's widest point marks the beginning of the turbulent zone, or wake, behind it.

That has been observed with the PfISH turbine, as well. The turbine's widest point is the outlet of the exhaust. Flow rushes past that part, and there the turbulent zone begins. A sketch is attached that illustrates this effect (Fig. 7). Getting back to the emulation of the fish, its gills are mounted just <u>before</u> its widest part, but the backflow preventer was mounted just <u>behind</u> the turbine's widest part, and it is smaller than the outlet of the exhaust. A sketch is attached that illustrates the backflow preventer smaller than the exhaust (Fig. 8). Even with a ring of vanes attached in the opening between, the exhaust's discharge opening is mainly behind the turbine's widest part. Whether that discrepancy in emulating the fish is the cause of the disappointing result has yet to be determined.

Perhaps the backflow preventer should be <u>larger</u> than the outlet of the exhaust. One configuration that will be built and tested might look like this sketch (Fig. 9). It makes a slightly larger obstruction behind the exhaust outlet, in effect putting the discharge of the exhaust into the swift-moving part of the stream rather than the turbulent zone. Bernoulli's equation states that kinetic energy plus pressure equals a constant. Thus where kinetic energy goes up (the swift-moving part of the stream), the pressure goes down. Perhaps, according to Bernoulli's equation, spent flow will be drawn away if discharged right into the swift-moving part of the stream. If so, how much suction force that draws spent flow away, and how much spent flow can be removed, will be tested and observed.

Depending on the success of that proposed experiment, other add-on structures will be built and tested, too. All will have in common that they put spent flow into the swift-moving part of the stream, rather than into the turbulent zone behind the turbine. Once a beneficial configuration is discovered, then a new exhaust channel will likely be designed that incorporates the best of all new findings.

The effort continues, "Exploiting patterns of separated flow to increase power in an enclosed hydropower turbine."

END

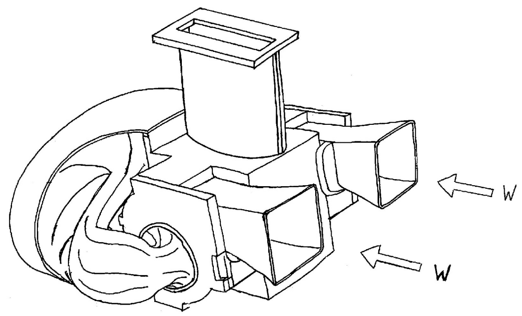


Figure 1 - Turbine of novel design

Figure 2 - The PfISH turbine

~~Msmt~~ #	GPS heading (degrees)	GPS speed (knots)	Shaft speed (rpm)	Measured power (watts)	Comments
1	NA	0.0	0	0.0	Stopped in the water
2	208	4.1	270	9.1	Clamp loose
3	205	3.9	144	16.4	
4	028	4.6	292	11.1	Clamp loose
5	028	4.6	175	20.4	
6	192	4.0	272	9.9	Support shimmed
7	205	4.1	116	14.4	
8	205	4.1	204	17.8	
9	018	4.3	233	18.4	
10	018	4.3	285	10.1	Clamp loose
11	018	4.3	257	16.4	
12	201	4.9	325	20.2	
13	192	4.8	343	14.3	Clamp loose
14	212	4.8	194	30.5	
15	022	3.5	130	5.2	Just starts turning
16	022	3.5	193	-3.4	Band removed
17	202	3.8	191	10.2	Band replaced
18	020	4.2	288	11.0	“going with tide”
19	NA	0.0	0	0.0	Clamp loose

Figure 3: Measurement data from Test Report #3, of 5/15/2012

Figure 4 - Gills of a pollock

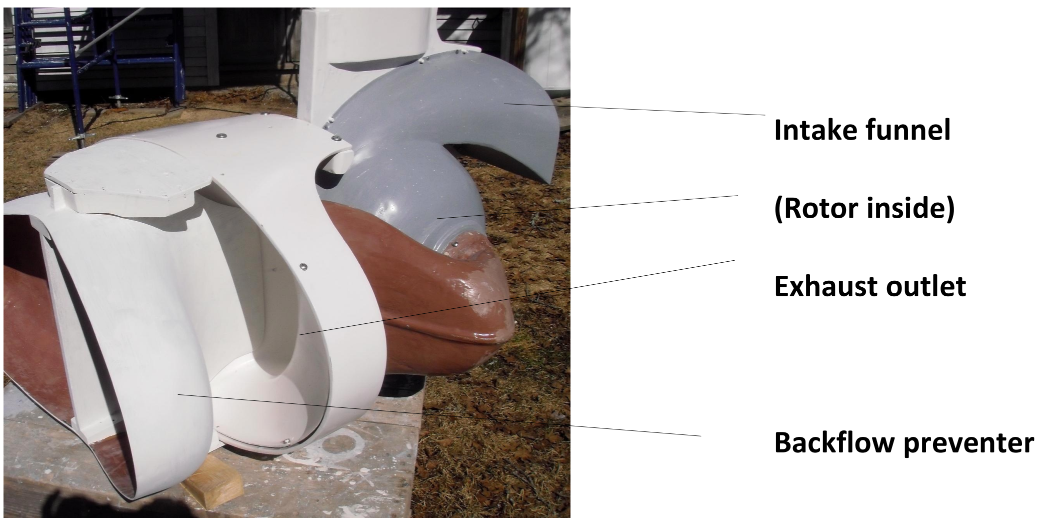


Figure 5 - PfISH turbine with backflow preventer

Figure 6 - PfISH turbine with backflow preventer and exhaust vanes, mounted for testing

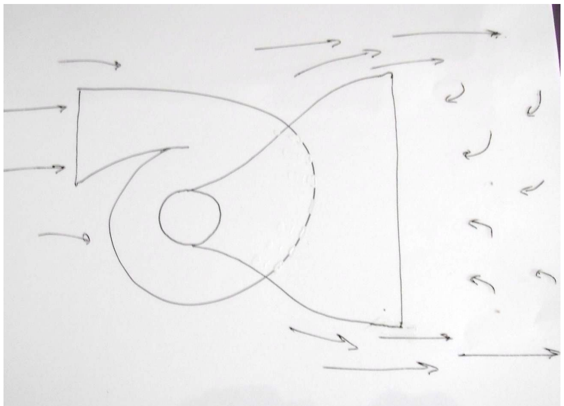
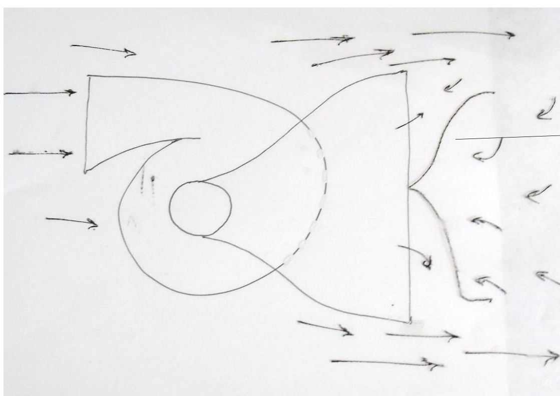
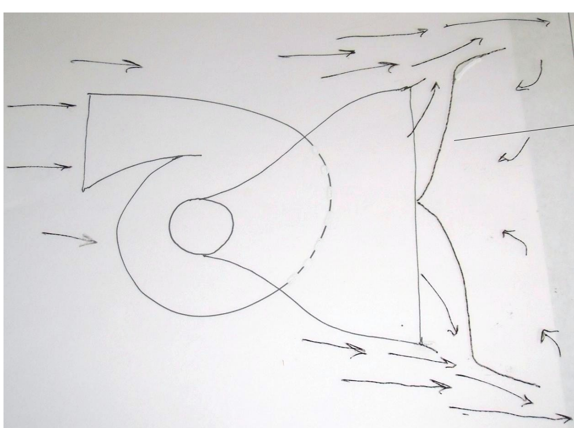


Figure 7, Swift-moving current past the turbine’s exhaust - its widest part



Backflow preventer

Figure 8, Backflow preventer smaller than exhaust outlet



Backflow preventer

Figure 9, Backflow preventer <u>larger</u> than exhaust outlet

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