ABSTRACT

Turbine types suit specific ranges of head, flow rate and shaft speed and are categorized by specific speed. In the Low-head range, under 20 m, the optimal specific speed becomes heavily divided between two different methods, Impulse Turbines and Reaction Turbines. Both of methods suffer from serious problems in Ultra Low-Head range, below 2 m. The Impulse turbines, like the gravitation machines, are not able to function with heavily variable water levels, or their size makes their large scale usage impossible. The Reaction Turbines, practically Kaplan and propeller Turbines, specific speeds increases in to the levels where the performance becomes very sensitive and is thus unable to been maintained in a target point. This paper explains the new technical solution, named Jokela-Turbine, to overcome these problems. The Run-of-the-river hydropower suffers also from various other technical problems. The worst is the simple fact that conventional weir-concept looses head in high flows, also other aspects like flood-flows, sediment transportation/erosion and river life must be solved. This paper explains a new approach to overcome these problems; MEL-Drop Structure. Finally the affordability requires robust, low-cost and maintenance free details throughout the power plant. This paper explains also one new idea to rake-cleaning. This Paper gives also new idea to explain turbulence.

INTRODUCTION

Typically, selecting hydro turbines is based on the specific speed of the turbine, a non-dimensional parameter that includes head, output power and output shaft speed. It is easy to notice from Fig. 1. that in low head-range there is a huge gap in these specific speeds; There was no machine available before in range H=0,,20 m and with nq = 70,,150-250. Turbine types suit specific ranges of head, flow rate and shaft speed and are categorized by specific speed

This leads to the known problems in ultra-low head turbines [1]; An increase in specific speed of turbine is accompanied by lower maximum efficiency and greater draft tube. The runner of too low specific speed with low available head increases the cost of generator due to the low turbine speed. It also increases the size of the runner.

The increase in size and thus costs already practically ruins the usability of impulse turbines in ultra low heads, but finally, it just becomes impossible to install a D=1 m machine which needs to work always above the water level, to a H= 1 m, if the water levels varies >1m, which is easily the case in the rivers with somehow remarkable flows, ie. Aare, Thun 2011,Qm=111 m3/s, where the variation was already 2.15 m. [2] As it can easily be noted, any interesting sized (>1 MW) low head hydro power will either suffer from low efficiency, high
costs, or would be just technically impossible to realize in the “run-of-the-river”-mode. The conclusion found here, is that we need to lower the Specific speed to stabilize the turbine performance without increasing the Turbine-size but rather decrease the size, if possible.

The varying head also makes another requirement as a must; turbine must be regulated. This head variation can’t be solved with parallel installation of many machines, though this matrix is practically mostly used purely caused by the power density and machine dimensions.

This Varying head problem can also be approached with the simple question; why the head varies? As the Sea level don’t rise, and also the mountain tops hold their places? The Head-loss, is not an energy loss, its physical basic is the Bernoulli’s equation. The reservoir overflow has high velocity and thus high velocity-Head. The downstream instead, has typically a low velocity because the energy is destroyed in turbines and in the spillway. Over 1 m Head loss is achieved already by velocity difference of 2 m/s -> 5m/s. As the problem is recognized, it is obvious that this head-loss could be avoided by simply holding the flow velocity constant. Which is not as simple as it seems, because the hydro-power plant simply needs a weir, Head, and though the head could produce velocity, too much Head will just dissipate it all in Turbulence.

![Fig. 2: Suitable Specific speed \( n_q \) of common hydro turbines in various heads. Yellow; “Impulse”, Blue; “CRT, Jokela”, Red; “Reaction”](image)

Counter-Rotating Turbine (CRT)

If the common guide-wane and runner combination is replaced with a two counter-rotating runners, the specific speed can be approximately halved without any loss in power density. Depending from the optimization aspects, the counter-rotating turbine can even have a higher power density than a conventional turbine. As generally less angular change is needed for the same pressure head, and maximum absolute velocity defined by the pressure head remains the same, the meridian component of the flow can be bigger. Which means that also the meridian flow velocity must be bigger, which leads to a higher power density.
Yet, these Counter-rotating systems are nothing really new. The first concept was patented by F. W. Lanchester in 1909. And though they were found to be 6-16% more efficient as propellers, this advance was not enough to accept the additional noise and complexity. And in turbine usage this efficiency advance compared to conventional concepts, is not even reached. The main reason in additional efficiency in propeller usage is in contradiction to the noisiness and is actually lead only to the added guide-wane function.

**JOKELA-TURBINE, Solution to the continuity Problem**

![Fig. 3: Continuity](image)

The main characteristic of the Jokela-Turbine compared to CRT is the difference in runner diameters, and thus also all the runner parameters between the first- and the second runner. The reason why this is beneficial can be traced to the conservation law’s of physics, more precisely to continuity equation, which in a bit simplified form just says that total energy remains the same, so if velocity changes the pressure must change to an opposite direction. Of course in a Turbine, the total energy doesn’t remain the same, but its’ reduced, and thus also the velocity and pressure should be reduced accordingly. And this indeed is the case when turbine has a guide wane. Fig 2. “Kaplan”.

In a case of a typical counter-rotating orientation, the runners are placed in a cylinder shaped tube, and the runners have same outer diameter. This leads to a continuity problem in the first runner. The Energy level goes down, but the velocity is accelerated. This causes a dramatic pressure drop causing a disturbance on the flow and a difficult turbulence between the runners, which further has an impact to the second runner functionality. This case is presented in Fig 2. as a “CRT”.

In the case of the Jokela-Turbine, the flow is already accelerated to the maximum before the first runner, and together with created angular velocity, the turbine opens in away which causes the absolute velocity to drop, and thus the pressure will also drop very smoothly as the energy is taken out. Thus the flow remains very laminar-alike, and the second runner functionality is not compromised.
TURBULENCE

Why the efficiency of high specific-speed turbine drops in low heads? The reason is of course the mixing work, which proportion grows bigger. By developing this turbine I noticed that the definition of Turbulence is still incomplete. Its characteristics are “chaotic, mixing, rotational and energy dissipation”. There is i.e. Reynolds number or Navier-Stokes equation, which tries to explain this. There is even a Mathematical problem called “Navier-Stokes existence and smoothness” which assumes, that this all could be explained and solved mathematically. But it can’t be done. There is no solution. Because the physical background of the problem is not correctly defined.

While developing this hydropower concept, I also needed to optimize all the details outside the turbine, as hydro power plant always starts from an open channel flow, and ends to an open channel flow. In the open channel the Turbulence can be simplified to two dimensional eddies. And also in open channel the continuity can been used efficiently to minimize the energy losses. And these led me to notice old paper from Gordon McKay. [3]

It’s the only paper from this art, which clearly states that fixing Turbulence and velocity with a causality “must be grossly in error”. Though they do correlate, there is no causality. Reynolds number speaks about this Correlation, and there truly is statistically remarkable dependence. But there is no Causality. This can be verified from many sources, i.e. Ven Te Chow states clearly that flow can be laminar with Reynolds number “as high as 50 000”, and “It should be noted that there actually is no definite upper limit”. [4]

So if turbulence is not connected in velocity, what is it? A hint can be found from a 2D field; there the vortex forms a relatively simple minimal surface pattern, shown in figure 3.

Blue/cyan lines describe the rolling parabolas. Black lines describes the axis along the parabola is rolled, and also to destination of the green line and the end of green line describes the focus of the blue parabola, which follows the red curvature forming a catenary. The size of the pattern must then slightly grow just to fulfil the continuum laws (yellow lines); the vortex centre rotates as the end result of the rolling parabola, and these rotations are then forcing the fluid to move perpendicular to the original flow direction. But as there are always two similar flows on counter directions, (Simply must be, according to Newton) this doesn’t of course increase the volume/width of the pattern, it is the change on temperature, what does it. Note that all these Parabolas and catenaries are drawn with the same parameters. Only their positions are slightly corrected as can been noted from black & yellow lines. It is also to been noted, that the parabola defines also the interval of the eddies.

The velocity and the pressure profile of a vortex forms a minimal surface. In 2D field it is a catenary. I.e. a soap bubble is a minimal surface. -> Surface! The water has surfaces in it. The Turbulence is a nothing else but the water cut to a many fluid components having their own surfaces. And these surfaces slides against each other giving a relief compared to viscous forces which causes the rotational movement. (Rotation characteristic) This molecular cut in fluid aloud increased convection through the fluid, i.e. aeration in white waters. And the increased surface amount makes also the chemical dissolution very efficient. (Mixing characteristic) Cutting the existing fluid, and creating more surface having surface tension is also very energy consuming it self; with water, the Surface energy is 0.072 J/m2 (Energy
dissipation characteristic). This energy can not be returned to pressure or velocity, so when this eddies disappear, it will be transferred to heat.

![Image](image.png)

**Fig. 3: Karman vortex-street, rolling parabolas(Cyan) and Catenaries (Red)**

**Navier-Stokes existence and smoothness problem**

The further conclusion which can be drawn from all this above, is, that the premises of this mathematical problem are wrong. As there is not only one three dimensional volume, but a volume which is divided by their own surfaces to many different volumes, which can’t continuously transfer velocity and pressure over their own surface’s, so the three dimensional flow will finally always become to it’s topological limits and must thus explode. This is not the case in 2D field, where the vortex surfaces are more able to transfer the velocity and pressure over their perpendicular surfaces. Shortly, continuity is not possible over the surface, but only collision forces can be transferred. This makes the turbulence flow really chaotic; as the collisions are of course dependable on the surface and collision angles. And this is highly variable in case of fluids.

**Simple calculation about the water splitting energy**

If a laminar flow is cut to a typical drop size; 0.05 ml = 50 mm3 cubic-shaped drops assumed, the surface energy consumed by a 1 m3 of water is 270 x 270 x 270 drops, each with a 81 mm2 surface, totalling 1628 m2, 0.072 J/m2 each, sums up 117 J, Which already makes a head loss of a 1.2 cm. If the splitting is made with a sudden pressure shock, the drop size will of course be much smaller, and the surface amount exponentially higher, A head loss of 1 m, needs actually only that the water is split to a particle size of 132 m2/kg (Blaine fineness), and though that might sound much, i.e. a normal Cement has typically 500 m2/kg, and Micro-cements over 1200 m2/kg.

This calculation example doesn’t even include the energy losses caused by the viscous losses in the rotating vortices of the turbulent flow. This all concludes the great importance of holding the continuity and avoiding all kind of flow disturbances. In open channel flows, the form losses could count up to 92% of the total loss, so the meaning of surface roughness can be only 8 % of the losses. [5]
JOKELA-TURBINE, Regulation

As the Runners of the Jokela-Turbine are optimally shaped also according to the continuity rule, providing really stable performance, they can quite easily have the same rpm ratio, and thus they can be fix-connected to just one generator. So the whole set has only 3 rotating components. And the whole regulation can been made with a really simple way; generator is rpm-variable Permanent-Magnet-Generator, where the Voltage and Current are variables and the frequency can been used to define the exact rpm of the turbine. This aloud the turbine to be exactly adjusted to Pressure-Head changes and the flow is adjusted at least similarly as the simple-regulated Kaplan.

MEL-Structures, Minimum Energy Loss-Structures

MEL-structures were invented by Gordon McKay in 1959. They are designed simply by the continuity rules, which amazingly also results the Minimum Energy Loss conditions. The continuity is hold by calculating the constant total head, also constant total Energy amount. The flow conditions are optimized by Froude-number. The form changes are streamlined very similarly like in Venturi-tube. The pressure change is corrected with Elevation change. This aloud use of higher flow velocities and smaller cross-sections. The velocity is created with lower water surface level and river bed. This provides very economical Culverts.

Also MEL-Weirs have been made. They are basically overflow embankments, and they are beneficial as they allow an additional water to be stored in the reservoir without flood problems. These Mel-Weirs are not dissipating energy. Their purpose is to conserve the energy and to make the downstream flow velocity higher and thus also the flood-flow capacity higher.

It should be noted, that the though the Froude-number correlates perfectly with the flow condition and the energy losses, it doesn’t even need to be one. As long as it’s kept below FR=$\sqrt{3}=1.73$, and the changes are streamlined, the energy losses remains negligible, as shown in Figure 4. [6]

![Fig. 4: USBR-experimental curve](image-url)
The reason why the Froude number $\sqrt{3}$ is the limit where the turbulence called “hydraulic jump” begins in open channel flow at that point, can also been read from this figure above. It’s the point where the flow depth doubles from 0.4 to 0.8 over the hydraulic jump. Shortly said it simply supports perfectly my theory about Turbulence. I mostly think this through small balls, and with one ball you can’t push more then two balls wide at front of you, as the two balls in front will split apart at the point where the ball behind them is pushed between them, which must lead to a flow separation, -> Turbulence. But explaining this further is out of the scope of this paper.

**MEL-Drop Structure**

This Structure is very similar with MEL-Weir, but the difference is that this structure is primarily developed for efficient energy dissipation in low heads and high flows. The majority of the dams in world are these kind low head dams, and their energy dissipation is normally based on a hydraulic jump, which capability to dissipate energy typically disappears in high flows or the dam must be so high that the fish migration is prevented.

![MEL-drop structure, top view](image)

In MEL-Drop Structure the energy dissipation is based on vertical vortices created by a nozzle kind of arrangement in the flow. As the vertical vortices can’t be over floated, their capability to dissipate energy doesn’t disappear in any imaginable flow situation.

Further advance of this structure is that as the Water level is dropped without energy losses, it’s possible to construct the hydropower plant’s intake and draft tube in a way that no “Head loss” will occur in high flows. “The head”, when defined with water level differences isn’t constant, as the Velocity head varies, but the total energy remains constant. As the flood flow energy is dissipated after the turbine Draft-tubes, it is even possible to catch a part of this overflow energy in a form of an additional total head.

**Jokela-Turbine + MEL-Drop structure**

So now when we have a regulated, high power density turbine for the lowest heads, with affordable price AND a weir construction which eliminates the Head losses in high flows, we are able to take a complete new approach to hydropower plant building. The ship hydrodynamics have been defined by Froude number ever since William Froude discovered this rule. And it can be noted that also alluvial streams reformates by the Froude law. Simply; where the flow velocity is high, the water is deep. These natural streams tend to reformate also
according to the soil material to a certain shape of open channel. It’s also well known, which is the most efficient cross-sectional shape; semi-circle.[7] But for constructive reasons the trapezoidal channel is mostly used. Further, the rectangular channel where \( B=2d \) provides the most compact solution. It can also be noted that the Yearly HQ or simply duration curve, and the river width has a certain correlation. With these parameters, the downstream side of the hydropower plant can be defined. We choose yearly HQ, and calculate the optimum shape for it; \( B=2d \). According to my experience the river widths of these yearly HQ’s in typical Persistent Regime duration curves are approximately 3x this width; upstream side defined. Now maximum amount of Turbines should be mounted to this kind of weir. All the dimensions of these turbines can be defined by Turbine diameter, the intakes and draft tubes must have enough space etc. After many iterations I have came to Froude-number scalable power plant as shown in this table 1.

The Concept nominal size is simultaneously the Turbine Nominal Diameter, The nominal Head of the hydropower plant and even 1/10 of the River Nominal width. And as can been seen, the Turbined flow is approximately \( \frac{1}{4} \) of the Yearly HQ with three Turbines. There practically isn’t any more space for more Turbines. And there definitely is no space for powerhouse. The estimated energy production can also be calculated, and with this typical duration curve, it provides enough flow for the turbines that the first Turbine can run all year round, the second 300 days, and the third 215 days. The production is calculated with 90% machine up-time.

<table>
<thead>
<tr>
<th>Table 1:</th>
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<tr>
<td><strong>MEL + Jokela Turbine = Total Solution.</strong></td>
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<tr>
<td><strong>Froude Number scalable Hydro Power Plant.</strong></td>
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<tr>
<td>Concept nominal Size</td>
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<td>River Nominal Width</td>
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<td>Yearly HQ, HQ 1</td>
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<tr>
<td>Total Q of Turbines</td>
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<tr>
<td>Electric Power</td>
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<td>Estimated production</td>
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**Comparison to other techniques**

S.J. Williamson’s work titled “Low Head Pico Hydro Compared using Multi-Criteria Analysis” [8] has made a really covering comparison from the 13 other turbine system architectures found in existing literature. We have even contacted Mr. Williamson to make sure that our comparison is made with the same criteria. The Results are shown in the Figure 6. and 7; Blue; “Jokela”, Red; “Reaction” Yellow “Impulse”.

As can been seen, this concept is able to combine the best aspects from both turbine types, and is even better then none of the existing machines.
Comparison of Energy production

A calculation example has been made from River Aare, in measurement station Thun, with the measurement data from 2011. The results are shown in Figure 8.

The nominal head used in this calculation example is 2.4 m. The black line is the measured flow. The red is the measured downstream water level, and the potential power which these provide with constant upstream water level. The yellow line is the Head, and potential power in a case where the downstream side is held in critical flow conditions and the upstream side remains constant.

The blue line is the potential Head and power if the upstream water level varies too with flow; Head is constant. The “bump” in this constant head is the additional head gained from the supercritical overflow. The total potential gain in year is in this case 38.2 %.

The same case was calculated with the different turbines of same size; “Jokela”, “propeller turbine” and “Kaplan”. Though in reality the Kaplan turbine can’t even be used in this construction because its regulated guide vanes needs regular service and thus a turbine house. The space needed by the guide vanes was taken into account. The main reason why Kaplan is shown here is to make visible how the power density is more important issue in low head.
installations than highest efficiency with wide and flat regulating curve. The comparison results are shown in Table 2.

Other aspects

This kind of power plant provides also solution to sedimentation/erosion of the reservoirs. As the flow is hold nearly critical in both sides of the plant, no sedimentation should be expected to happen on the upstream side, and also no erosion on the downstream side. The complete concept includes also a fish pass, which is placed optimally in middle of the plant so that it can be easily expected that the fishes find it. A certain type of fish pass is developed for this concept, as the bed load transportation is expected to pass also through this fish pass. First tests have been very promising.

Rake cleaning is another, very important aspect in such a run-of-the-river hydropower plant. Here this new turbine provides a very interesting solution. As the Turbine generator is actually a pressure/flow-sensor it self and can be very easily regulated in shortest reaction times, it can be also used in rake cleaning. in this concept the water intake to Turbine must anyhow be made from near the surface, and if the intakes are shaped with the MEL-Principe they can have a falling water surface and thus such an horizontal rake can be used which has an open edge remarkably lower than the upstream side water level. The rake cleaning is then based on the same concept as the flow regulation. The Turbine doesn’t know what the reason for a pressure drop is; maybe it’s because there is less flow in river and thus the water level has dropped, or maybe the rake is blocked, and the penstock pressure is there for dropped. The result is the same; the turbine rpm is lowered, and the Turbined flow is reduced. In the case of rake blockade this leads to an overflow, which cleans the rake, and immediately as the rake is cleaned the Turbine feels more pressure and regulates the rpm up again.

Table 2:

<table>
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<tr>
<th>Yearly production with same Turbine size.</th>
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<tr>
<td>- 3 x JT+M&lt;sub&gt;EEL&lt;/sub&gt;,</td>
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<td>- 3 x JT, Qnom=120 m&lt;sup&gt;3&lt;/sup&gt;/s,</td>
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<tr>
<td>M&lt;sub&gt;EEL&lt;/sub&gt;, +36.1%, KT-&gt; JT+M&lt;sub&gt;EEL&lt;/sub&gt; +54 %</td>
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<td>- 3 x „Hydromatrix“+M&lt;sub&gt;EEL&lt;/sub&gt;,</td>
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<tr>
<td>- 3 x „Hydromatrix“, Qnom=98.4 m&lt;sup&gt;3&lt;/sup&gt;/s</td>
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<td>M&lt;sub&gt;EEL&lt;/sub&gt;, +31.2%, KT-&gt; „Hydromatrix“+M&lt;sub&gt;EEL&lt;/sub&gt; +35.8%</td>
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<td>(Disclaimer: The character of „Hydromatrix“ is not fully known.)</td>
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<td>- 3 x KT + M&lt;sub&gt;EEL&lt;/sub&gt;,</td>
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<td>- 3 x KT, Qnom=69 m&lt;sup&gt;3&lt;/sup&gt;/s</td>
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<tr>
<td>M&lt;sub&gt;EEL&lt;/sub&gt;, +31.0%</td>
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<tr>
<td>Example calculated for River Aare, Thun, with 2011 data</td>
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<td>And with nominal Head, H=2.4 m</td>
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Acknowledgements

This paper holds my first properly published, somehow complete view about the continuity and Turbulence. I’ve had this idea for a long time. I tried to publish this Figure 3, in “Annals of Physics” at October 2012, but my one A4 paper was found not to be fulfilling the requirements given for such a scientifical-paper. I shared this same paper and idea with Hubert Chanson already at that time. And as I thanked him then, I want thank him again for these words “Interesting, original, not conventional” -he replied me. Actually they are the only supporting words so far, which I’ve had without need to fight against some prior assumptions during the struggle I’ve had with these developments.

As I’ve also read the Book of Mr. Chanson, and I must share the comment of Canadian Journal of Civil Engineering about him; “Reading through the book, one cannot miss the tremendous enthusiasm the author has for hydraulic engineering.”

I also want to thank Arun Kumar, for his requirement that I must provide a paper which is not published before. This forced me to create this complete new paper from scratch in last 3 days, and opened the possibility to take this step. But most of all, I want to thank “CH”, an energy source which provided myself the energy and tremendous enthusiasm I needed myself to finally step forward and say loud these unconventional thoughts of mine.

Jouni Jokela, Frutigen, Switzerland 10.1.2015

References / Data sources


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