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# A reference pelton turbine - design and efficiency measurements

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**Abstract.** The Pelton turbine has been subject to a varying degree of research interest since the debut of the technology over a century ago. Despite its age there are gaps in the knowledge concerning the flow mechanisms effecting the flow through the turbine. A Pelton turbine has been designed at the Waterpower Laboratory at NTNU. This has been done in connection to a Ph.D. project focusing on the flow in Pelton turbine buckets. The design of the turbine has been conducted using in-house knowledge in addition to some comments from a turbine producer. To describe the geometry multiple Bézier curves were used and the design strategy aimed to give a smooth and continuous gradient along the main flow directions in the bucket. The turbine has been designed for the operational conditions of the Pelton test rig installed at the Waterpower Laboratory which is a horizontal single jet test rig with a jet diameter( $d_s$ ) of 35 mm. The diameter( $D$ ) of the runner was set to 513 mm and the width( $W$ ) of a bucket 114 mm, leading to a  $D/W$  ratio of 4.5. Manufacturing of the turbine has been carried out in aluminium and the turbine has undergone efficiency testing and visual inspection during operation at a head of 70 m. The turbine did not performed as expected and the maximum efficiency was found to be 77.75%. The low efficiency is mainly caused by a large amount of water leaving the bucket through the lip and hence transferring close to zero of its energy to the shaft. The reason for the large lip loss is discussed and two possible causes are found; the jet is located too close to the lip, and the inner surface of the bucket does not lead the water away from the lip. The turbine geometry and all data from both measurements and simulations will be available upon request in an effort to increase the amount of available data concerning Pelton turbines.

## 1. Introduction

In a time where the environmental crisis caused by human activity becomes more evident each year, the need for further development within renewable energy technology increases. The Intergovernmental Panel on Climate Change (IPCC) promotes a number of technologies as means to mitigate the effects of the climate change, one of which is hydro power [1]. On a world wide basis the work done within hydro power projects are either mainly refurbishments of existing power plants, or construction of new ones. The ratio between existing and potential installation differs vastly between continents; above 60% in Europe and North America, and in the order of 20% in Asia, Africa and South America [2]. Multiple types of hydro power turbines exists, and this paper will focus on one of them; the Pelton turbine. The Pelton turbine is defined as an impulse turbine as it utilizes only the kinetic energy from the water as it passes through the turbine. The Pelton turbine operates in an open housing and is usually installed in areas with a high head and a relatively low flow.



The Pelton turbine was first developed over a century ago, but despite its long history there are still gaps in the knowledge regarding the turbine. This is especially true for the flow mechanisms effecting the water as it flows through the bucket.

A Ph.D. project at the Waterpower Laboratory at the Norwegian University of Science and Technology is currently working on improving the knowledge regarding the flow in Pelton turbines[3]. Due to the natural limitations concerning publication of results concerning turbines from commercial companies, one of the goals of the project has been to design and manufacture an open reference Pelton turbine.

Few publications exist regarding the design of Pelton turbines, fewer still go deeper into the substance than suggesting a general shape of a single cross section. In his book *Freistrahlturbinen: Hydromechanic und Auslegung*, Zhang derives a set of equations to define a single cross section with the use of elliptic curves, and suggests that the longitudinal shape of the bucket should also have an elliptic shape[4]. The method utilizing elliptic shapes includes no method for controlling the location of the deepest point of each cross section, and therefore, the method is not used in this paper. To the authors knowledge there are no published description of how the full 3D geometry of a Pelton turbine bucket should be defined.

## 2. Design parameters and strategy

The basis for the design is that the water reacts better to a smooth and continuous gradient than to large changes through the bucket. In addition the water is believed to follow the path of least resistance, i.e. the deepest line on a surface. As a basis for the main dimensions and defining ratios, the empirical rules of thumb published by Brekke[5] have been used as a basis for the turbine presented here. In Figure 1, the main dimensions of a Pelton turbine bucket are denoted, and Table 1 lists their quantities along with characteristic factors. In addition to the empirical rules of thumb the dimensions of the turbine are also limited by the available test rig[3].

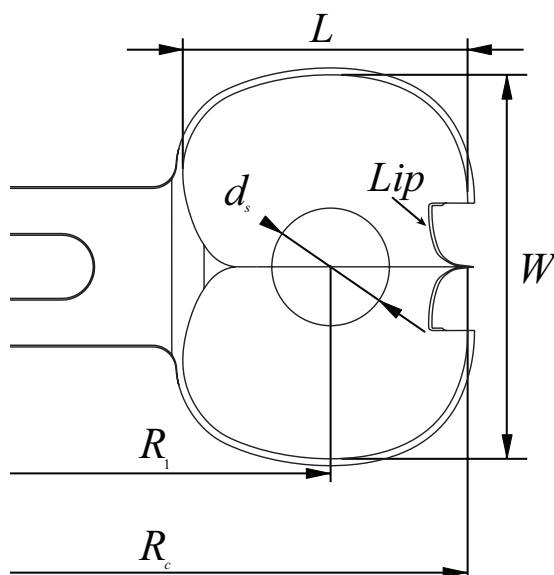


Table 1: Physical Dimensions.

Parameter	Value
Head ( $H$ )	70.0 m
Pitch Radius ( $R_c$ )	256.7 mm
Tip Radius ( $R_1$ )	297.9 mm
Width ( $W$ )	114.2 mm
Length ( $L$ )	84.7 mm
Jet Diameter ( $d_s$ )	35.0 mm
Number of buckets	23
$D/d_s$	14.68
$B/d_s$	3.26
$D/B$	4.5

Figure 1: Main dimensions of the bucket

As seen in the table above, the  $D/d_s$  ratio is close to 15 which is the recommended value from

Brekke for an  $H$  of 1400 m[5]. This was done due to the fact that two other runner discs made for 22 and 21 buckets are available at the laboratory. The buckets were designed so that they may be mounted on said discs to study the effect of the number of buckets.

### 3. Design steps

A parametric design program for Pelton turbines has been created in steps to build the model of the bucket. The procedure relies heavily on Bézier curves to define the edges and cross sections of the bucket. The general definition of an  $n$  control point Bézier curve is shown in Equation 1[6]. In the equation  $\mathbf{C}$  denotes the coordinates of a point at the position  $t$  along the curve,  $n$  the number of control points, and  $\mathbf{P}_k$  the coordinates of the  $k$ -th control point.

$$\mathbf{C}(t) = \sum_{k=0}^n \binom{n}{k} \cdot t^k \cdot (1-t)^{(n-k)} \cdot \mathbf{P}_k, \quad t \in [0, 1] \quad (1)$$

#### 3.1. General geometry definition

Bézier curves are used to define the outline of the bucket and the deepest line along the length of the bucket. The edges are split into 4 segments as shown in Figure 2, and each of them were defined by a Bézier curve with 2 to 5 control points. As seen in the figure the lip is defined as a straight line in the design program, but is later cut from the surface as a CAD operation, with the geometry as defined in Section 3.3. The deepest line along the length of the bucket is defined by a 7 control point Bézier curve, and is connected to the outline of the bucket at the junction points of the lip and outlet edge, and the outlet and root edge. The vertical angle at the end points of the deepest line is defined by the angle at the connection points on the outline.

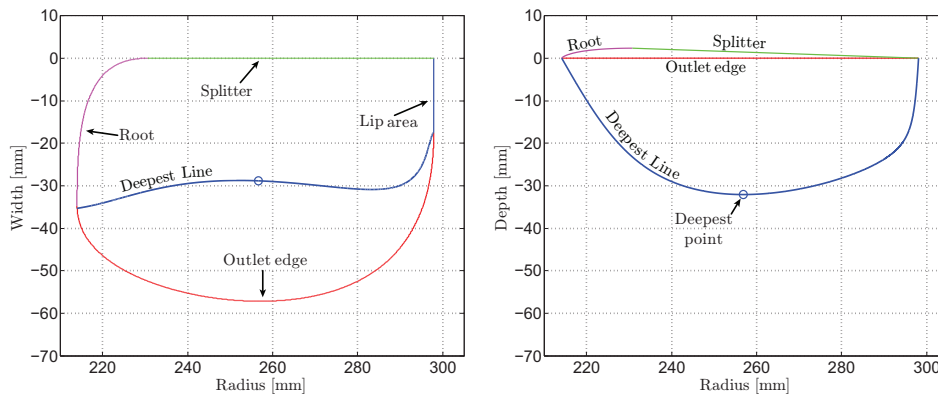


Figure 2: Outline and the deepest line of the bucket geometry

Along the edges the angle of the inner surface is defined as a continuous curve as shown in Figure 3. In the figure the location 0 denotes the junction point of the splitter and lip edge, and the location increases in the clock wise direction, with each edge having a unit length.

#### 3.2. Cross section generation

To define the different cross sections in the bucket, a function was created to find the correct cross section based on four input parameters listed below, and defined in Figure 4.

- Inlet and outlet angles ( $\alpha$  and  $\beta$ ).

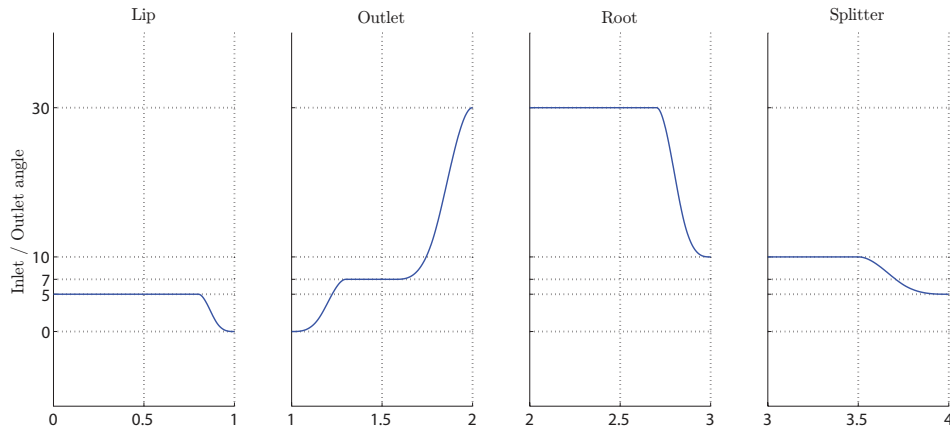


Figure 3: Angles of the inner surface along the outline

- The location of the deepest point in the cross section ( $X_b$  and  $Y_b$ ).
- The height of the inlet relative to the outlet ( $\Delta h$ ).
- The width of the bucket ( $W$ ).

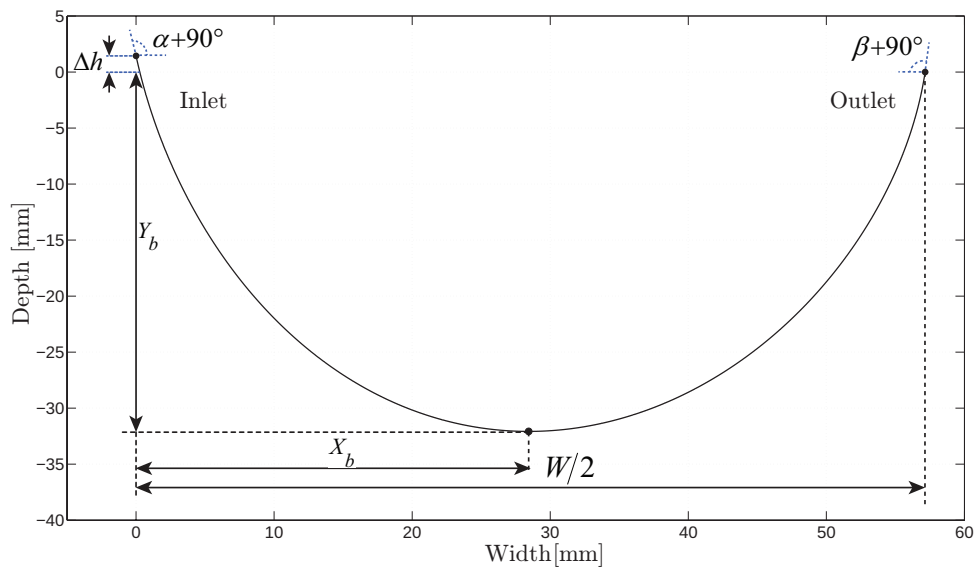


Figure 4: Input parameters of cross section creator

The cross section is defined by a 5 control point Bézier curve and the interpolation is done by placing the end points as defined by  $\Delta h$  and  $W$ . The inlet and outlet angle are defined by using the adjacent control point to each end point, and placing it at the defined angle below the end point. The centre control point is used to place the deepest point at the specified position.

### 3.3. Lip and cut-out definition

The lip is defined based on the timing of the cut into the jet. Figure 5 shows the time of jet interaction, at the top, and the resulting lip contour below. The time of jet interaction is defined

as a  $\chi_5^2$  probability density function. This is chosen to ensure a quick initial cut and then a near linear propagation of the lip into the jet. The jet position in the bucket at  $90^\circ$  impingement is shown in Figure 6.

Due to the complex geometry of the inner surface of the bucket, the lip is found by first defining the shape of the lip curve, estimating the corresponding cut in the inner geometry, and thereafter moving the estimated lip curve 1 mm away from the geometry at an angle of  $70^\circ$  downwards. This is due to the importance of a correct lip location when calculating the back side of the bucket in the lip area, i.e. the cut-out. It is also the cause of the small surface at the lip as seen in Figure 1.

The cut-out surface is defined by calculating the relative path of the last water that passes the lip and hits the the previous bucket. This is done for all widths of the jet, and hence a surface is acquired. This surface is then tilting  $10^\circ$  toward the bucket to ensure no impingement of the water that passes close to a bucket on the path to another.

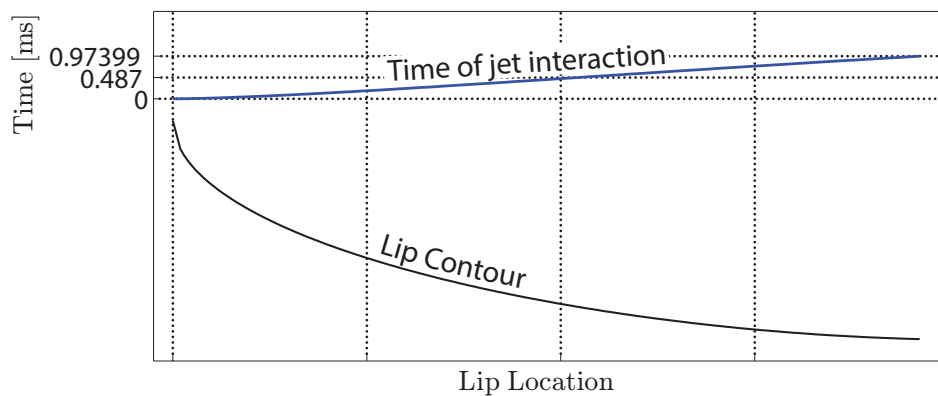


Figure 5: Propagation of the lip into the jet

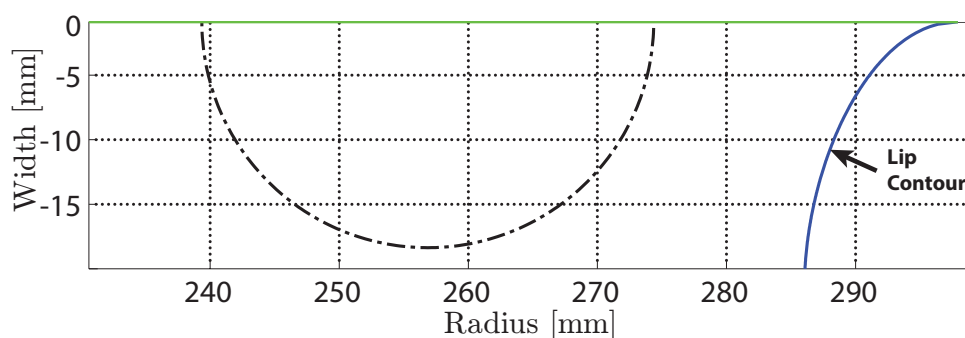


Figure 6: Jet position relative to lip at  $90^\circ$  impingement

### 3.4. 3D definition of the bucket

After the outline with corresponding surface angles and the deepest line are defined, the design program produces 29 cross sections through the bucket. One cross section through the deepest point of the bucket, and 14 on both sides. The inner surface of the bucket is then divided in two pieces, one being the upper right quadrant of the bucket where the lip is to be cut, and

the other consisting of the remaining 3 quadrants. In the upper right quadrant the surface is defined by a rectangular grid while the other surface quilt is defined by 16 contour lines as seen in Figure 7. The lines forming the rectangular grid are extensions of the height contours so that the curvature over the junction between the two surfaces is continuous.

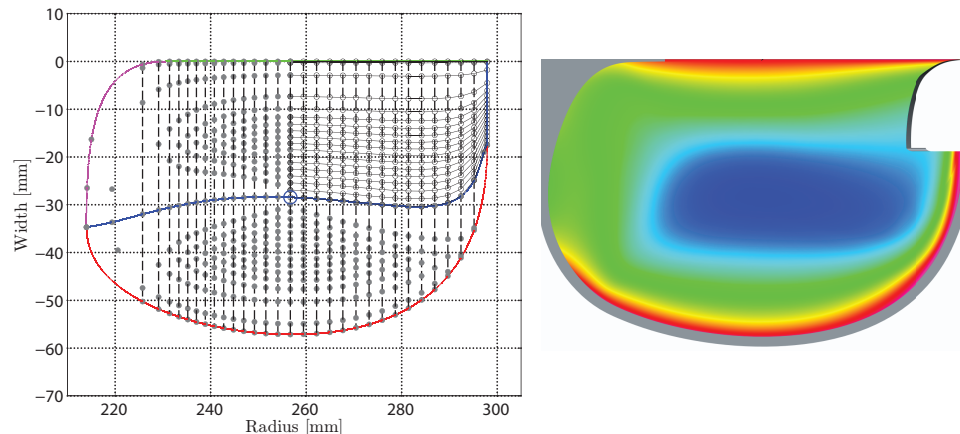


Figure 7: 3D definition of the bucket and the resulting CAD model with the slope indicated

### 3.5. CAD modelling of the bucket

The points shown in Figure 7 are implemented into CAD using Creo Parametric where splines are created through the points making up the different contour and grid lines. Each contour line is made with a continuous curvature to a horizontal and vertical grid line. Two surfaces are created from the grid and contour lines respectively. The lip is cut from the front surface, and the surfaces are merged with the cut out section. The outer surface of the bucket is created with a combination of a 2 mm offset from the inner surface and a flat surface at the center of the bucket. All surfaces are merged and the bucket is solidified.

## 4. Results

The design presented above was manufactured by milling individual buckets from aluminium and a runner disc for 23 buckets milled from stainless steel. The buckets were mounted on the disc and fastened with two bolts. After assembly the turbine underwent a complete efficiency measurement in the test rig at the Waterpower Laboratory [3]. The resulting hill diagram with an absolute uncertainty in the order of  $\pm 0.25\%$  is shown in Figure 8. As seen from the figure the highest efficiency of the turbine is  $77.75 \pm 0.24\%$  and the best efficiency point is located at a very low  $Q_{ED}$  level.

At the operational points marked in Figure 8, high speed filming of the turbine in operation was conducted. Pictures from these films, at approximately the same bucket position, are shown in Figure 9 with the  $Q_{ED}$  and  $n_{ED}$  data for each point noted.

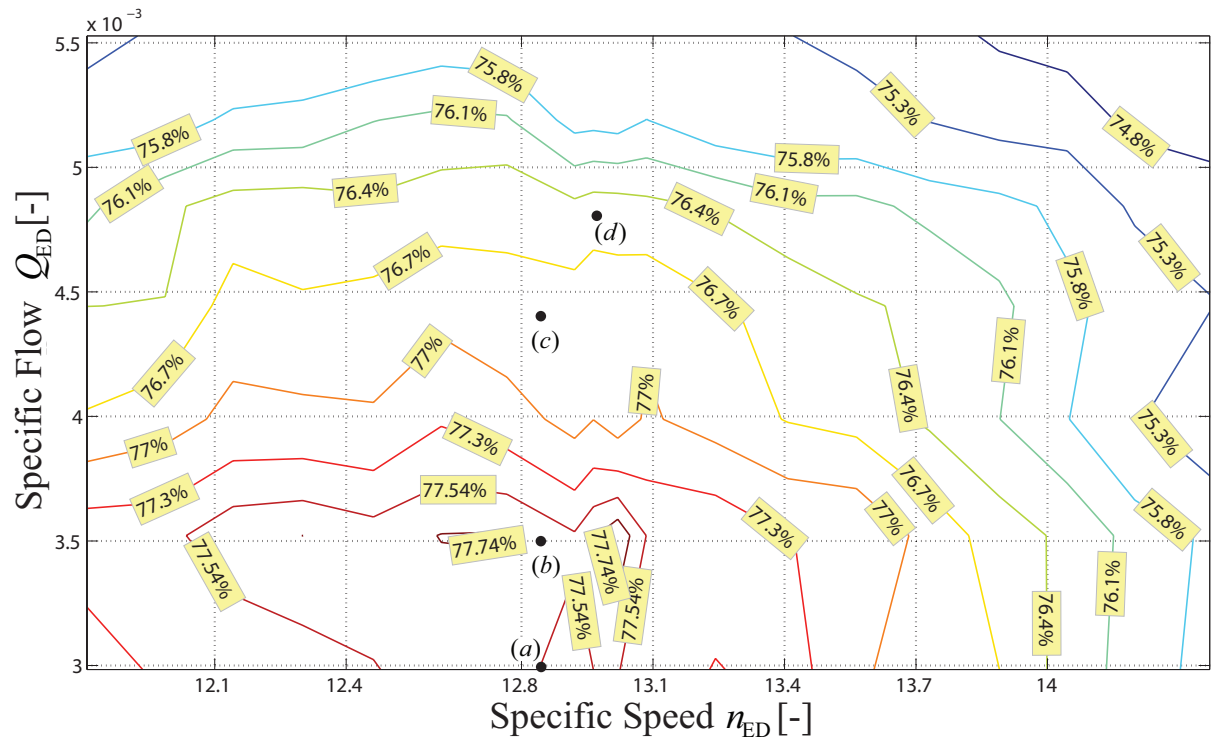


Figure 8: Hill diagram with operational points of Figure 9 indicated



(a)  $n_{ED} = 12.82$   $Q_{ED} = 3.0 \cdot 10^{-3}$ (b)  $n_{ED} = 12.82$   $Q_{ED} = 3.5 \cdot 10^{-3}$ (c)  $n_{ED} = 12.82$   $Q_{ED} = 4.4 \cdot 10^{-3}$ (d)  $n_{ED} = 12.96$   $Q_{ED} = 4.8 \cdot 10^{-3}$ 

Figure 9: Pictures from high speed camera filming at different operational points

## 5. Discussion

The turbine design presented in this paper shows a low efficiency and the best point of efficiency is located at a much lower flow rate than the design flow. When studying the flow in the lip area at the different operational points shown in Figure 9 one can see that the amount of water leaving the bucket through the lip increases severely as the normalized flow increases. The lower quality of the picture shown in Figure 9d is caused by less light reaching the bucket due to a larger amount of water in the air, and flowing along the plexiglass, blocking the light. Studying Figure 6 one may conclude that the jet is too close to the lip area. This is also confirmed by Arne Kjølle in his book *Vannkraftmaskiner*[7] where it is stated that the ratio  $(R_c - R_1)/d_s$ , as denoted in Figure 1, should be 1.3 – 1.6. For the turbine presented here the ratio is 1.17, and hence the jet is too close to the lip when it impinges the bucket at  $90^\circ$ . In addition to the jet location, the gradient, as shown in Figure 6, does not increase towards the lip, and hence, will not lead to any repelling effects on the water as it would if the lip was preceded by a increasing gradient. When testing the turbine, the amount of water leaving the bucket through the lip caused a large amount of vibrations and accompanying noise due to water hitting an angled plexiglass window in the rig with a high velocity. The pictures in Figure 9 also show some back wash, i.e. water leaving one bucket hitting the back of the consecutive bucket. This can be seen in the form of relatively flat sheet of water originating at the outside of the lower bucket in the area close to the root. This back washing is believed to be caused by the small angle,  $7^\circ$ , at the centre of the outlet edge, as shown in Figure 3. This also causes a lowering of the efficiency but it is not believed to be the main culprit.

## 6. Conclusion

The design method presented in this paper is believed to be a good tool for parametric design of Pelton turbines and gives the possibility to investigate the effects of parameters on the flow within the turbines. The efficiency of the turbine is lower than expected and this is mainly caused by a large amount of water leaving the bucket through the lip without transferring its energy to the turbine. This water leads to a lot of vibrations and noise when running the rig as it impinges on a plexiglass window in the test rig. To counteract this loss of energy the jet should be moved to a smaller radius relative to the lip. In addition, the inner surface of the bucket leading up to the lip should have an increasing gradient and thereby lead the water away from the lip. This can be implemented into the design method by defining the lip area based on the cut out surface, and achieve a steeper slope leading to the lip.

## 7. Further work

To further study the flow in the lip area of the turbine, changes in the jet position( $R_1$ ) relative to the lip will be investigated. Alterations to the test rig are planned to accommodate changing the jet position while the turbine is running so that these effects may easily be studied.

A parameter study of the design is planned and will consist of three to four new designs being tested where the following changes are proposed:

- Changing the length of the bucket ( $L$ ) while keeping all other parameters constant.
- Altering the surface close to the lip with the cut out as a basis as proposed above.
- Redefining the shape of the lip curve.

## References

- [1] Intergovernmental Panel on Climate Change 2011 *Renewable Energy Sources and Climate Change Mitigation* Summary for Policymakers and Technical Summary : Special Report of the Intergovernmental Panel on Climate Change (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press)
- [2] International Journal of Hydropower & Dams 2010 *World Atlas & Industry Guide 2010* (Wallington, Surrey, UK: Aqua Media Int'L)

- [3] Solemslie B W and Dahlhaug O G 2012 *IOP Conference Series: Earth and Environmental Science* **15** 032005
- [4] Zhang Z 2009 *Freistrahltubringen: Hydromechanik und Auslegung* (Springer)
- [5] Brekke H 2003 *Pumper & Turbiner* (Vannkraftlaboratoriet NTNU)
- [6] Weisstein E W Bézier Curve, From MathWorld - A Wolfram Web Resource URL <http://mathworld.wolfram.com/BezierCurve.html>
- [7] Kjølle A 1980 *Vannkraftmaskiner* 2nd ed (Trondheim: Universitetsforlaget)